

**15th International Conference on the
Scientific and Clinical Applications of
Magnetic Carriers**
Paris, France



Coffee mug design © 2026 by Ilaria Armenia (University of Insubria) and Gianluca Tomasello (3D protein imaging studio - 3Dproteinimaging.com).

Welcome Message – Bonjour à Tous

It is our great pleasure to welcome you all to the 15th International Conference on the Scientific and Clinical Applications of Magnetic Carriers. This year marks the 30th anniversary of our conference which is and has always been centered on the world of small magnetic particles and microspheres that have been life-long friends for many of us. And like children that pass through many different stages to reach adulthood and finally their senior years, magnetic particles change, challenge and surprise us again and again.

This year we are meeting in the heart of Paris, at the Sorbonne University, one of the most prestigious educational institutions in the world. It has been a symbol of French intellectualism for more than 750 years, received 33 Nobel prizes and is particularly well known for Marie Curie, who joined its Faculty of Sciences in 1891, was the first woman to teach here as a professor, and received two Nobel prizes.

While we're here at the Sorbonne University we're looking forward to discussing, with you all, the insights, basic principles and new applications in physics, chemistry, biology, medicine and imaging of magnetic particles that were developed and investigated since our last conference. The evolution and the new exciting trends in our field should be enough to take your minds off world politics for a few days, and let you enjoy magnetic particle talks, the exchange of exciting information, meeting colleagues, old and hopefully new collaborators, the poster sessions, and our traditional boat trip.

We hope that this sense of exceptionalism will spur you on to discuss your results with your colleagues and enjoy a very special week, both professionally and personally. As the French say: joignez l'utile à l'agréable, et profitez bien de cette conférence !

Your organizers,

Emilie Secret, Sorbonne University, CNRS, Paris, France

Urs Hafeli, University of British Columbia (UBC), Vancouver, Canada

Social Program

Tuesday, May 26th

We will celebrate the start of our meeting with a reception at Sorbonne University. This reception is generously sponsored by [micromod](#).



Wednesday, May 27th

During the day, a spouse tour is organized. Spouses and children will go to Giverny to visit Claude Monet's house and garden. An enjoyable visit, especially at this time of the year! For the participants, please be at the registration desk at 9:00.



On the evening, we will have the second poster session on the patio above the auditorium, with Pretzels and Beers. This poster session is generously sponsored by [Superbranche](#).

Thursday, May 28th

On Thursday evening, we will have our gala dinner with the traditional boat trip on the Seine. We will walk to the boat, which will wait for us right across the street from the University, just after the last session of the day. Make sure that your accompanying family meet us at the auditorium by 19:00. The boat tour is generously sponsored by [NanoTherics](#).

Poster awards, gererously sponsored by the journal [Magnetic Medicine](#) and by the [Nanoscale Journal Family](#), [Royal Society of Chemistry](#), will be handed out.



Conference location & maps

Our 15th meeting will take place at Sorbonne University, on the Pierre and Marie Curie campus, which is situated in the center of Paris. The address is “4 place Jussieu, 75005 Paris”, and the conference will take place in the CICSU Auditorium. There are two entrances on the campus, the front entrance is located on the “place Jussieu”, the back entrance is located on the “quai Saint Bernard”.

You can easily come to the university by metro (lines 7 and 10 are just in front of the university entrance, stop “Jussieu”) or by bus (line 63, 67 and 89).

Once on campus, the entrance of the auditorium is located between tower 54 and 55 (circled in purple on the map):





15th International Conference on the Scientific and Clinical Applications of Magnetic Carriers

Tuesday, May 26, 2026				
9:00	Registration desk opens at the CICSU auditorium, Université de Sorbonne, 4 Place Jussieu			
10:00	Secret, Emilie	Opening of the Conference and Welcome Address by the Organization Committee	Paris, France	Intro 1
10:10	Schuetz, Wolfgang & Zborowski, Maciej	Our International Conference is 30 Years Old - An Informal History by the Founders	Rostock, Germany & Cleveland, OH, USA	Intro 2
10:30	Häfeli, Urs	Short Review of the Last 2 Years of Magnetic Carriers Research	Vancouver, BC, Canada	Intro 3
11:00	Coffee break			
11:30	Battle, Xavier	Short Magnetic Nanoparticle Tutorial: The Magnetic Nanoparticle Iceberg	Barcelona, Spain	Tutorial 0
	Session 1: Magnetic Microrobots and Nanorobots			<i>Chair: Christine Ménager</i>
12:00	Zabow, Gary	Turning non-magnetic particles magnetic	Boulder, CO, USA	Talk 1
12:15	Bami-Chatenet, Yann	Magnetically-Steerable Drug-Loaded Microspheres for the Transarterial Chemoembolization of Liver Tumors via Magnetic Resonance Navigation	Montreal, Canada	Talk 2
12:30	Ghosh, Ambarish	Magnetic Helical Nanobots as Local Sensors: from model fluids to cells, and inside living animals	Bangalore, India	Talk 3
12:45	Mistral, Jules	Quantitative Accumulation of Magnetotactic Bacteria for Tumor Targeting by Application of Gradient Magnetic Fields	Saint-Paul-lez-Durance, France	Talk 4
13:00	Park, Myungjin	Magnetic Torque Trapping Enables Enhanced Retention and Translocation of Microrobots	Zürich, Switzerland	Talk 5
13:15	Lak, Aidin	Magnetic DNA origami nanorotors	Braunschweig, Germany	Talk 6
13:30	Lunch			
	Session 2: Biological Applications I			<i>Chair: Sylvie Bégin-Colin</i>
14:45	Kaub, Leon	Imaging Magnetic Stray Fields from Magnetite Nanoparticles in Human Brain Tissue with Nitrogen-Vacancy Centers	Paris, France	Invited Talk 1
15:30	Ko, Min Jun	Magnetically Programmable NK Cell Clusters Enabled by Magnetic Mesocrystals for Cancer Immunotherapy	Chicago, IL, USA	Talk 7
15:45	Ota, Satoshi	Tumor characterization via magnetization dynamics of magnetic nanoparticles for cancer theranostics	Hamamatsu, Japan	Talk 8
16:00	Coffee break			
	Session 3: Biological Applications II - Flash Talks			<i>Chair: Lucia Gutierrez</i>
16:30	Aderhold, Eric	Continuous Coagulation Monitoring of Human Blood via Magnetic Particle Spectroscopy	Lübeck, Germany	Talk 9
16:37	Gomez, Jenifer	Iron Regulation Proteins and Magnetic Behavior of Breast Cancer Stem Cells: Could Iron Be A Universal Marker for Label-Free Sorting?	Lubbock, TX, USA	Talk 10
16:44	Ma, Yunn-Hwa	Tannic Acid-Coating Augments Nanoparticle Uptake by Laminin Receptor-Mediated Endocytosis: Implication in Tumor Targeting	Tao-Yuan, Taiwan	Talk 11
16:51	Paez Rodriguez, Amira	Dynamic behavior and intracellular assembly of magnetic nanoparticle-loaded vesicles under AC magnetic stimulation.	Zaragoza, Spain	Talk 12
16:58	Reichl, Teresa	Magnetic Nanoparticles as Sensor for Brain Perfusion	Würzburg, Germany	Talk 13
17:05	Wang, Xuyiling	Characterising exogenous and endogenous magnetic nanomaterials in biological samples using a magneto-optical multifunctional microscope	Stoke-on-Trent, UK	Talk 14
17:12	Marsalin, Akash	Structural Engineering of Fe ₃ O ₄ Mesocrystals for Enhanced Magneto-Optical Cancer Therapy	Chennai, India	Talk 15
17:19	Zhang, Huan	Boosting T1 Relaxivity with Trace Mg-Doping in Ultrasmall Iron Oxide Nanoparticles for Subsegmental Pulmonary Embolism Imaging	Chengdu, China	Talk 16
17:30	Pellegrino, Teresa	Magnetic Nanoparticles: From Their Synthesis to Magnetic Hyperthermia, Cancer Immune Therapy and Cell Tracking Applications	Genoa, Italy	Invited Talk 2
18:15	Poster session I (Posters 1-53)			
19:30	Reception, generously sponsored by micromod			
21:00	Go and enjoy the night life in Paris			

Wednesday, May 27, 2026				
8:30	Registration desk opens at the CICSU auditorium, Universite de Sorbonne, 4 Place Jussieu			
	This is also the day of the spouse tour (Monet garden in Giverny)			
9:00	Van Leuven, Levy	Chemistry and Derivatization of Magnetic Nanoparticles - Part 1	Mons, Belgium	Tutorial 1
	Session 4: Magnetic Separation			Chair: Anna Bakenecker
9:30	Bünning, Matthias	Continuous-Flow Lithium Extraction from Geothermal Brines Using Magnetic Nanoparticles	München, Germany	Talk 17
	Session 5: Magnetic Particle Imaging (MPI)			Chair: Anna Bakenecker
9:45	Bermudez-Berrios, Esteban	Quantitative Evaluation of Nanoparticle Delivery to Lymph Nodes Using Magnetic Particle Imaging	Gainesville, FL, USA	Talk 18
10:00	Rösch, Esther	SMART RHESINs: A Comparative Specific Absorption Rate Analysis of Native and Encapsulated Synomag Nanoparticles for MPI-Assisted Magnetic Fluid Hyperthermia	Karlsruhe, Germany	Talk 19
10:15	Coffee break			
10:45	Nozka, Aniela	Formulation of nanocluster tracers with tunable magnetic particle imaging performance	Gainesville, FL, USA	Talk 20
11:00	Valdes, Daniela	Quantification of Magnetic Particle Imaging Signal in Biomedically Relevant Conditions Using a Mouse Phantom	Gainesville, FL, USA	Talk 21
11:15	Zhong, Jing	Mixing-Frequency Magnetic Particle Imaging System for 3D in-vivo Tumor Imaging	Beijing, China	Talk 22
11:30	Dutz, Silvio	Project harmoMPI: Scanner-Independent Functional Phantoms for Harmonizing Magnetic Particle Imaging	Zwickau, Germany	Talk 23
11:45	Bulte, Jeff	Engineering Magnetotheranostics for Magnetic Particle Imaging	Baltimore, MD, USA	Invited Talk 3
12:30	Lunch			
	Session 6: Magnetic Imaging Methods (MRI / Ultrasound)			Chair: Jeff Bulte
13:45	Brero, Francesca	Performance Analysis of Quantitative Susceptibility Mapping Algorithms in Phantom and Preclinical MRI Data	Pavia, Italy	Talk 24
14:00	Horak, Daniel	Magnetically Responsive Upconversion Nanoparticles: Optical Luminescence and MRI of Langerhans islets	Prague, Czech Republic	Talk 25
14:15	Levy, Benjamin	Ultrasound-Based Magnetic Nanoparticles Imaging: Improved Magnet Geometries and Elastometry	Easton, PA, USA	Talk 26
14:30	Reniaud, Jules	Shape-Dependent Magnetomotive Forces: A Framework for Optimizing Particle Geometry in Magnetomotive Ultrasound Imaging	Lund, Sweden	Talk 27
14:45	Mefford, Thompson	Gadolinium-Doped Iron Oxide Nanorods and Nanoflowers as Dual Modality Agents for Magnetic Hyperthermia and MRI	Clemson, SC, USA	Talk 28
15:00	Fan, Haiming	A Mitochondria-Specific Nanoparticle for Wireless Dynamic Regulation of Cellular Function in Vivo	Xi'an, China	Talk 29
15:15	Coffee break			
	Session 7: Magnetic Hyperthermia			Chair: Jérôme Fresnais
15:45	Rabade Chediak, Maura	Magnetic Hyperthermia-Induced Disruption of Collagen Scaffolds: A Strategy to Overcome the Extracellular Matrix Barrier in Solid Tumours and Fibrotic Diseases	Zaragoza, Spain	Talk 30
16:00	Castro-Torres, Jorge	Histopathological Assessment of Magnetic Fluid Hyperthermia in a Porcine Prostate Model Using a Handheld Induction Heater	Mayaguez, Puerto Rico	Talk 31
16:15	Gascon Gubieda, Alicia	Determining the mechanisms of action of magnetosomes in magnetic hyperthermia cancer treatment	Leioa, Spain	Talk 32
16:30	Hanson, Lise	Improving Measurements of Magnetic Nanoparticle Heating Power	Kgs. Lyngby, Denmark	Talk 33
16:45	Lopez Vazquez, Iago	SLPcalculator: Open-Access Software for Statistically Validated SLP Determination in Magnetic Nanoparticles	Santiago de Compostela, Spain	Talk 34
17:00	Patri, Sofia	Magnetic nanogels for combined hyperthermia and chemotherapy of prostate cancer	London, UK	Talk 35
17:15	Anker, Jeffrey	Catching and Counting Molecules with Buoyant Microbubbles and Magnetic Microspheres for Rapid yet Ultrasensitive Point-of-Care Diagnostics	Clemson, SC, USA	Invited Talk 4
18:00	Poster session II (Posters 54-107) - with Pretzel and Beer generously sponsored by Superbranche			
19:30	Free evening - go and get collaborations going!			

Thursday, May 28, 2026				
8:30	Registration desk opens at the CICSU auditorium, Universite de Sorbonne, 4 Place Jussieu			
9:00	Van Leuven, Levy	Chemistry and Derivatization of Magnetic Nanoparticles - Part 2	Mons, Belgium	Tutorial 2
	Session 8: Magnetic Drug Delivery I			Chair: Jeffrey Anker
9:30	Lafuente, Aritz	Opto-Magnetically Guided Monocytes for Enhanced Nanotherapy in 3D Bioprinted Tumor Models	Barcelona, Spain	Talk 36
9:45	Gigoux, Veronique	Magnetic Field-Induced Drug Delivery From Magnetic Microporous Nanocomposites Through Magnetic Nanoparticles Heating or Motion	Toulouse, France	Talk 37
10:00	Castellanos-Rubio, Idoia	Magnetic Hybrid Microdiscs as Tunable Carriers for Remote Actuation and Biomolecule Delivery	Leioa, Spain	Talk 38
10:15	Kuzhir, Pavel	Physical aspects of field-enhanced degradation of hydrogel networks: a step closer to thrombolysis	Nice, France	Talk 39
10:30	Coffee break			
	Session 9: Magnetic Drug Delivery II			Chair: Simone Schürle
11:00	Santi, Athena	On-Demand Magnetic Field-Responsive Nanodrug for Pain Modulation	San Antonio, TX, USA	Talk 40
11:15	Selzer, Solange	Senolytic nanoplatform to target and eliminate senescent melanoma cells	Zaragoza, Spain	Talk 41
11:30	Trizac-Mattern, Ludvine	Polyhistidine and doxorubicin functionalized magnetic nanoparticles enhancing intracellular heating efficiency in magnetic hyperthermia	Paris, France	Talk 42

11:45	Zelenakova, Adriana	Magnetic Nanocargo-Delivery Platform for Targeted Delivery of Anticancer and Antiviral Drug	Kosice, Slovakia	Talk 43
12:00	Espinal, Maider	Magnetothermally Activated 3D-Printed Implants for Programmable Drug Delivery	Pamplona, Spain	Talk 44
12:15	Begin-Colin, Sylvie	Engineering of Magnetic-Based Nanoplatfroms for Theranostic with a Focus on Targeting Strategies	Strasbourg, France	Invited Talk 5
13:00	Lunch			
	Session 10: Magnetic Methods / MPS I			<i>Chair: Pankhurst, Quentin</i>
14:15	Ackers, Justin	Measurement uncertainty analysis of a one-dimensional Magnetic Particle Spectrometer	Lübeck, Germany	Talk 45
14:30	Wang, Jian-Ping	Systematic analysis of parameters affecting colorization performance for magnetic particle spectroscopy applications	Minneapolis, MN, USA	Talk 46
14:45	Naeimabadi, Mina	1D Reconstruction of Magnetic Nanoparticles in an Unshielded Environment Using OPM-Based Magnetorelaxometry	Innsbruck, Austria	Talk 47
15:00	Stockdale, Arabella	Interpreting Magnetic Particle Spectroscopy Through Hierarchical Modeling of Interacting PEG-Coated Iron Oxide Nanoparticles	Clemson, SC, USA	Talk 48
15:15	Veile, Thomas	Simultaneous High-Frequency Magnetometry and AC Calorimetry for Magnetic Nanoparticle Characterization	Kgs. Lyngby, Denmark	Talk 49
15:30	Zverev, Vladimir	Dynamic Magnetic Response of Magnetic Multicore Particles: Competing Anisotropies	Vienna, Austria	Talk 50
15:45	Coffee break			
16:15	Bakenecker, Anna	Magnetic Particle Imaging and Functional Hydrogels for Micro- and Nanorobotics	Darmstadt, Germany	Invited Talk 6
	Session 11: Magnetic Characterizations / Methods / Analytics II			<i>Chair: Leon Kaub</i>
17:00	Arsalani, Soudabeh	Reference measurement site to characterize magnetic nanoparticles employed in biomedical applications	Berlin, Germany	Talk 51
17:15	Liu, Wenzhong	Real-time, rapid optical imaging method for single magnetic nanoparticles	Wuhan, China	Talk 52
17:30	Wang, Yihao	Magnetic molecular nanorulers for resolving conformational changes in nucleic acids at sub-nanometer spatial resolution	Braunschweig, Germany	Talk 53
17:45	Wen, Yumei	QCM Sensing the Magnetically Driven Motion of Particles for Biomolecular Analysis	Shanghai, China	Talk 54
	Session 12: Preparation of Magnetic Nanoparticles I			<i>Chair: Jean-Michel Siaugue</i>
18:00	Stoer, Philip	synomag-pro - The Benchmark for Theranostics	Rostock, Germany	Talk 55
18:15	Cotin, Geoffrey	Dendronized iron oxide: Superspio20 as MPI tracer and magnetic hyperthermia agent	Strasbourg, France	Talk 56
18:30	Meier, Nils	Tuning Core Size of Iron Oxide Magnetic Nanoparticles in Liposome-Based Nanoreactors: An In Situ Approach	Mainz, Germany	Talk 57
19:15	Walk to the Boat			
19:30	Boat tour on the "The River's King" with dinner, generously sponsored by NanoTherics			
21:30	Poster award hand-outs on the boat, generously sponsored by the new journal Magnetic Medicine and by the Nanoscale Journal Family, RSC			
23:30	Return to the Pier			

Friday, May 29, 2026				
8:30	Registration desk opens at the CICSU auditorium, Universite de Sorbonne, 4 Place Jussieu			
9:00	Van Leuven, Levy	Chemistry and Derivatization of Magnetic Nanoparticles - Part 3		Tutorial 3
	Session 13: Preparation of Magnetic Nanoparticles II			<i>Chair: Jean-Michel Siaugue</i>
9:30	Roca, Alejandro	Controlled Solvothermal Growth of Iron Oxide Nanorods with Tunable Size and Magnetic Properties for applications in Biomedicine	Cerdanyola del Valles, Spain	Talk 58
9:45	Shlapa, Yuliia	Magnetic CeO ₂ -Based Nanocomposites: Influence of the Synthesis Route on Structure, Morphology and Bioactivity	Kyiv, Ukraine	Talk 59
10:00	Descours, Pierre-Louis	Novel Magnetic Nanohybrids Coated with Peptides to Cross the human Blood-Brain Barrier and to Target Neuronal Mitochondria	Dijon, France	Talk 60
10:15	Alvaro Gallo Cordova	Continuous-flow microwave polyol synthesis enables scalable production of metallic nanoparticles	Madrid, Spain	Talk 61
10:30	Coffee break			
11:00	Pankhurst, Quentin	Translational R&D - the Endomagnetics Story	London, UK	Invited Talk 7
	Session 14: Preparation of Magnetic Nanoparticles II			<i>Chair: Teresa Pellegrino</i>
11:45	Guerrero Porras, Gabriel	Vectorization of functionalized IONPs with beta-amyloid-targeting ligands to obtain specific MRI contrast agents for the detection of Alzheimer's disease	Strasbourg, France	Talk 62
12:00	Mayr, Erik	Superferromagnetic Disk Particles for Magnetic Particle Imaging and Magnetic Particle Spectroscopy	Zürich, Switzerland	Talk 63
12:15	Radon, Adrian	Carbon-Coated Magnetite in Cancer Therapies: Challenges and Perspectives	Gliwice, Poland	Talk 64
12:30	Ehrlich, Victor	Pressure-Controlled High Temperature Continuous-Flow Synthesis of Iron-Based Nanoparticles: From Metastable Phases to Gold-Iron Heterodimers	Paris, France	Talk 65
12:45	Bouvet, Basile	In-Depth Investigation of the Magnetically Related Properties of Iron Oxide Nanospheres	Paris, France	Talk 66
13:00	Weisspflog, Maria	Magnetothermal-Triggered Response and Self-Healing of Recyclable and Reprocessable Nanocomposites for Actuation Systems	Hamburg, Germany	Talk 67
13:20	Announcement of the next Magnetic Carrier Meeting 2028			
13:30	End of the Meeting			

Turning Non-Magnetic Particles Magnetic

Gary Zabow

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Given their ability to readily penetrate fluids, magnetic fields are often used to interact with magnetic particles in biomedical, imaging, microfluidic, and self-assembly setups. This contact-free manipulation has proven so advantageous that it has even been employed on non-magnetic particles, albeit indirectly, typically through some ferrofluid medium that displaces the non-magnetic particles as the ferrofluid itself responds to the applied field. Here, an alternative means is explored to directly magnetically manipulate non-magnetic particles that does not rely on any magnetic properties of the surrounding medium, eliminating any ferromagnetic contamination and enabling operation in normal fluids or biological media. The process functions by employing RF magnetic fields to generate eddy currents in metallic particles that temporarily renders these non-magnetic particles effectively magnetic and thus able to generate their own magnetic fields and exert their own magnetic forces. One example of this is demonstrated in the figure below, which shows non-magnetic copper microdisks magnetically repelling each other, but the process potentially also opens new opportunities for non-magnetic particles across several other domains that were previously limited to magnetic particles only. While RF magnetic fields can require higher powers than DC fields — which may ultimately limit the size of the particles that can be used — the scheme potentially enables new areas of research into patterning / self-assembly of non-magnetic structures as well as new forms of magnetic sensing and new background-free magnetic resonance imaging not possible with traditional magnetic particles.

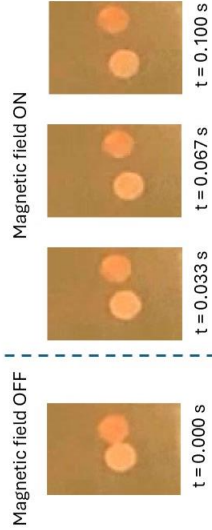


Figure: Non-magnetic copper disks magnetically repelling each other. A pair of small disks (3 micron thick, 500 micron diameter) made from pure, non-magnetic copper are shown floating on a water surface and then magnetically repelling each other after an RF magnetic field is activated normal to the plane of the disks.

Talk 1

Magnetically-Steerable Drug-Loaded Microspheres for the Transarterial Chemoembolization of Liver Tumors via Magnetic Resonance Navigation

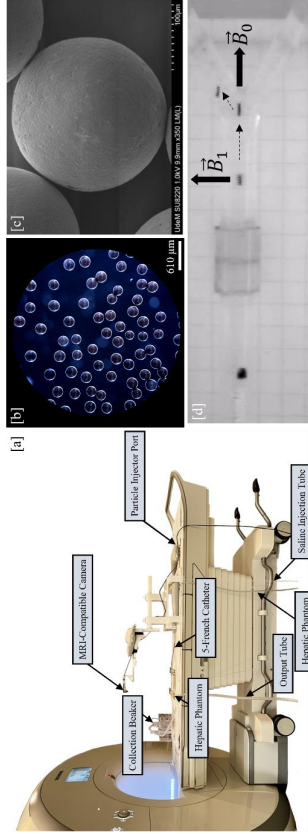
Yann BAMI-CHATENET^{*1,2}, Jennifer LIU^{*1,3}, Ning LI¹, Audrey FOHLEN^{1,3,4}, Mahdi REZAEI ADADRIANI^{1,3,5}, Cyril TOUS¹, Mariela GOMEZ PEREZ^{1,6}, Katayoun Saatchi⁷, Simon LESSARD¹, Urs O. HAFELI⁷, An TANG^{1,3,4}, Sophie LEROUGE^{1,2}, Gilles SOULEZ^{1,3,4}

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Transarterial chemoembolization (TACE) is a standard treatment for intermediate-stage hepatocellular carcinoma, combining intra-arterial chemotherapy with vascular occlusion. Drug-eluting beads (DEBs) can be used as embolic agents and drug carriers, enabling treatment of patients with impaired hepatic function; however, they require complex superselective catheterization under fluoroscopy with limited tumor visualization, leading to frequent reinterventions. This project aims at conceiving and investigating micrometric magnetic DEBs (MDEBs) encapsulating magnetic nanoparticles (MNPs) and doxorubicin (DOX), to be injected in the proper hepatic artery and magnetically steered across arterial bifurcations to the tumor site by Magnetic Resonance Navigation (MRN), using clinical MRI gradients.

Superparamagnetic biphosphonate-coated iron oxide MNPs (mean diameter of 12.0 ± 3.6 nm) are synthesized via co-precipitation and co-encapsulated with doxorubicin base in a poly(lactic-co-glycolic acid) polymeric network using microfluidic droplet generation to produce spherical micrometric MDEBs. Their morphological, mechanical, pharmacological, and magnetic properties are characterized via SEM, micro-compression tests, vibrating sample magnetometer, fluorescence spectroscopy, laser-scanning confocal microscopy and *in vitro* MRN sequence in a hepatic arterial phantom (fig. a). Drug release profiles were performed for DOX-MDEBs and DOX-loaded DC BeadsTM in FBS/PBS 1:1 using High-Performance Liquid Chromatography (HPLC).

Monodisperse and spherical MDEBs were generated (figs. b & c, 220.2 ± 25.8 μ m diameter, $n=115$). With regards to the size, their high rigidity (secant modulus at 10% strain is 1.7 ± 5 MPa) shows that MDEBs are ideal to penetrate the tumor, while limiting risks of distal embolization. Encapsulation of iron oxide nanoparticles in MDEBs was successful, allowing to reach a saturation magnetization of 36.7 ± 1.4 emu/g (versus 65 emu/g for MNPs). 100% success rate was obtained in MRN steerability experiments in a hepatic arterial phantom (fig. d) using a clinical MRI (significant difference of left-right steering ratios is confirmed by Fisher's test, $p < 0.001$). DOX encapsulation efficiency is 43.7% and our DOX-MDEBs reach a DOX loading content equal to 80.4% of that of DC BeadsTM. HPLC results showed that DOX-MDEBs released 30.7% of the DOX content released by DC BeadsTM over 5 days ($n=3$, $N=3$). Therefore, DOX-loaded MDEBs are promising candidates for the targeted treatment of liver tumors by MRN-guided TACE.



[a] Photograph of the experimental set-up for Magnetic Resonance Navigation experiments performed with a clinical-grade MRI machine; [b] Microscopy image of DOX-loaded MDEBs; [c] MDEB imaged with secondary electron microscopy; [d] Chronograph of a MRI magnetic navigation experiment in a hepatic arterial phantom

Talk 2

Abstract

Mapping mechanical and physicochemical properties in complex, heterogeneous microenvironments is a significant challenge that requires tools to be both high-speed and highly sensitive. Inspired by Richard Feynman's vision of "tiny machines" looking around while navigating the body, we report the development of helical magnetic nanobots—maneuverable, fuel-free probes fabricated via Glancing Angle Deposition (GLAD). We introduce a novel frequency-chip actuation technique¹ that achieves high micron-scale spatial resolution with a 200-fold improvement in sensitivity for local viscosity measurements, allowing for rapid rheological mapping in environments where motion is severely constrained^{2,4}. We demonstrate this platform's versatility by measuring microviscosity in model fluids; measurements remained possible using statistics even when the nanobots moved through a constrained microcapillary media, the interior of living cells^{3,5} by using generalized extreme value distributions. In the crowded cytoplasm of living cells, measurements were successfully obtained even when linear motion was hindered. Finally, we sensed the local microviscosity of the peritoneal fluid in living mice at depths of several millimeters, utilizing NIR-enabled upconversion nanoparticles (UCNPs) for real-time deep-tissue visualization.

Beyond mechanical probing, the platform has been extended to include local quantum sensing⁶ and charge measurement. By integrating nitrogen-vacancy (NV) center-containing nanodiamonds, we developed a Mobile Quantum Sensors (MQS)⁷, which achieve full 3D positioning while enabling robust, in-situ optically detected magnetic resonance (ODMR) and coherent spin control (Rabi oscillations) for precise local sensing of temperature and magnetic fields. Furthermore, these nanobots have been utilized to sense physicochemical heterogeneities in tumor microenvironments⁸. We observed that they preferentially adhere to cancer-proximal extracellular matrices due to specific steric acid linkages, effectively mapping local charge variations that signal disease progression. We show, in addition to local sensing, the ability of the bots to travel through tiny spaces in diverse biological environments, can have important therapeutic applications, such as in dentistry⁹, which has been commercialized recently.

References

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8. D. Dasgupta, S. Peddi, D. K. Saini, and A. Ghosh, "Mobile Nanobots for Prevention of Root Canal Treatment Failure," *Advanced Healthcare Materials*, 11(14), 2200232, 2022.

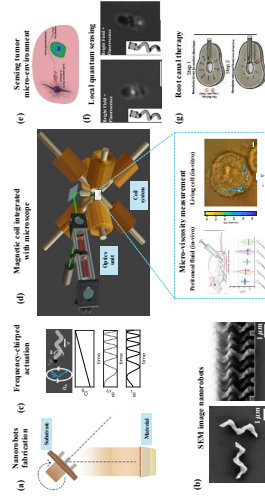


Figure 1: Magnetic Helical Nanobots as Local Measurement Probes. (a) Fabrication of nanobots using GLAD, (b) SEM images, (c) Frequency Chirped actuation of nanobots, (d) Nanobots as a tool for micro-viscosity measurement inside living cells and animal, (e) Tumor micro-environment sensor, (f) Local quantum sensing tool, (g) Dental therapy: root canal treatment.

Quantitative Accumulation of Magnetotactic Bacteria for Tumor Targeting by Application of Gradient Magnetic Fields

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Magnetotactic bacteria (MTB) are environmental micro-organisms that have the unique ability to biomineralize magnetosomes, consisting in magnetite or greigite nanocrystals surrounded by a biocompatible phospholipidic membrane. Within the cell body, magnetosomes are organized in chain like structures, allowing MTB to sense and adapt their swimming to the earth magnetic field (MF). Depending on their morphology, MTB can swim exclusively in the MF direction (polar magnetotaxis) or both parallel and antiparallel to the MF lines (axial magnetotaxis).

The unique magnetic properties exhibited by MTB make them interesting candidates for various biomedical applications. In particular, MTB can be used as carriers for functionalized magnetosomes. Thus, a precise, efficient and tunable guidance strategy needs to be developed to maximize the amount of MTB accumulated in the therapeutic region.

In this work, we first develop a guidance strategy based on the use of gradient MF and the generation of a field free point (FFP) at the targeted location. Gradients are produced using permanent magnets. The efficiency of this protocol is assessed on 2 different MTB strains, *Magnetospirillum gryphiswaldense* (MSR-1) and *Magnetovibrio blakemorei* (MV-1), that respectively exhibit axial and polar magnetotaxis. The amount of MTB accumulated in the targeted region under various experimental conditions is quantified by RGB image analysis.

In a second time, we conduct modeling experiments to determine optimal MF parameters for maximizing MTB accumulation, as well as to tune the desired location of MTB accumulation. Based on both the experimental and modeling results, a strategy for building an optimized portable device for preclinical studies is discussed.

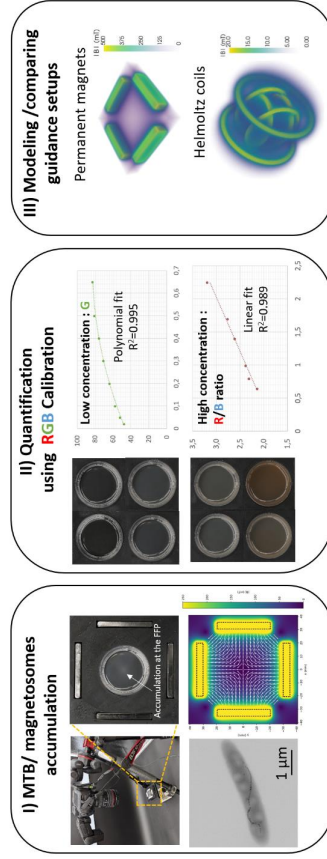


Figure 1: From gradient-based accumulation to quantification and magnetic guidance of MTB

Magnetic DNA Origami Nanorotors

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Self-assembled DNA nanostructures show great promise as functional devices, highly configurable materials, and in nanorobotics. Magnetic control can provide a powerful actuation mechanism in a broad range of contexts, since it affords a high-level of external control, it is biocompatible, and orthogonal to chemical or electrical stimuli. Early studies mainly used $\sim \mu\text{m}$ magnetic beads in magnetic tweezers assays and have provided key insights into the mechanics of nucleic acids, cells, and recently proteins. However, $\sim \mu\text{m}$ beads provide only limited control at the molecular scale and often bind to several molecules simultaneously due to their size. Magnetic nanoparticles with sizes $< 25\text{ nm}$ have, inherently, a small magnetic moment m of $\approx 1 \cdot 2 \cdot 10^{-18}\text{ A m}^2$, and are only able to generate $\approx \text{fN}$ forces even at few hundreds of mT. This force regime is orders of magnitudes too low to manipulate cellular processes, such as molecular motors and cell surface receptors that typically require 1-100 pN.

Here we demonstrate magnetic molecular nanoactuators by leveraging the unique site-specificity of DNA origami to assemble highly anisotropic magnetic nanocubes on high-aspect ratio DNA origami bundles. We traced and controlled 100s of our DNA origami nanorotors at the single-rotor level and demonstrated their programmable magnetic clamping and controlled rotation under uniform and rotating magnetic fields. By varying the population and inter-particle spacing of the nanocubes, magnetic torque values in the order of 10-100 pN are achieved at field strengths $< 10\text{ mT}$. Monte Carlo simulations reveal that assembly of nanocubes on DNA origami rotors leads to collective magnetic properties, with numerically estimated torque values in good agreement with the experiments. Our magnetic nanorotors offer a foundation for biocompatible nanorobotics, as well as high-throughput magnetic force and torque tweezers [1].

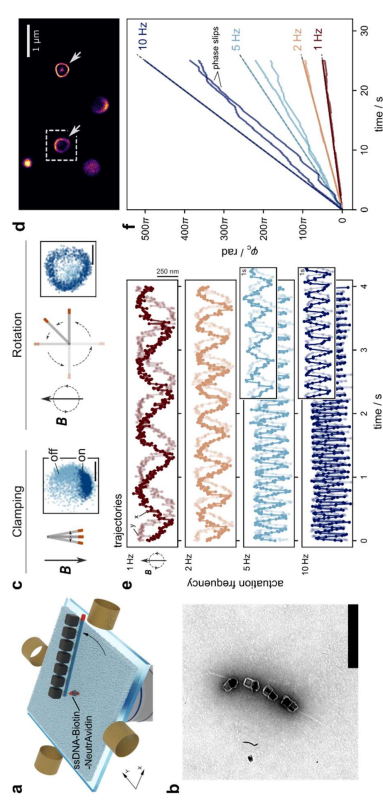


Figure. Magnetic clamping and rotations of magnetic DNA origami nanorotors (MADONAs). (a) Scheme of on-substrate magnetic actuation assays at the single-rotor level. (b) Negative-stain transmission electron microscopy (TEM) micrograph of a single MADONA rotor covered with multiple MNPs (scale bar 200 nm). (c) Clamping and rotation actuation modes and their effects on rotor motion. Light blue shows the localizations during diffusion and dark blue upon magnetic actuation. Scale bar is 250 nm. (d) Localization heatmap in false colors of a TIRFM-rotating magnetic field (RMF) experiments. Arrows indicate functional rotors. The dashed box corresponds to rotors that follow the RMF synchronously. (e) Particle trajectories in Cartesian coordinates (scale 250 nm) of an exemplary rotor during actuation at 2.7 mT and different RMF frequencies. (f) Particle trajectories shown as cumulative angle for three different rotors when driven by RMFs with the rotation frequencies indicated in the figure legend at 2.7 mT.

[1] Rothfischer, Weiß and Wang et al. bioRxiv 2026.

Talk 6

Magnetic Torque Trapping Enables Enhanced Retention and Translocation of Microrobots

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Despite tremendous progress regarding new drugs and formulations, cancer therapy remains challenging as only a very small fraction of the administered dose typically reaches the target tissue. Microrobots have emerged as promising carriers for more targeted cancer therapy because they can actively transport therapeutic agents to disease sites. Magnetic actuation has been widely explored as means to control these microrobots, primarily through magnetic field gradients or rotating magnetic fields. Gradient based actuation can enhance microrobot accumulation and tumor penetration, but its clinical translation is constrained by poor scalability, as it generally requires magnetic field gradients exceeding $\sim 10\text{ T/m}$. In contrast, rotating magnetic fields provide excellent scalability and can drive torque-induced locomotion, enabling enhanced tumor infiltration and colonization. However, these approaches lack mechanisms to retain intravenously injected microrobots at specific target sites. Here, we introduce a torque-trapping strategy that enables spatial localization of microrobots using a Lissajous function based magnetic field actuation (LMF). By generating spatially dependent torque, the proposed magnetic field configuration uses rotational motion while simultaneously trapping microrobots at the target site under both static and flow conditions. Moreover, the spatially dependent torque actuation generates focused convection flows that enhance translocation of microrobots across the biological barriers. We experimentally evaluated the retention and translocation performance of the proposed actuation scheme, demonstrating its potential to significantly improve microrobot targeting efficiency.

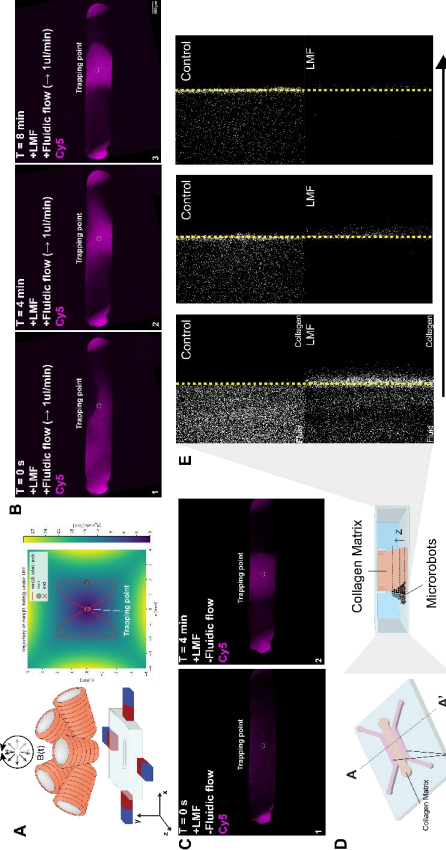


Figure 1. (A) Schematics of the magnetic actuation system, consisting of electromagnets generating time-varying fields and permanent magnet array generating static fields. The static magnetic field distribution produced by the permanent magnets is illustrated, along with the trajectory of B_{min} resulting from the superposition of the Lissajous magnetic field and the static magnetic field. A trapping point is formed at the center. **(B)** Time-lapse fluorescence images of the retention experiment under dynamic flow conditions. **(C)** Retention experiments under static flow condition. **(D)** Microfluidic chips used for the translocation experiments. **(E)** Results of the translocation experiments, imaged along the z axis, from the bottom of the glass slide upwards along the channel height.

Talk 5

Nitrogen-Vacancy Center Imaging of Magnetite Nanoparticles in Human Brain Tissue

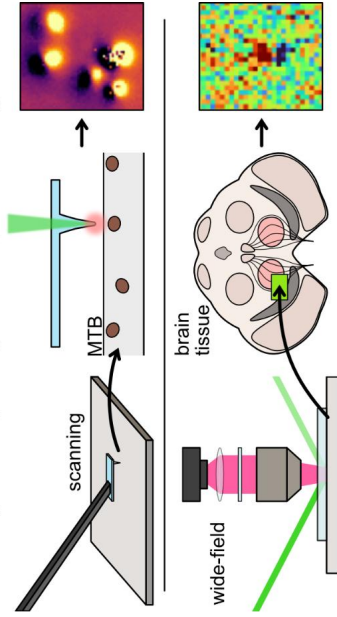
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Magnetic nanoparticles are naturally present in a variety of organisms. While magnetite crystals within magnetosomes of magnetotactic bacteria (MTB) are well-studied and unequivocally biosynthesized, the origin of magnetic particles in human brain tissue remains debated. Their presence has been reported primarily through bulk tissue measurements or electron microscopy of extracted particles. However, the *in situ* identification and characterization of individual magnetite particles in brain tissue is highly challenging due to their nanoscale size and low concentration. Magnetometry based on nitrogen-vacancy (NV) centers in diamond enables mapping of magnetic stray fields at a sample surface with ultra-high sensitivity. For dipolar signals, this technique allows direct quantification of the magnetic moments of the underlying sources. We applied scanning NV magnetometry to resin-embedded MTB, enabling determination of magnetic moments at the single-cell level. This approach combines high sample throughput with single-cell moment quantification and correlative electron microscopy, thereby overcoming key limitations of conventional methods for measuring MTB magnetic moments. With their well-characterized magnetosomes, MTB provide a benchmark for validating NV magnetometry before applying it to more complex biological samples. We further applied wide-field NV magnetometry with a Quantum Diamond Microscope to map human brain tissue. Our protocol involves repeated, slightly offset magnetic field maps acquired with high sensitivity and long acquisition times, allowing reliable discrimination of naturally occurring magnetic sources in human and rodent brain samples. Systematic application of NV magnetometry to brain tissue will contribute to a better understanding of the processes underlying the presence of magnetic nanoparticles in the brain.

NV magnetometry of magnetic nanoparticles in organisms



Magnetically Programmable NK Cell Clusters Enabled by Magnetic Mesocrystals for Cancer Immunotherapy

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Multicellular clustering of natural killer (NK) cells can promote NK cell proliferation and antitumor activity, motivating remote and non-genetic strategies for controlled modulation of NK cell behavior.¹ Magnetic nanoparticles provide a promising platform for remote modulation of immune cells through magnetic targeting and field-responsive stimulation, yet their use for controlled programming of cell cluster phenotype and function remains limited. In this work, we have developed a magnetic mesocrystal-based system for magnetically programmable clustering of NK cells as a strategy to enhance NK cell function for cancer immunotherapy (Figure 1a). Magnetite (Fe₃O₄) mesocrystals with an overall size of approximately 100 nm were assembled from crystallographically aligned ultrasmall unit nanocrystals of approximately 4 nm, enabling strong collective magnetic responsiveness through their hierarchical architecture (Figure 1b).² Following hyaluronate functionalization, the mesocrystals were associated with CD44-expressing NK92MI cells and were used to induce magnetic clustering under external magnetic fields. As magnetic field waveforms were varied among constant, sine, and biased sine modes ($B_{max} = 10$ mT, $f = 0.2$ Hz), the magnetic pulling forces acting on labeled NK cells varied, leading to different clustering tendencies and final cluster morphologies. Optical microscopy revealed waveform-dependent differences in cluster morphology. A biased sine waveform induced the formation of larger, circular, and more compact multicellular clusters than the other waveforms (Figure 1c). Confocal laser scanning microscopy confirmed dense aggregation of NK cells with significant F-actin expression (Figure 1d). These magnetically programmed NK cell clusters exhibited enhanced proliferation and antitumor activity relative to untreated NK cell clusters. These findings establish magnetic mesocrystal-labeled NK cells as a programmable platform enabling dynamic NK cell clustering for NK cell-based cancer immunotherapy.

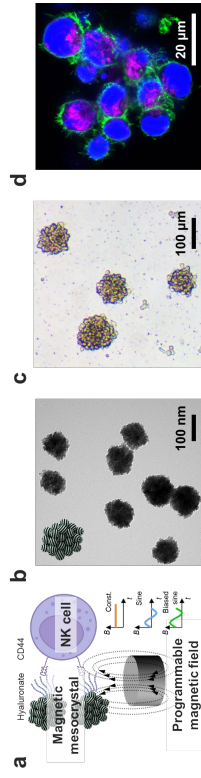


Figure 1. Magnetic mesocrystal enabled programmable clustering of NK cells. **a**, Schematic illustration of magnetic mesocrystal-based programmable magnetic clustering of NK cells. **b**, Representative transmission electron microscopy image of Fe₃O₄ mesocrystals. **c**, Optical microscopy image of representative NK cell clusters formed under programmed magnetic field. **d**, Confocal laser scanning microscopy image of magnetically programmed NK cell clusters, where blue, green, and magenta indicate nuclei, F-actin, and magnetic mesocrystals, respectively.

[1] M. Kim *et al. Sci. Rep.* 7, 40623 (2017)

[2] B.C. Park *et al. Nat. Commun.* 13, 1144 (2022)

Tumor characterization via magnetization dynamics of magnetic nanoparticles for cancer theranostics

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Understanding of the magnetization dynamics of magnetic nanoparticles (MNPs) is important for their biomedical applications such as cancer theranostics. We have investigated the effects of the particle structure,¹ magnetic field strength,² and properties of the surrounding environment such as the intratumor environments³ on the magnetization dynamics. This was evaluated by the magnetic relaxation time spectrum, τ -spectrum based on the magnetic relaxation process as the time-domain magnetic relaxometry using the pulsed magnetic field. In this study, the tumor microenvironment was characterized using viscosity as a feature by analyzing the magnetization dynamics of MNPs injected into the tumor.³

Iron oxide MNPs, Resovist[®] (PDR Pharma Co. Ltd, Tokyo, Japan), were dispersed in viscous liquids in the viscosity $\eta = 0.87\text{--}45$ mPa·s by mixing diluted water with glycerol. MNPs were also solidified using epoxy resin. The liquid and solid samples were prepared as the non-biological samples with the MNP concentration of 2.75 mg-Fe/mL. For the *in vivo* measurement, human fibrosarcoma HT1080 or pancreas adenocarcinoma BxPC3 cells were implanted subcutaneously into the right hip of BALB/c nu/nu male mice. The 10 μ L solution of MNPs at 140 mg-Fe/mL was injected into the tumor, which was covered by a coil set including excitation, detection, and cancellation coils to measure the magnetic relaxation process (Fig. 1a).

Figure 1b shows the τ -spectrum in HT1080 and BxPC3 tumors. The first peak of the shortest τ value was associated with the rise time of the applied pulsed magnetic field. The second and third peaks of the τ -spectrum fitted by a Gaussian distribution were analyzed to characterize the tumor using those in the non-biological samples, as shown in Fig. 1c. The volume fraction of the non-biological components in the HT1080 tumor was different from that in the BxPC3 tumor due to the different tumor properties. We will present our characterization approach for the magnetization dynamics of MNPs in detail.

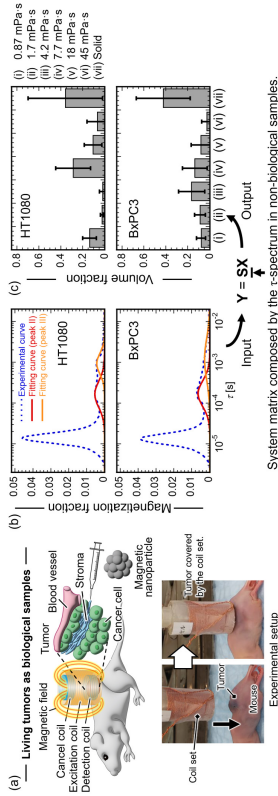


Fig. 1. (a) Schematics of the characterization of living tumors using MNPs and the experimental setup, (b) measured τ -spectrum in tumors, and (c) estimated volume fraction based on the non-biological samples.³

Acknowledgements: This work was partially supported by JSPS KAKENHI grant numbers 20H05652, 23K226114, and 25H00736, JST ACT-X grant number JPMJAX21A5, Takahashi Industrial and Economic Research Foundation, Terumo Life Science Foundation, and Hamamatsu Foundation for the Promotion of Electronic Science.

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2) S. Hayashi *et al.*, *Appl. Phys. Lett.*, **128** (2026) 072404. [doi: 10.1063/5.0138555]

3) S. Ota *et al.*, *Adv. Mater.*, **36** (2024) 2404766. [doi: 10.1002/adma.202404766]

Continuous Coagulation Monitoring of Human Blood via Magnetic Particle Spectroscopy

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Magnetic particle spectroscopy (MPS) is a quantitative technique for analysing magnetic nanoparticles (MNPs) by measuring their nonlinear magnetization response to an alternating magnetic field. Due to the sensitivity of MNP dynamics to the local microenvironment (e.g. viscosity, temperature, and molecular binding), MPS is a versatile analytical method with diverse applications in scientific, biomedical, and industrial contexts. In this study, the feasibility of continuous human blood coagulation monitoring with MPS by using a clinically approved MNP contrast agent is demonstrated.¹

In this ethics-approved pilot study, blood samples from five healthy volunteers were mixed with MNPs (Resotran[®], b.o.imaging GmbH, DE) and different reagents: a Resotran-infused sample (exp. I), a Resotran-infused sample subjected to mechanical stress by 10s vortexing at 15 and 30 min (exp. II), and three Resotran-infused samples anticoagulated with EDTA, Heparin or Citrate (exp. III). For all experiments (Fig. 1), suspensions containing 475 μ L blood and 25 μ L Resotran were prepared and vortexed to ensure a homogeneous distribution, resulting in an iron concentration comparable to that of a clinical bolus (1.4 mg mL⁻¹). All samples were measured in a custom-built MPS, using an identical measurement protocol, with sinusoidal excitation of 20 mT amplitude at 25 kHz, one second averaging and a measurement every 15s for a 45-minute period. Potential thermal effects were assessed by continually monitoring the temperature inside the sample vial using a fibre optic thermometer positioned above the sample. The recorded data was subsequently analysed by tracking and comparing the signal trajectories of the fifth-harmonic amplitude extracted from the transfer-function corrected amplitude spectra.

The signal of blood samples infused exclusively with Resotran (exp. I) exhibited an inverted sigmoidal decline over time, approaching a plateau at approximately 62% of the initial amplitude, with a signal-to-noise ratio exceeding 255 relative to the mean background signal. As expected, additional anticoagulants (exp. III) modulate the signal, resulting in either no significant decrease (e.g. EDTA, citrate) or, in the case of heparin, a smaller decay depending on the sample. For all experiments conducted, temperature variations affected multiple signal parameters, with initial temperature changes resulting in differences in the starting amplitude and, in one instance where the overall temperature was reduced, the signal decay exhibiting a significantly delayed response (Fig. 1, M2).

The observed signal decay is hypothesized to be primarily driven by an increase in sample viscosity during coagulation, which affects the Brownian relaxation time of the particles. This hypothesis is supported by the absence of signal change in the presence of anticoagulants and by a signal decrease following the application of mechanical stress, a known procoagulatory stimulus. The study is limited by the small cohort size and by certain methodological decisions, namely the initial vortexing and the use of glass tubes, which may induce platelet aggregation and bias coagulation dynamics across all samples.

Although larger clinical studies, integration with standard coagulation assays, temperature-stabilized hardware, and refined sample-handling protocols are planned, the feasibility of continuous monitoring of human blood coagulation with MPS was demonstrated in this study. This supports the development of MPS as an analytical laboratory investigation method for coagulation assessment.

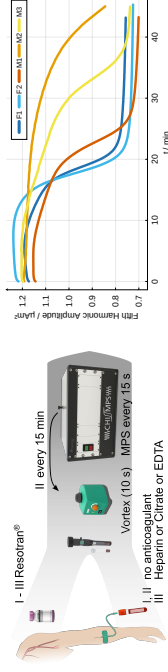


Fig. 1: Experimental setup (exp. I, II, and III) (left) and fifth harmonic amplitude traces from Resotran-infused blood samples of five volunteers (Female, Male) showing inverted sigmoidal response traces reflecting the coagulation dynamics (right).¹

Author's statement

This experimental pilot study was approved by the ethics committee of the University of Luebeck (LAES04-2025), the University of Hamburg (ProMed 146-2), and the University of Helsinki with prior informed consent. No conflict of interest.

Acknowledgments

This work was funded by the University of Luebeck (LAES04-2025), the University of Hamburg (ProMed 146-2), and the University of Helsinki with prior informed consent. No conflict of interest.

¹Buhag MJ et al. Continuous Coagulation Monitoring in Human Blood Samples via Magnetic Particle Spectroscopy. *Int. J. Nanomedicine*. 2026;2:1-12. 10.2147/IJN.S561511.

Iron Regulation Proteins and Magnetic Behavior of Breast Cancer Stem Cells: Could Iron Be A Universal Marker for Label-Free Sorting?

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Breast cancer stem cells (CSCs) are a key subpopulation of tumor cells driving tumor initiation, metastasis, and therapeutic resistance, yet their isolation from heterogeneous tumor cell mixtures remains technically challenging. In this study, we investigate the potential of label-free magnetophoresis to isolate breast CSCs based on intrinsic differences in their magnetic susceptibility arising from altered cellular iron metabolism. Single-cell magnetometry measurements (Figure 1 b) reveal that CSC populations derived from multiple breast cancer cell lines (Figure 1 a) exhibit significantly increased magnetic responses relative to non-stem tumor cells (Figure 1 e), indicating a distinct magnetic susceptibility. This behavior is attributed to differences in intracellular iron uptake and regulation, as further supported by our molecular analyses showing upregulation and/or downregulation of iron uptake, storage, and export genes in CSCs.

Building on the magnetic measurements, we performed numerical simulations of magnetophoretic sorting in a quadrupolar magnet (Figure 1 c-d). The simulations demonstrate that separation performance is governed by the balance between magnetic and viscous forces and can be tuned by adjusting flow rate (Figure 1 f). This enables controlled trade-offs between CSC recovery and purity when separating mixed populations of stem and non-stem tumor cells. Overall, our results establish magnetic susceptibility rooted in distinct cellular iron regulation as a robust physical parameter for CSC discrimination and separation without external labels. This work highlights the potential of magnetophoretic platforms as scalable, low-complexity systems for biological separations, with implications in cancer biology and therapy.

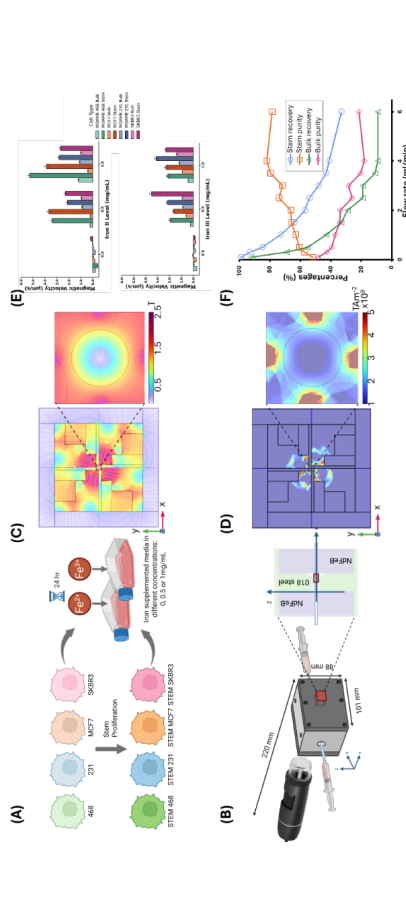
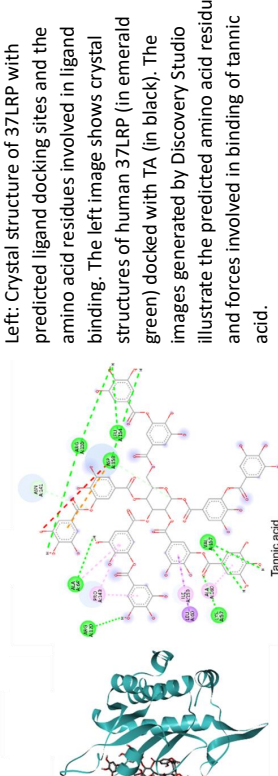


Figure 1. Magnetometry analysis and magnetic isolation of breast cancer stem cells. (A) Breast cancer cell lines used in this study and methodology. (B) Cell Tracking Velocimeter for single-cell magnetometry analysis. (C) Magnetic flux density and (D) magnetic energy gradient generated by the separator. (E) Single-cell magnetometry results with bar plots of the average magnetic velocity, error bars represent 95% confidence intervals. (F) Simulation results of the flow rate dependent recovery and purity of MDAMB 468 stem and non-stem cells supplemented with 0.5 mg/mL of ferrous iron.

Tannic Acid-Coating Augments Nanoparticle Uptake by Laminin Receptor-Mediated Endocytosis: Implication in Tumor Targeting

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Magnetic nanoparticles (MNPs) exhibit great potential as drug carriers for targeted delivery, with an external magnetic field to enhance local drug retention and reduce systemic side effects. It has been shown that tea catechins, including epigallocatechin-3-gallate, and other gallates enhance D-COOH MNP (nanomeg) uptake by tumor cells, which is likely *via* interaction with a 67-kDa laminin receptor (67LR) overexpressed in a variety of tumors. We ask whether other polyphenolic compounds, such as tannic acid (TA) or quercetin, may enhance cellular uptake by tumor cells *via* 67LR-mediated endocytosis. After incubation with MNPs in culture of A549 cells for 2 hr, both TA and quercetin enhanced uptake of D-COOH MNP in a concentration-dependent manner, as determined by a colorimetric iron assay; the enhanced cellular uptake was synergistically augmented by the application of an NdFeB magnet at the bottom of each well. TA-coated MNP (TA-MNP) with γ -Fe₂O₃ core was prepared, characterized, and demonstrated with enhanced cellular uptake by 2.6-fold; however, magnetic force reduced the uptake of TA-MNPs. A549 cells with internalized TA-MNP exhibited much higher 67LR expression compared to the subpopulation of cells with much less uptake and remained in the supernatant after magnetic separation. Either siRNA-mediated knockdown of 67LR, a 67LR inhibitor, or a 67LR antibody reduced the effects of TA, TA coating, or quercetin on MNP uptake. *In vivo* uptake by tumor cells was observed one hr after *iv* administration of MNPs (10 mg Fe/kg) using transmission electron microscopy and magnetic resonance imaging in nude mice bearing tumor, with enhanced signals from MNPs with γ -Fe₂O₃@CS-TA composition. Elemental analysis reveals predominant accumulation in reticuloendothelial system organs, particularly spleen and liver, together with significantly enhanced tumor deposition for surface-functionalized @CS-TA and @NH₂-TA compared with bare γ -Fe₂O₃. These results suggest a positive correlation between 67LR expression and nanoparticle internalization by A549 cells; both gallate and catechol moieties may be responsible for 67LR binding. Our studies offer a novel strategy for optimizing nanoparticle-based cancer theranostics.



Dynamic behavior and intracellular assembly of magnetic nanoparticle-loaded vesicles under AC magnetic stimulation.

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The use of magnetic nanoparticles (MNPs) exposed to alternating magnetic fields to generate heat, known as magnetic hyperthermia (MH), is a widely established technique that is being used in diverse industrial and biological applications. In the frame of in vivo biological applications of magnetic hyperthermia, understanding the MNPs organization within cells is fundamental to evaluate its impact on their heating performance when exposed to AC fields.

Recent observations showed that MH induces the chaining of MNP-loaded vesicles inside cells [1]. The current contribution focuses on studying the dynamic evolution of the spatial organization of such MNP-loaded vesicles. For that, we incubated a murine macrophage cell line with ~13 nm iron oxide magnetic nanoparticles. Combining fluorescence microscopy (Fig. 1a) and electron microscopy (TEM) (Fig. 1b) we were able to observe the vesicle spatial organization within the cell and the nanoparticle distribution within vesicles when exposed to AC magnetic fields. Moreover, we have developed different strategies for image quantification to evaluate the impact of the different conditions on vesicle alignment during the magnetic hyperthermia experiments. Using fluorescence microscopy, we have studied how the time of the AC field exposure and the AC field conditions affect chaining. We observed that, longer times increase the degree of vesicle alignment (Fig. 1c). Increasing AC magnetic field amplitudes also increase the vesicle alignment in cells. Additionally, we are simulating the impact that this vesicle arrangement, occurring during the AC field exposure, may have on the heating performance of the material and the mechanical forces triggered by the field. To assess biological consequences, we are investigating lysosomal alterations induced by MNP-magnetic field interactions. Specifically, we tested whether magnetic stimulation of lysosome-confined MNPs could generate forces sufficient to disrupt membrane integrity (Fig. 1d).

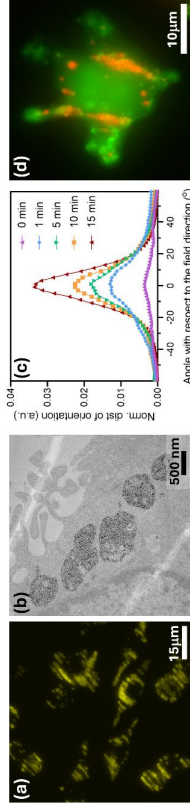


Fig. 1: (a) Representative fluorescence image showing RAW264.7 cells with aligned fluorescent vesicles loaded with MNPs under an AMF. (b) Representative TEM image showing intracellular nanoparticle-loaded vesicle forming an elongated structure inside a cell. (c) Comparison of vesicle orientation distributions with respect to the field direction for different exposure times of AMF. (d) Representative fluorescence microscopy image displaying both MNP (red) and Dextran (green), after AMF exposure. Dextran absence from MNP loaded vesicles and the accompanying increase in cytosolic Dextran demonstrates vesicle rupture and content leakage.

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Magnetic Nanoparticles as Sensor for Brain Perfusion

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Introduction: Stroke as a major global health burden affects 15 million people annually, with 5 million deaths¹. As incidence rises with aging and lifestyle factors, early diagnosis and treatment are essential especially in the first hours – because **time matters, imaging guides**. This work introduces **StrokeCap**, a portable, real-time diagnostic device based on magnetic nanoparticle (MNP) detection^{2,3}. The cap-like system⁴ uses multiple transmit-receive (tx/rx) coils to detect and localize brain perfusion abnormalities through magnetic response from administered MNP-tracer into the blood.

Methods: The basic idea is the measurement of blood perfusion in different areas of the brain using dedicated coils. The presence of MNPs near a local sensor causes an unambiguous signal in form of higher harmonics due to the nonlinear magnetization response to a sinusoidal magnetic field (**Fig.1**). Within a dedicated simulation framework⁵ multiple tx/rx coil geometries as well as multiple operation modes have been implemented and compared for their performance. The performance of the best detection approach was tested with the help of signal time curves of acute stroke pathologies derived from real CT-perfusion data.

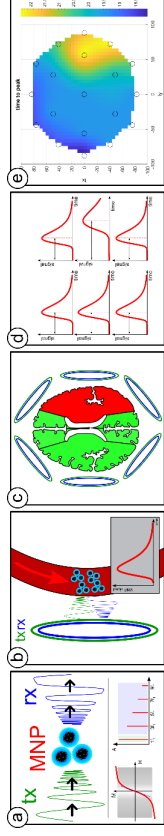


Fig. 1: (a) MNP detection basics: nonlinear magnetization response of MNPs to sinusoidal magnetic fields. (b) Single-sided local sensors provide spatio-temporal detection of MNPs. Using an array of these sensors provides full brain coverage (c). The MNP signal of each local sensor (d) can be visualized in different ways, e.g., as time-to-peak representation (e).

Results: All tx/rx operation modes enable time-resolved tracking of the tracer bolus in the brain. However, depending on coil geometry, significant differences in detection sensitivity for single localized sensors was found. Considering simplicity as well as detection efficacy, the best tested solution is a large solenoid coil acting as a global sensor, combined with multiple smaller coils that generate localized static offset fields to induce higher even harmonics.

Discussion and Conclusion: Using the simulated time curves from the CT-perfusion data of acute stroke, all approaches allow detection perfusion abnormalities with direct interventional consequences. The offset-based second harmonic operation mode offers the best trade-off between performance and system complexity for the intended use.

Acknowledgements: We thank Dr. Michael Angerer from Kliniken Nordoberpfalz AG Weiden for providing CT perfusion datasets for simulations.

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Characterising exogenous and endogenous magnetic nanomaterials in biological samples using a magneto-optical multifunctional microscope

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Nanoscale magnetic materials, such as magnetic nanoparticles (MNPs), have attracted interest in biomedicine due to their diverse applications in areas such as drug/gene delivery, cancer therapy (magnetic hyperthermia), and tissue engineering. Apart from these useful exogenous MNPs, nanoscale magnetic materials have also been found to link with the pathology of certain diseases such as Alzheimer's [1]. Here, a unique multifunctional, scanning laser microscopy system was developed to help track and investigate these nanoscale magnetic materials by incorporating magnetic signal detection with other modalities, such as fluorescence (lifetime) and high-sensitivity birefringence imaging [2]. The magnetic signal detection, encompassing magnetic mapping and submicron-level AC hysteresis loop measurement, utilizes the magneto-optical Faraday effect (MOFE), whereby the magnetically induced rotation of the polarization of light transmitted through a sample, is detected. In addition to magnetic mapping with a spatial resolution of <1 µm, this multifunctional microscope can measure AC hysteresis loops at the same spatial resolution under field frequency up to ~500 kHz and field intensity up to ~50 mT.

Combining these different imaging modalities, detailed investigations of both exogenous and endogenous nanoscale magnetic materials in different biological systems were possible (Figure 1). For example, the combination of magnetic detection and *in situ* brightfield/fluorescence microscopy allowed for the investigating of internalized MNPs at specific cellular locations for magnetic hyperthermia. Besides, the recently-developed sensitive birefringence imaging was combined with magnetic detection to probe amyloid deposits from brain tissue samples and investigate iron metabolism/biomaterialization for Alzheimer's disease. What's more, for neural tissue engineering, the brightfield and magnetic mapping were combined to visualize internalised MNP clusters within developing neurites of embryonic rat cortical neurons to understand the uptake of these clusters in the neurites.

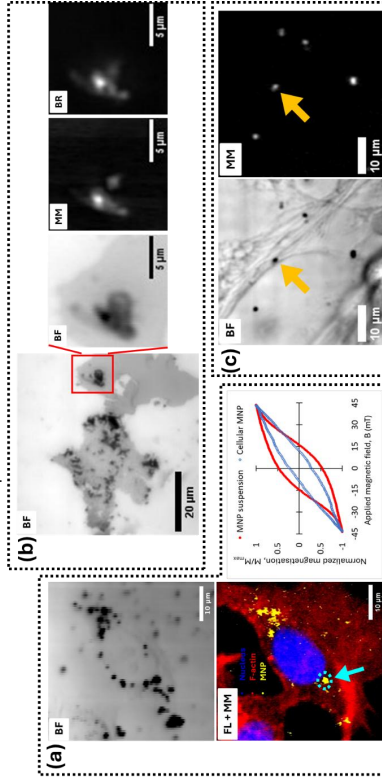


Figure 1. (a) Brightfield (BF, top left) and fluorescence image with *in-situ* magnetic mapping (FL + MM, bottom left) of fixed breast cancer cells (MCF-7) with the AC hysteresis loop measured from one cellular MNP aggregate (magnetite with core size of 21nm) compared with same MNP in suspension form (bottom right). The AC hysteresis loops were measured at a field frequency of 64.8 kHz. (b) Brightfield (BF) with enlargement, magnetic mapping (MM) and birefringence (BR) of resin embedded cortical mouse brain tissue, taken from an APP/PS1 transgenic mouse model used in Alzheimer's research. The enlarged images (bottom panel) show strong similarities between the recorded MM and BR signals. (c) Brightfield (BF) and magnetic mapping (MM) of fixed embryonic (E17) rat cortical neurons (8 days in vitro) following 48 h incubation of magnetic nanoclusters (magnetite core with polyacrylic acid coating). MNP clusters were visible within developing neurites (yellow arrow).

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Structural Engineering of Fe₃O₄ Mesocrystals for Enhanced Magneto-Optical Cancer Therapy

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Non-invasive thermal therapy requires precise heating of cancer cells, where the heat generation depends on size, shape, anisotropy, and materials property. Conventional magnetic nanoparticles suffer from surface spin disorder and weak magnetic coupling, limiting energy dissipation and low photothermal efficiency. Whereas Mesocrystals a hierarchically aligned assembly of nanoparticle provides an enhanced magnetic exchange correlation thus reducing surface disorder results in improved magnetic heating. Furthermore, aligned assembly of nanoparticle improves intravalent charge transfer between the nanoparticle and thus the optical heating. Herein, we establish a structural correlation to optimize mesocrystal driven heating for synergistic cancer therapy. The Fe₃O₄ mesocrystal was synthesised using a modified solvothermal method. Upon increasing the reaction temperature, the systematic increase in magnetization along with the transformation from polycrystalline aggregates to single crystalline nature was observed as shown in Figure 1. The mesocrystals exhibited high saturation magnetization of 87 emu g⁻¹ compared to nanoparticles (55.29 emu g⁻¹) due to collective behavior arising from the exchange interaction promoted by the crystallographic alignment of the nanoparticle subunit. It also reaches an optimal therapeutic temperature of 45 °C in both water and 2% agar medium under the applied field strengths of 20 and 26.7 kA m⁻¹. Furthermore, irradiating with nIR (808 nm) laser achieved the hyperthermia range with in 70 sec at the power density 1.5 W cm⁻² in 200 µg mL⁻¹ sample concentration. Along with its heat generation, their capability as a drug carrier is tested to understand the impact of internal voids and porous nature. It exhibits a high encapsulation efficiency of 41.09 % for paclitaxel drug without additional functionalization. *In vitro* studies reveal 82% biocompatibility with L-929 fibroblast cells and Fe₃O₄ mesocrystals embedded with PTX show a 95% reduction in cancer cell viability against HCT 116 cell line.

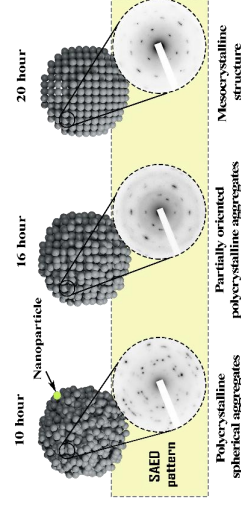


Figure 1. Schematic representation of time-dependent transformation of spherical aggregates (polycrystals) into (single crystal-like) mesocrystals¹.

¹ Marsalin et al. *J. Mater. Chem. B*, 2025, 13, 10635-10647

Boosting T₁ Relaxivity with Trace Mg-Doping in Ultrasmall Iron Oxide Nanoparticles for Subsegmental Pulmonary Embolism Imaging

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Accurate magnetic resonance imaging (MRI) of a microvascular disease remains a clinical challenge because of the inherent limitations of clinical Gd-based contrast agents (CAs). Although substantial investigations have been reported in design of high performance USIO-based blood-pool CA, the most critical challenge lies in the fact that achieving a substantial increase in T₁ relaxivity under the prerequisite of safety remains unfilled.

Herein, we develop a trace magnesium-doped USIO (Mg_{0.03}-USIO) that exhibits substantially enhanced T₁ relaxivity without compromising safety in Figure (a). We reveal, for the first time, that trace Mg²⁺ doping at surface octahedral-site iron vacancies of USIO, rather than bulk doping, is responsible for significantly enhanced T₁ relaxivity in USIO systems in Figure (b). The Mg_{0.03}-USIO exhibited an exceptionally high T₁ relaxivity enhancement per molar Mg dopant up to 12.6 mM⁻¹s⁻¹, 261 times higher than the USIO. Importantly, unlike previous studies limited to rodent models, our validation is performed in a large animal model (pig), directly supporting clinical translation. The Mg_{0.03}-USIO enables clear visualization of SSPE-associated vascular anatomy and perfusion abnormalities, which has not been achieved previously in MRI research in Figure (c). *In vivo* blood biochemistry, hematology, and histopathology (H&E staining) collectively confirm the excellent biosafety profile of the Mg-USIO (Figure d-f).

Overall, our work represents a fundamental breakthrough in the field of MRI contrast agents, providing a timely solution to the critical challenge of precisely detecting and assessing the risk of microvascular diseases that are prevalent in the majority of middle-aged and elderly individuals worldwide.

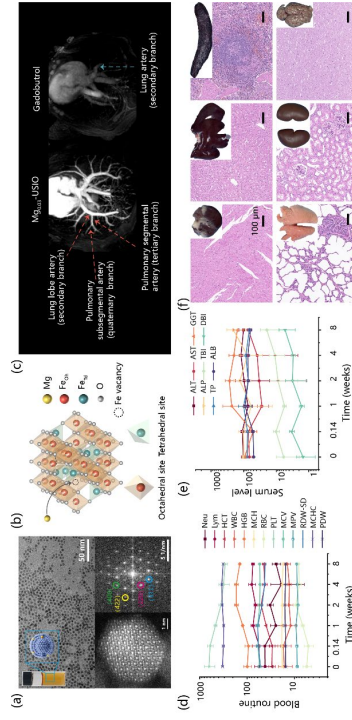


Figure. (a) Transmission electron microscope images of Mg_{0.03}-USIO. The inset image shows representative enlarged high-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM) images of Mg_{0.03}-USIO and a fast Fourier transform (FFT) pattern. (b) Schematic diagram of spinel structure of Mg_{0.03}-USIO nanoparticle. (c) Representative DCE-MRI images of the pulmonary artery vasculature using Mg_{0.03}-USIO and gadobutrol on the pig model. (d-f) Hematological evaluation of Mg_{0.03}-USIO in pigs. (e) Gross pathological and histopathological analyses of major organs of a randomly selected pig.

Invited talk

Design and Application of Inorganic Nanoparticles for Magnetic Hyperthermia, Radio-Imaging, and Immune Cell Modulation

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Inorganic nanoparticles exhibit unique physicochemical properties that make them powerful tools in nanomedicine for both imaging and therapy. Among them, magnetic nanoparticles (MNPs), particularly iron oxide, are widely studied for their ability to convert magnetic energy into heat under alternating magnetic fields (AMF), enabling tumour treatment via magnetic hyperthermia (MHT). [1] This remote actuation occurs without tissue-depth attenuation under clinically relevant conditions, allowing localized heating and synergistic combination with conventional therapies while reducing side effects. In parallel, semiconductor nanoparticles such as Cd-free quantum dots offer robust photoluminescence for multiplexed imaging and can also function as photothermal or radiotherapeutic agents upon cation exchange. [2]

Cancer immunotherapy, which harnesses immune cells such as T cells and natural killer (NK) cells to generate specific and durable anti-tumour responses, is transforming cancer treatment. However, efficient tracking and functional modulation of these cells remain key challenges. In this context, we have developed magnetic nanoparticle-based strategies to interface nanomaterials with immune cells.

Here, I will present our recent advances in the synthesis and functionalization of nanoparticles for magnetic hyperthermia, MRI, MPI, and drug delivery (Figure 1). [3] [4] I will also describe the immunomodulation effect of magnetic nanoparticles [5] [6] and a novel magnetic approach that promotes efficient MNP internalization into immune cells while preserving their viability and functionality preserving cytotoxic activity against tumour models. [7]

Acknowledgement: This work was partially funded by the European Research Council (Consolidator grant GIULLIA, contract no. ID N. 101044020).

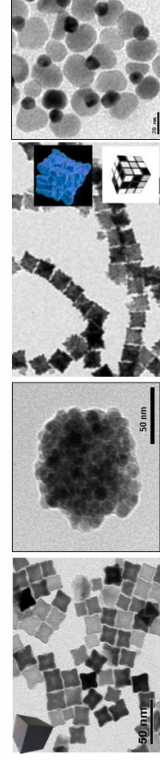


Figure 1. Examples of iron oxide-based nanoparticles, assembly and heterostructure produced in our lab.

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Continuous-Flow Lithium Extraction from Geothermal Brines Using Magnetic Nanoparticles

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Geothermal brines processed in geothermal power plants represent a promising and largely untapped source of critical resources such as lithium, with concentrations on the order of 10-200 mg/l. However, large-scale recovery from these fluids remains challenging due to the low concentrations of target species and their complex ionic composition.

In this work, we propose a continuous-flow reactor concept based on magnetic nanoparticles that selectively bind dissolved lithium ions via crown ether functionalization of the particle surface. The particles are magnetically retained inside the reactor by external magnetic field gradients opposing hydrodynamic transport (see Fig. 1(a)).

The transport and retention of nanoparticles in flowing electrolyte solutions are investigated using numerical simulations combining fluid flow fields obtained from COMSOL Multiphysics with stochastic particle tracing implemented in Python. The model accounts for hydrodynamic drag, magnetophoretic forces, and cavitation-induced perturbations associated with an ultrasonic field at the reactor boundary. These perturbations slightly shift the particle distribution away from the reactor walls, promoting redistribution into regions of increased lithium exposure. The simulations reveal experimentally relevant parameter regimes in which magnetic trapping overcomes hydrodynamic transport, enabling stable nanoparticle retention under continuous-flow conditions (see Fig. 1(b)). For a representative flow rate of 2.88 l/min, a clear reduction in particle loss is observed with increasing magnetic drift velocity. Under these conditions, no particle loss is observed above a critical drift velocity of 0.75 mm/s.

Experimental studies to validate nanoparticle retention in the proposed reactor concept are currently underway. The proposed concept provides a promising and scalable approach for the continuous extraction of lithium and other critical resources from geothermal brines.

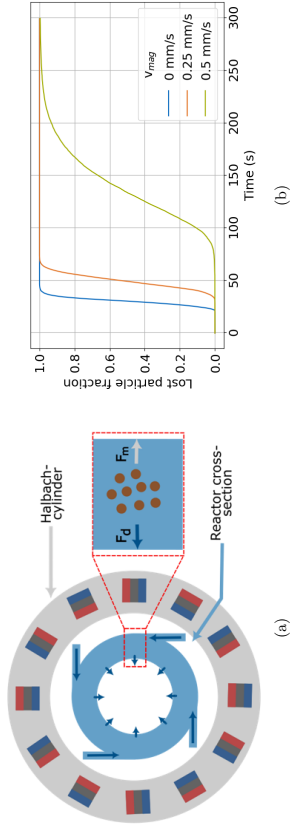


Figure 1: (a) Illustration of a continuous flow reactor concept. A Halbach cylinder surrounds the cylindrical geometry of the reactor, creating a nearly constant radial magnetic gradient on the inside. The tangential inlets and normal outlets (dark blue arrows) of the reactor generate a mainly azimuthal flow field with a small radial component pointing inward. If hydrodynamic and magnetic forces are properly balanced, particle retention can be achieved. (b) Simulation results showing the fraction of particles ($N_{tot} = 10,000$) lost through the outlet over 300 s. Magnetic retention is observed for increasing effective magnetic drift velocities at a fixed mass flow rate of 2.88 l/min.

Quantitative Evaluation of Nanoparticle Delivery to Lymph Nodes Using Magnetic Particle Imaging

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Sentinel lymph node (SLN) biopsies are often performed under image guidance for cancer staging and prognosis. The SLN drains the tumor microenvironment and provides information on cancer invasion into the lymphatic system. To perform a SLN biopsy, a tracer is injected to identify the tumor-draining lymph node (LN). While the performance of the clinical gold standard lymphoscintigraphy using technetium-99m is reasonable, there are issues associated with using radioactive tracers, such as poor spatial resolution and short half-lives. As biopsies can lead to patient discomfort and co-morbidities, a balance must be reached to obtain the most clinically relevant information by excising the minimal number of LNs. Furthermore, pre-clinical imaging studies in rodents and clinical trials in humans using magnetic nanoparticles have demonstrated safety in humans with non-inferior performance compared to lymphoscintigraphy. Here, we evaluate magnetic particle imaging (MPI) to quantitatively monitor nanoparticle accumulation in LNs using different tracer formulations. Tracers optimized for MPI synthesized by our group were injected in mice and tracked using MPI overlaid on computed tomography scans. One tracer, coated with poly(maleic anhydride-alt-1-octadecene), showed inconsistent signal detection in a group of mice ($n = 5$) within the same nanoparticle batch. In contrast, two polyethylene glycol (PEG)-coated tracers with single or clustered nanocrystal cores administered in mice ($n = 5$ each) displayed excellent accumulation, enabling quantification at the SLN and tracking transport patterns to upper echelon LNs (Figure A). There was a strong linear correlation between *in vivo* and *ex vivo* MPI signal of the popliteal LNs ($R^2 = 0.9198$), suggesting that this technique provides accurate detection of the true mass of nanoparticles longitudinally and noninvasively (Figure B). Quantification of percent injected dose (%ID) at the LNs showed an apparent hierarchy of accumulation, where the popliteal had the highest accumulation, followed by the iliac, sciatic, and inguinal nodes. Among the PEG-coated particles, accumulation of 8%ID was observed for the single-core and 6%ID for the multi-core tracer at the popliteal LN (Figure C). Further studies using new tailored tracers suggest that surface charge also influences accumulation rates in the LNs and biodistribution patterns. These observations demonstrate the potential of MPI for sensitive quantitative tracking of nanoparticle transport to LNs, with potential applications for cancer diagnosis.

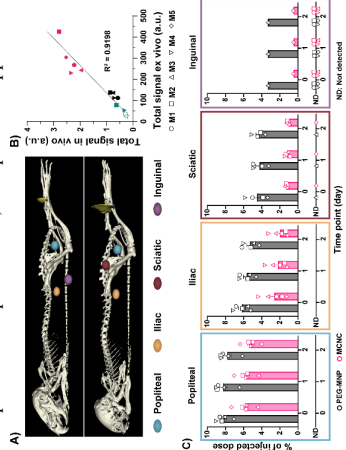


Figure: A) Three-dimensional volume render of MPI scans overlaid on computed tomography demonstrate the capability of imaging various LNs simultaneously. B) There is a strong linear correlation between *in vivo* and *ex vivo* signal. C) Nanoparticle accumulation can be quantified at each LN with respect to the total injected dose.

SMART RHESINS: A Comparative SAR Analysis of Native and Encapsulated Synomag Nanoparticles for MPI-Assisted Magnetic Fluid Hyperthermia

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For theragnostic applications, MPI tracers must not only provide robust imaging performance but also retain functional heating properties for magnetic fluid hyperthermia (MFH). Magnetic Particle Imaging (MPI) uses superparamagnetic nanoparticles to generate signal contrast and is therefore highly attractive for such combined diagnostic and therapeutic concepts.^[1,2] The tracers' signal is strongly dependent on their state and environment, which is of particular importance during *in vivo* applications where these parameters are drastically altered. In this context, SMART RHESINS have been developed as nanocapsule-based tracers containing synomag nanoparticles with well-defined magnetic relaxation characteristics.^[3,4]

To determine whether encapsulation affects hyperthermia performance, the specific absorption rate (SAR) of SMART RHESINS loaded with synomag-D70 was evaluated against native synomag-D70 and empty nanocapsules (**Figure 1**). The control experiments first established that the capsule material itself does not contribute measurably to heating, as empty nanocapsules exhibited negligible SAR. Against this background, the comparison between native and encapsulated synomag-D70 showed that the magnetic core remains highly functional after incorporation into SMART RHESINS. Although native synomag-D70 yielded the highest SAR values overall, encapsulated particles displayed only a limited reduction and preserved the characteristic increase in SAR with field amplitude and frequency. This behavior indicates that the relevant magnetic relaxation processes are largely maintained despite confinement within the capsule structure.

Taken together, these preliminary findings suggest that SMART RHESINS are promising multifunctional tracers that combine reliable MPI performance with retained MFH capability, thereby supporting their further development for integrated theragnostic use.

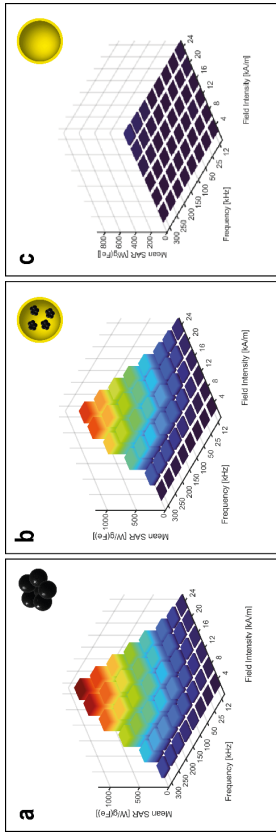


Figure 1: SAR evaluation of the investigated sample types; insets indicate the corresponding particle/capsule design. **a)** Native synomag-D70 nanoflowers exhibited the highest SAR values. **b)** Synomag-D70-filled SMART RHESINS showed a comparable field- and frequency-dependent SAR profile with only minor reduction after encapsulation. **c)** Empty nanocapsules displayed negligible SAR, confirming that heat generation originates exclusively from the magnetic nanoparticles. At 12 kA/m, native synomag-D70 reached 40 W/g and 509 W/g at 300 kHz, whereas encapsulated synomag-D70 reached 26 W/g and 327 W/g, respectively.

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Formulation of nanocluster tracers with tunable magnetic particle imaging performance

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Magnetic particle imaging (MPI) is a novel preclinical imaging technique where biocompatible iron oxide nanoparticles respond to applied magnetic fields, generating a quantitative signal. This technique has been studied for many biomedical applications including image-guided drug delivery, lymphography, blood-pool imaging, and more. Typically, iron oxide nanoparticles for these applications are singly coated, limiting their potential to carry therapeutic or tune their magnetic performance beyond changing the iron oxide particle itself. Utilizing flash nanoprecipitation (FNP), iron oxide nanoparticles can be encapsulated in clusters, with or without additional loading of other hydrophobic molecules like drugs or polymers. This process relies on hydrophobic interactions between the core materials as they are being pushed into their antisolvent, water, and the subsequent stabilization with an amphiphilic surface polymer, offering them stability in water. FNP is a rapid and scalable process, rendering it possible to test a range of conditions on a benchtop scale and scaling up to a production level later. Herein, formulation parameters in flash nanoprecipitation were probed to understand their effect on the magnetic imaging performance of the tracers formed, namely the signal intensity and the full width at half maximum (FWHM). We found that by increasing the amount of hydrophobic homopolymer added to the formulation, one can improve both the signal and resolution of the tracers. This is at odds with size, where more hydrophobic polymer increases the diameter of the particles. We see the properties of these formulations remain when production is scaled-up, and after injection and imaging *in vivo*. We then demonstrate the utility of these particles in the application of color MPI, whereby the signal generated from a mixture of two tracers can be separated into the contribution from each particle, allowing us to determine the composition of the mixture from the image. We demonstrated a pre-clinical application of color MPI using our formulated nanoclusters in 3D printed mouse phantoms bearing tumor and brain capillaries, and a liver cavity. A mixture of two particles was loaded into the liver, mimicking accumulation of both particles, and particle A was loaded in the brain and particle B was loaded in the tumor. We were able to determine the mass ratio of each particle in the solution from the MPI image and comparing this to ground truth values, we show great success. This work demonstrates the potential of FNP as a method of formulating tunable MPI tracers for a wide range of applications.

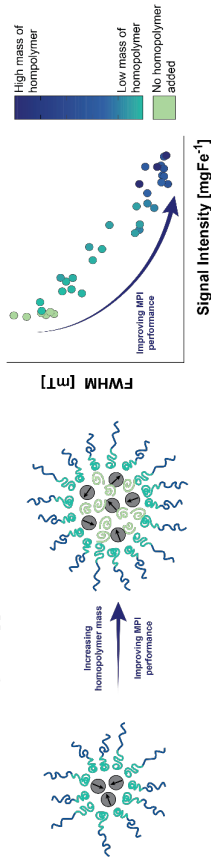


Figure. Increasing homopolymer mass in nanocluster formulations improves MPI performance, demonstrating the tunable formulation of tracers for MPI

Quantification of Magnetic Particle Imaging Signal in Biomedically Relevant Conditions Using a Mouse Phantom

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There is growing interest in developing faster, more cost-effective and informative alternatives to animal testing, known as new approach methodologies. These approaches aim to complement or replace traditional animal studies while adhering to the principles of the 3Rs: replacement, reduction, and refinement. Magnetic Particle Imaging (MPI) supports these efforts by enabling longitudinal imaging, reducing the number of animals required to study nanoparticle pharmacokinetics.

Furthering the efforts, we used additive manufacturing to create anatomically accurate mouse phantoms based off the Digimouse atlas [1], which enabled controlled reproduction of biomedically relevant scenarios. The models emulate systemic delivery of magnetic nanoparticles (MNPs), characterized by dominant liver uptake and low accumulation at target sites, a biodistribution pattern that remains a major challenge for both quantitative imaging and therapeutic applications. Under these conditions, where less than 1% of the injected dose may reach tumors [2], strong off-target accumulation can bias quantification at low-signal regions due to spillover effects [3].

The 3D-printed mouse phantom was used to obtain MPI images of MNP-filled brain, lung, and hind flank regions of variable intensity in the presence of a strong liver signal. Using this platform, we compared several MPI quantification strategies including threshold-based segmentation (50% of the maximum), constant-volume spherical segments (CV), and subtraction methods designed to account for liver signal spillover (CVS). Both 2D and 3D MPI scans were evaluated. Threshold segmentation was reliable for isolated high-signal regions but tended to overestimate signal in low-signal targets near the liver or under low signal-to-noise conditions. CV segmentation improved signal separation, while subtraction approaches further mitigated overestimation due to signal superposition. Using the subtraction strategy with 3D MPI, signals as low as 0.05% and 0.25% of the injected dose could be quantified in the brain/lung and hind flank regions of the mouse phantom, respectively (see Figure).

These results highlight the importance of accounting for spillover effects when quantifying MPI signals in biodistribution studies. Anatomically accurate phantoms provide a reproducible platform for evaluating quantification strategies and refining MPI analysis methods while supporting the 3Rs.

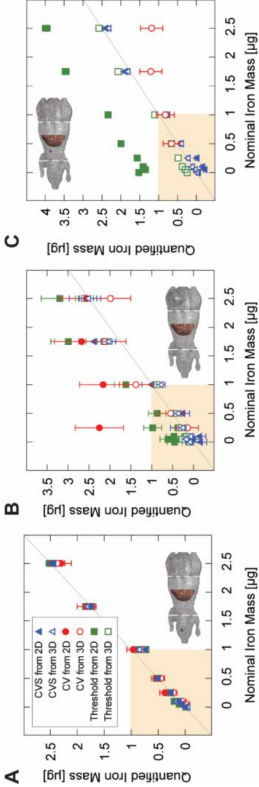


Figure. Comparison of Threshold, CV and CVS approaches for the quantification of MPI signal for all datasets. Quantified Iron Mass from the threshold, CV and CVS segmentation approaches as a function of Nominal Iron Mass for the (A) brain (B) flank and (C) lung datasets. The yellow shaded region highlights doses that represent 1% of the injected dose and lower values.

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Mixing-Frequency Magnetic Particle Imaging System for 3D in-vivo Tumor Imaging

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Magnetic particle imaging (MPI) is an emerging tracer-based imaging modality that enables sensitive and quantitative visualization of magnetic nanoparticles (MNPs). In this work, we develop a mixing-frequency MPI system for three-dimensional (3D) in-vivo imaging, as shown in Figure 1. A pair of permanent magnets is used to generate the field free point (FFP). Two orthogonal drive coils produce magnetic fields along the x and y directions. The developed MPI system employs an ac magnetic field with frequency of 4.98 kHz in x-direction to drive MNPs and an ac magnetic field frequency of 97 Hz to modulate the spectra of the MNPs. The two-frequency ac magnetic can also scan the field free point (FFP) in xy plane with a Lissajous trajectory. In addition, a scanning coil provides a bias field along the z direction for 3D imaging. In x-direction, a gradiometric receive coil is used for MNP spectra detection. Figure 1(b) shows the photograph of the scanner, which enables 3D MPI with a field of view of 30×30×30 mm³.

For the in vivo experiment, self-developed MNPs were administered to mice via tail-vein injection, followed by serial MPI scans from 0 to 72 h post-injection. Figure 1(c) shows the MNP images of MNP biodistribution in the liver and tumor, obtained by overlaying MPI images with a photograph of the mouse. Longitudinal imaging reveals that the MPI signal intensity in the liver gradually decreases over time. In contrast, the MPI signal in the tumor initially increases and reaches saturation.

Furthermore, ex vivo MPI measurements of excised organs and tissues at 72 h post-injection, as shown in Fig. 1(d), confirm the presence of strong MPI signals in the tumor, with additional signal distributions observed in the liver and spleen. These experimental results demonstrate that the developed mixing-frequency MPI system enables 3D in vivo imaging of tumor-associated MNPs. The system shows strong potential for preclinical investigations of MNP accumulation and biodistribution in organs and tumors.

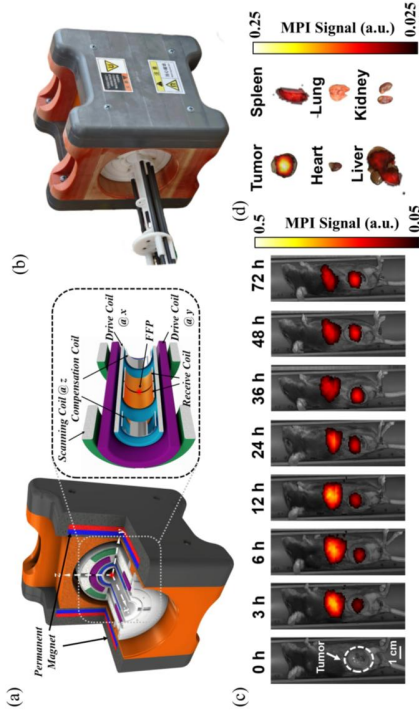


Figure 1. (a) Schematic of the mixing-frequency MPI scanner. (b) Photograph of the MPI scanner. (c) In-vivo MPI images of mice acquired from 0 to 72 h after intravenous administration of engineered MNPs. (d) Ex-vivo MPI images of excised organs and tissues at 72 h post-injection, showing the MNP accumulation in tumor, with additional distribution in the liver and spleen.

Project “harmoMPI”¹: Scanner-Independent Functional Phantoms for Harmonizing Magnetic Particle Imaging

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Magnetic Particle Imaging (MPI) is an emerging tomographic modality specifically detecting magnetic nanoparticles (MNP), resulting in quantitative, real-time 3D imaging with high sensitivity. Since its initial description in 2005, different preclinical MPI scanners have been developed and tested, but a cross-platform comparison is lacking due to missing standardized phantoms and operation procedures. Present developments focus on upscaling of scanner geometries to reach human-sized field of views. A harmonization of existing MPI technology is essential to obtain applications beyond the preclinical research phase.

Within the “harmoMPI” research project, we intend to develop platform-independent, modular phantoms that enables a reliable assessment of the key performance parameters for a consistent performance evaluation across different MPI systems. By close interaction and collaboration with the MPI research community, “harmoMPI” aims to harmonize MPI technology, foster the collaborative research, and advance the detection of clinically relevant applications.

For consistent comparison and harmonization across different MPI systems, we are focusing on the development of scanner independent phantoms and standardized operational recommendations. For realization of this goal, a collaborative workflow based on the state-of-the-art in MPI research work and results has been designed.

First, we started with developing a classification scheme for existing MPI scanners to identify the requirements on phantoms for harmonization. We then will develop static, flow and physiological phantoms that can be modularly adapted to different scanner architectures, enabling extensive round robin studies in MPI labs all over the world. By using a dedicated, standardized evaluation protocol, this will enable performing cross-platform comparative investigations.

Finally, by interpreting the data collected in these studies, a planning tool will be set-up that helps to identify the optimal scanner configuration for given research questions. The planning tool will make possible an efficient experiment planning, support quality assurance, and minimize unnecessary animal testing by reducing trial-and-error approaches.



Figure 9: Workflow of the project: Dedicated test objects and functional phantoms for developing a consistent performance evaluation procedure and a planning tool for efficient experiment planning.

Acknowledgements

This work was supported by Deutsche Forschungsgemeinschaft (DFG) in the frame of the project “harmoMPI” (project no 540328102) and the COST action NexMPI - Magnetic Particle Imaging for next-generation theranostics and medical research (CA23132).

Engineering Magnetotheranostics for Magnetic Particle Imaging

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Magnetic nanoparticles, including those formed of superparamagnetic iron oxides (SPIOs), are employed in various magnetic imaging and therapeutic techniques. *In vivo* imaging techniques include magnetic resonance imaging (MRI), magneto-motive ultrasonography (MMUS), magneto-photoacoustic imaging (MPAI), and magnetic particle imaging (MPI). An early example of magnetotheranostics are magnetically labeled therapeutic cells i.e., immune cells for immunotherapy or stem cells for stem cell therapy, that can visualize their target after homing through tropic signaling, hereby also providing a diagnostic tool. More recently, the field of stem cell therapy has shifted towards “cell-free” therapy after recognizing that many of the active biomolecules are released by extracellular vesicles (EVs). Similar to their parental cells, EVs can be tracked *in vivo* after proper magnetic labeling, offering diagnostic information on for instance sites of inflammation in addition to exerting immunosuppressive therapeutic effects. Our lab and others have been exploring MPI to not only visualize the dynamic homing processes but also to provide quantitative information using MPI “cytometry”.

A recent development in MPI-guided therapy has been the use of magnetotheranostics for magnetic fluid hyperthermia (MFH) or, when combined with gold nanoparticles, for photothermal therapy. This has been demonstrated to be feasible not only for naked nanoparticles but also for labeled stem cells that can carry the nanoparticles towards the tumor for subsequent heating. Preclinical data indicate that the physical conditions required to heat up magnetic nanoparticles, including energy considerations, particle modifications, localization, and exposure time, can be dynamically modulated during a single treatment procedure by monitoring imaging data acquired from the same magnetic nanoparticles. This allows to selectively and precisely heat tumor locations while avoiding damage to surrounding healthy tissue, providing individualized treatment plans based on information about the biodistribution of magnetic nanoparticles within the tumor and adjacent organs, as well as the volumetric distribution of the thermal dose (**Figure**).

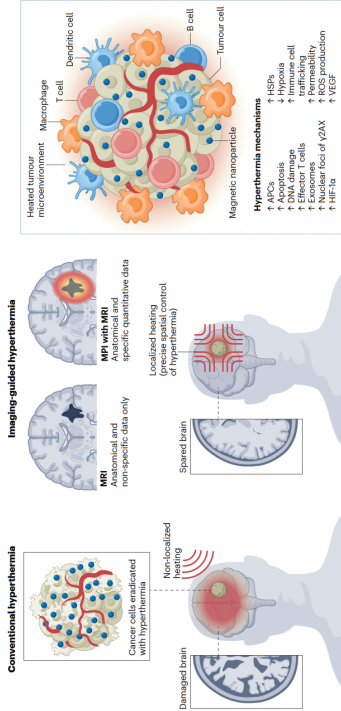


Figure 8: Traditional hyperthermia treatment often causes collateral damage to the healthy tissue surrounding a solid tumor, which can be circumvented by integrated, imaging-guided precision heating. For example, combining MRI with MPI enables both the distribution and concentration of magnetic nanoparticles to be determined. This integrated approach enables not only the confinement of thermal energy precisely and exclusively to the tumor region, but also the calculation of a suitable thermal dose, which facilitates the formulation of customized treatment plans for individual patients. From A. Shakert-Zadeh and J.W.M. Bulle, Nat. Rev. Bieng. 3, 245-260 (2025).

Performance Analysis of Quantitative Susceptibility Mapping Algorithms in Phantom and Preclinical MRI Data

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Magnetic susceptibility (χ) is a fundamental physical property that describes how materials respond to an external magnetic field. Magnetic Resonance Imaging (MRI) exploits variations in magnetic properties to provide non-invasive insights into tissue composition and microstructure. In particular, susceptibility differences between tissues induce local phase shifts in the MR signal, generating contrast that can reveal subtle structural and compositional features. Clinically, MRI is widely used for the diagnosis and monitoring of neurological, cardiovascular, and oncological diseases.

Quantitative Susceptibility Mapping (QSM) is an advanced MRI post-processing technique that reconstructs spatial maps of tissue susceptibility from phase data by solving an ill-posed inverse problem. QSM has gained increasing relevance in biomedical research for quantifying iron deposition, calcifications, demyelination, and the distribution of contrast agents. However, its accuracy is limited by noise, artifacts, and orientation dependence, motivating the development of multiple reconstruction algorithms.

In this work, we focus on tracking vesicles used as vehicles for targeted drug delivery in the treatment of neurodegenerative diseases. In this context, QSM enables the quantification of iron distribution, emerging as a powerful tool for mapping vesicle localization and concentration. We present a comprehensive evaluation of QSM algorithms proposed by Wang et al. [1], implemented within the SEPIA toolbox (MATLAB). The analysis was performed on a gel phantom containing nine concentrations of the superparamagnetic contrast agent VivoTrax, as well as on high-resolution rat brain datasets as preclinical models. MRI acquisitions were conducted at 7 T using a gradient-echo sequence optimized for phase contrast. Reconstruction performance was assessed in terms of susceptibility-concentration linearity, noise amplification, and artifact suppression.

Preliminary results indicate that some algorithms (e.g., TKD) achieve higher sensitivity at low contrast concentrations, whereas others (e.g., iLSQR and MEDI) provide improved artifact reduction in complex geometries. These findings highlight the trade-offs between accuracy and robustness in QSM reconstruction and may support the selection of optimal methods for preclinical studies, with potential implications for future clinical applications in the quantitative assessment of neurological and oncological pathologies.

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Magnetically Responsive Upconversion Nanoparticles: Optical Luminescence and MRI of Langerhans islets

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Diabetes mellitus, characterized by chronic hyperglycemia is an increasingly prevalent life-threatening disease worldwide. Its early detection and monitoring of progression are crucial for the advanced therapeutic treatments, such as Langerhans (pancreatic) islet transplantation.

In this work, newly designed monodisperse core-shell upconversion/magnetic NaYF₄:Yb,Er,Fe@NaGdF₄:Yb,Tb,Nd nanoparticles (CS-UCNPs) were prepared by high-temperature coprecipitation of lanthanide chlorides followed by epitaxial growth of a shell around the core. The particles were then coated with poly(methyl vinyl ether-*alt*-maleic acid) (PMVEA), which notably enhanced both their biocompatibility and colloidal stability in physiological media. Covering the surface of nanoparticles with a hydrophilic polymer containing both anchoring and functional groups for binding the target biomolecule is always of primary importance for achieving the applicability of particles in biological and medical applications. Thanks to the presence of elements with magnetic properties (Gd, Fe, Nd, Tb), CS-UCNP@PMVEA particles possessed dual-mode T₁- and T₂*-weighted magnetic resonance imaging (MRI) contrast enhancement combined with near-infrared-mediated upconversion luminescence (Figure). The ability of simultaneous MRI and upconversion luminescence by CS-UCNP@PMVEA particles thus represent an attractive platform for effective noninvasive real-time visualization of Langerhans islet grafts, even at significantly reduced islet volumes, which improves detection sensitivity and diagnostic precision. Monitoring pancreatic islet transplantation using CS-UCNPs is a key factor for their successful clinical translation.

Acknowledgement. This work was supported by the Czech Science Agency (No. 25-16155S).

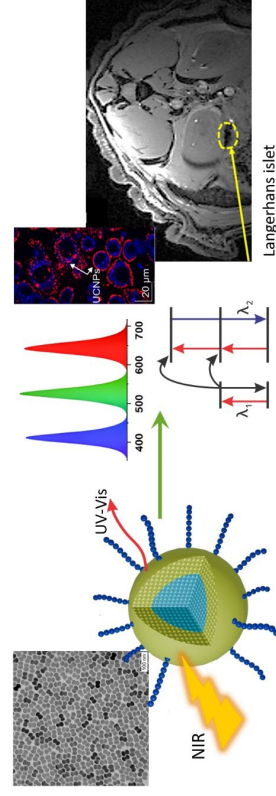


Figure. Optical and MR imaging of CS-UCNP@PMVEA nanoparticles in Langerhans islet.

Ultrasound-Based Magnetic Nanoparticles Imaging: Improved Magnet Geometries and Elastometry

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With an over sixty-year track record as a safe, cost-effective medical imaging modality, ultrasound is recognized for its broad range of clinical uses. However, despite its strengths, not all potential imaging targets within the human body are visible with this technique. Ultrasound contrasts mismatches in density and/or speed of sound, so targets that share these acoustic properties with surrounding tissue cannot be seen. Current microbubble contrast agents are restricted to blood vessels due to their large size, highlighting a critical need for novel, extravascular contrast agents.

Magnetomotive ultrasound (MMUS) bridges this gap by utilizing magnetic nanoparticles (MNPs) as tracers. By applying a temporally modulated magnetic field, MNP-labeled tissues are forced into submicron-scale motion, which is subsequently detected using phase-resolved ultrasound imaging. MMUS is currently being explored for applications including cancer therapy, drug delivery, and blood clot imaging.

As shown in Fig. (a), we recently demonstrated the use of MMUS for quantitative elastometry in clot-mimicking phantoms. Despite this promise, magnet design and placement remain significant hurdles. As depicted in Fig. (b), systems with solenoids positioned opposite the transducer yield strong signals but encroach on the imaging space. In contrast, "open-air" MMUS configurations place solenoids on the same side as the transducer, permitting unrestricted sample sizes. However, these setups require much stronger magnets, necessitating complex cooling systems and limiting operation to lower frequencies.

To accelerate magnet design, we developed a finite element model to predict MNP displacement amplitude for novel combinations of solenoids and permanent magnets. Using this model, we determined the optimal placement of two NdFeB permanent magnets (Fig. (c)) to enhance contrast in an existing MMUS setup. The model predicted a displacement increase by a factor of 2.2 ± 0.2 , which agreed with our experimental validation value of 2.2 ± 0.3 , as shown in Fig. (d). Applying these optimized geometries may enable open-air MMUS with smaller solenoids suitable for high-frequency modulation, quantitative elastometry, and broader clinical applications.

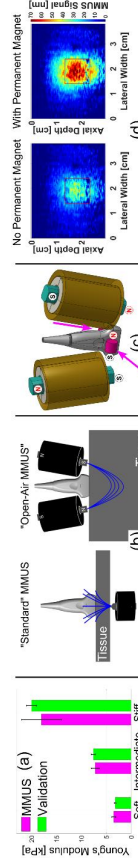


Figure: (a) Comparison of MMUS elastometry results with compression testing for three different types of blood clot-mimicking phantoms. (b) Schematic of the "standard" MMUS configuration in which the sample is placed between the transducer and the electromagnet, and the "open-air" configuration in which the magnets and transducer are located on the same side, allowing for an unrestricted imaging area, but requiring larger magnets. (c) The FEA model predicted a factor of 2.2 ± 0.2 increase in magnetically induced displacement when permanent magnets were placed as shown in magenta. (d) Comparison of MMUS displacement images of an MNP-laden inclusion in a gelatin phantom without (left) and with (right) the permanent magnets. Displacement amplitude increased by a factor of 2.2 ± 0.3 .

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Shape-Dependent Magnetomotive Forces: A Framework for Optimizing Particle Geometry in Magnetomotive Ultrasound Imaging

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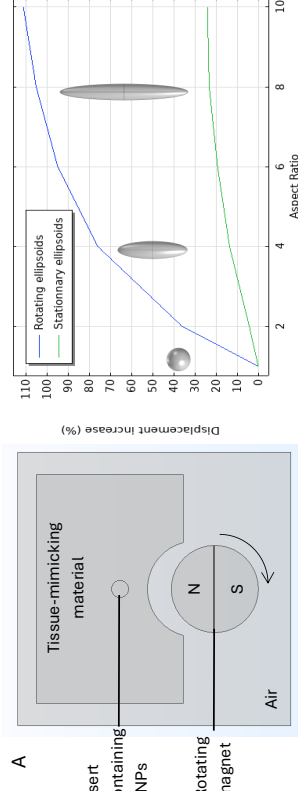
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Magnetomotive ultrasound imaging (MMUS) is an emerging technique that uses magnetic nanoparticles (MNPs) as a contrast agent for ultrasound. Tissue-embedded MNPs are set in motion by a rotating external magnetic field, and the resulting displacement is detected using ultrasound. However, the reach of the magnetic field limits MNP motion and thereby imaging depth. This limitation restricts clinical applications, such as tumor delineation. To address this, we investigate whether tailoring particle geometry increases the field-induced forces acting on the particles, thus increasing the resulting motion and improving imaging sensitivity.

We derive an extended expression for the magnetomotive force that incorporates particle-shape dependence through demagnetizing factors, providing a general framework for comparing geometries. This formulation was implemented in a simulation pipeline and applied to ellipsoidal particles, for which analytical demagnetizing factors are available. A finite-element model (COMSOL, Fig. A) was constructed to incorporate the shape-dependent force, and both magnetic and hydrodynamic torques were evaluated to assess particle rotation. The magnetoviscous time constant was estimated to determine whether particles can dynamically align with the applied field.

Our model predicts up to a 110% (Fig. B) increase in magnetically induced displacement when replacing a sphere with an ellipsoid of similar volume and aspect ratio of 10, assuming particles can reorient with the magnetic field. If particles are immobilized and randomly oriented, the predicted gain remains ~25% (Fig B.). Torque analysis indicates that rotational alignment is feasible only below an aspect ratio threshold, which itself depends on field strength and medical application depth.

These results suggest the existence of an optimal ellipsoid aspect ratio range for MMUS contrast agents that maximizes motion for a given depth, providing design guidelines for next-generation MNPs aimed at improving MMUS sensitivity.



(A) Finite-element model. (B) Displacement increase as a function of ellipsoid aspect ratio and particle shapes for aspect ratios 1, 4 and 8.

Gadolinium-Doped Iron Oxide Nanorods and Nanoflowers as Dual Modality Agents for Magnetic Hyperthermia and MRI

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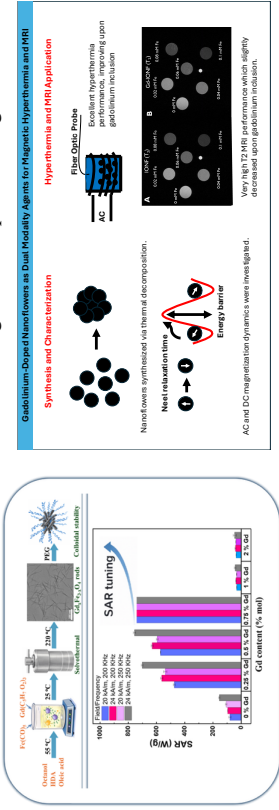
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Abstract

In this study, we produced both undoped IONFs and gadolinium-doped iron oxide nanoflowers (Gd-IONFs) through the introduction of a small amount of gadolinium acetylacetonate during the thermal decomposition reaction. In addition, we also conducted a systematic study of Gd_xFe_{3-x}O₄ nanorods (x = 0-2 mol% of gadolinium (Gd)) synthesized via one-pot solvothermal route and functionalized with PEG-nitroDOPA to achieve colloidal stability. Magnetometry measurements showed a decrease in powder magnetization upon doping the nanoflowers with gadolinium. The IONFs and Gd-IONFs exhibited excellent performance for magnetic hyperthermia under clinically relevant fields and frequencies of 200 kHz and 20 kA/m, with the magnetometric AC specific absorption rate (SAR) values reaching approximately 416 W/g and 482 W/g, respectively. Magnetic hyperthermia performance, quantified by specific absorption rate (SAR), evaluated by AC magnetometry and calorimetry under clinically relevant conditions (i.e., 20 kA/m, 200-205 kHz), peaked at 752-764 W/g for 0.75 mol % Gd. This strategy of combining moderate Gd doping with catechol-anchored PEG-coating offers a robust approach in developing high-heating, biocompatible Fe₃O₄ nanorods for enhanced magnetic hyperthermia applications. MRI relaxivity of the nanoflowers showed a decrease in transverse relaxivity *r*₂ from 600 L·mmol⁻¹·s⁻¹ to 560 L·mmol⁻¹·s⁻¹ upon the addition of gadolinium. Similarly, a decrease in longitudinal relaxivity *r*₁ from 2.7 L·mmol⁻¹·s⁻¹ to 2.3 L·mmol⁻¹·s⁻¹ occurred through the incorporation of gadolinium.



A Mitochondria-Specific Nanoparticles for Wireless Dynamic Regulation of Cellular Function in Vivo

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Mitochondria play essential roles in regulating cellular function and fate, making precise modulation of mitochondrial function a promising therapeutic strategy for intractable diseases. Although nanoparticles offer versatile functionalities, such as optical, magnetic and catalytic features, for mitochondrial intervention, their mitochondria-targeting efficacy remains undesirable.

Here, we report a mitochondria-targeting nanoparticle for the magnetic modulation of mitochondrial function and cell fate in vivo (Figure A). This system leverages the synergistic effect of surface Mn²⁺ and TPP ligands for efficient mitochondrial targeting. High-resolution SIM imaging reveals specific localization at the inner mitochondrial membrane. Mechanistic studies confirm that surface Mn²⁺ ions and TPP ligands synergistically drive this superior targeting performance in Figure B. Under alternating magnetic field (AMF), UMF-TPP exhibits real-time switchable catalase-like activity, enabling on-demand scavenging of mitochondrial reactive oxygen species (ROS) with spatiotemporal precision. This magnetic modulation is reversible and specific to UMF-TPP. For in vivo application, we engineer a reduction-responsive assembly system (UMF-TPP-AS) that enables intravenous delivery and tumor mitochondria accumulation (73.9% colocalization). In MDA-MB-231 tumor-bearing mice, UMF-TPP-AS achieves remote AMF-controlled mitochondrial ROS modulation and cellular fate regulation (Figure C-G).

Overall, this work establishes a new platform for remote magnetic regulation of mitochondrial physiology in vivo, achieving 95% targeting efficacy and real-time AMF-controlled catalase-like activity, with broad therapeutic implications for mitochondria-related diseases.

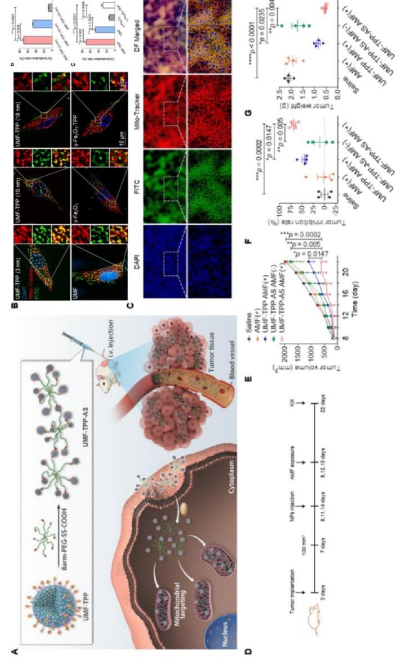


Figure. (A) Schematic illustration of Mn²⁺/TPP dual-targeting magnetic nanoparticle (UMF-TPP) for synergistic mitochondria targeting and AMF-regulated ROS modulation. Figure. (B) TPP and Mn ions synergistic mitochondrial-targeting mechanism of UMF-TPP. Figure. (C-G) In vivo mitochondrial targeting and magnetic regulation of mitochondrial function.

Magnetic Hyperthermia-Induced Disruption of Collagen Scaffolds: A Strategy to Overcome the Extracellular Matrix Barrier in Solid Tumours and Fibrotic Diseases

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Keywords: magnetic nanoparticles; crystalline lattice planes; magnetic hyperthermia; Specific Loss Power, collagen hydrogels

The tumor extracellular matrix (ECM) represents a dense physical barrier that severely limits the clinical efficacy of antitumoral therapies. This fibrotic network prevents the efficient transport of pharmacological agents, as well as the infiltration of cellular and molecular mediators with deleterious effects on the tumor mass. Aside from its water content, collagen constitutes the primary structural component of the ECM, forming a rigid scaffold that maintains high interstitial fluid pressure and mechanical resistance. In this context, magnetic hyperthermia (MH) emerges as a promising tool not only for thermal ablation mediated by heat dissipation, but for the direct mechanical disruption of the collagen scaffold.

In this work, we characterized commercially available magnetic nanoparticles (Micromod) using Transmission Electron Microscopy (TEM) ($D = 24.7 \pm 3.6$ nm), Dynamic Light Scattering (DLS) ($d = 35.9 \pm 0.8$ nm; $PDI = 0.12 \pm 0.01$; $ZP = -15.2 \pm 1.6$ mV), and SQUID magnetometry (Figure 1A). To evaluate their heating performance, calorimetric Specific Loss Power (SLP) assays were conducted under various magnetic field amplitudes and frequencies (10 to 30 mT; 163 to 763 kHz). Furthermore, High-Resolution TEM (HR-TEM) made possible to analyze the orientation of crystalline planes and the multi-core morphology of the particles (Figure 1B). Global and local temperature increments were estimated for three distinct Alternating Magnetic Field (AMF) conditions. Also, we studied the impact of the MH treatment on the ECM, using three experimental collagen hydrogel models simulating different administration routes. These models were analyzed by measuring hydrogel height contraction and characterizing microstructural alterations via Cryo-Scanning Electron Microscopy (Cryo-SEM) (Figure 1C and D), where a loss of ordered structure was observed, consistent with a collapse of the collagen scaffold.

These results suggest that MH is a promising therapeutic tool, capable of improving the distribution of anticancer drugs or functioning as a standalone treatment to break down the collagen barrier in different fibrotic diseases.

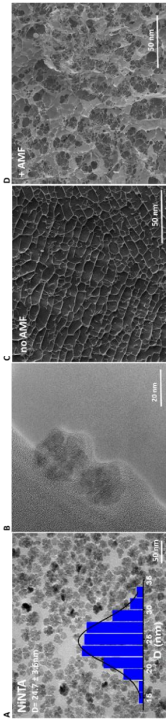


Figure 1. Disruption of collagen matrices via AMF. A. TEM image and size histogram of two nanoflowers, with AMF. B. HR-TEM of NINTA@MNPs. C. Collagen hydrogel incubated with NINTA@MNPs in the absence of AMF. D. Collagen hydrogel incubated with NINTA@MNPs treated with AMF.

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Histopathological Assessment of Magnetic Fluid Hyperthermia in a Porcine Prostate Model Using a Handheld Induction Heater

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Magnetic fluid hyperthermia (MFH) offers a minimally invasive focal therapy alternative for localized prostate cancer. The clinical translation of MFH requires controlled magnetic nanoparticle (MNP) delivery, predictable thermal dose, and correlation between MNP localization and therapeutic effect. We present an *in vivo* evaluation of a transrectal induction heater (TRIH) system in a normal porcine prostate model with histopathological analysis. Five-hundred μ L of Synomag-D PEG-OMe MNPs (50 mg_w/mL) were injected into the prostates of Large White domestic pigs ($n = 3$) at 6 mm and 13 mm depth. A maximum alternating magnetic field (AMF) of 28 kA/m at 300 kHz was applied for 1 hour using the TRIH. Control conditions included: 1) untreated, 2) AMF only, and 3) MNP only. Animals were sacrificed 1 hour post-treatment, and prostates were sectioned by depth: A (0-4 mm), B (4-8 mm), C (8-14 mm), and D (>14 mm). Hematoxylin & Eosin (H&E) and Prussian Blue (PB) staining, and initial histology review were performed by an independent pathology laboratory. Serial sections were analyzed for paired comparison. MNP distribution was quantified using QuPath (v0.6.0) pixel classification (Random Trees classifier), while thermal damage was assessed using a scoring system (0-4 scale) evaluating nuclear changes, architectural disruption, and coagulative changes. See Figure 1 for details regarding this study.

H&E analysis revealed a spectrum of thermal damage correlating with MNP distribution: Score 4 (severe thermal coagulative damage) in MNP-dense zones, transitioning through Score 2-3 (moderate damage) to Score 0-1 (normal or minimal changes) in regions with low or no iron presence. Controls (untreated, AMF-only, and MNP-only) showed no thermal damage, as expected. PB staining confirmed MNP deposition at injection sites. Nanoparticle presence was also observed in superficial sections despite injection at deeper levels, suggesting possible redistribution during AMF exposure. Notably, regions distal to injection sites showed iron presence without damage, likely due to reduced field intensities at these depths. PB-positive regions ranged 6-60% depending on section depth. Adjacent structures to MNP zones appeared intact, supporting localized treatment confinement. The TRIH system achieved localized MNP-mediated thermal effects in porcine prostates with clear correlation between MNP distribution and histological damage. These findings support the continued development of transrectal MFH as a focal therapy platform for prostate cancer.

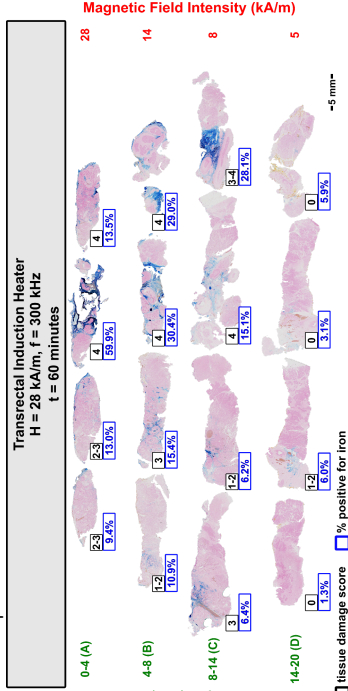


Figure 1. Representative Prussian Blue-stained normal porcine prostate sections following MFH with Synomag-D nanoparticles ($n=3$). Sections arranged by depth from the applicator surface. Labels indicate damage score (0-4, black) and PB-positive area (%). Magnetic field intensity (red axis) is derived from TRIH characterization. Depth (green axis) indicates the distance from the instrument surface. Each image represents a transverse section; serial slices within each depth region are spaced 3 mm apart.

Determining the mechanisms of action of magnetosomes in magnetic hyperthermia cancer treatment

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Magnetic hyperthermia (MHT) is a therapeutic technique that employs magnetic nanoparticles exposed to an alternating magnetic field to generate heat, increasing the temperature of the targeted tissue and resulting in cancer cell death. Amongst the nanoparticles being proposed as MHT agents are magnetosomes, magnetite (Fe_3O_4) nanoparticles enveloped by a proteolipid membrane and synthesised by magnetotactic bacteria. Magnetosomes exhibit high chemical purity, uniform morphology and narrow size distribution. These properties combined with their low toxicity and biocompatibility, make magnetosomes ideal candidates for MHT-based cancer treatments [1]. However, the mechanisms by which magnetosomes trigger cell death during MHT remain unknown.

In recent years, there has been a significant debate on the aspects of MHT that contribute directly to cell death. Proposed mechanisms include global temperature increases, localised nanoscale heating [2], and the generation of reactive oxygen species via Fe^{2+} induced Fenton reactions [3]. Determining the relative contribution of each mechanism is essential for optimizing magnetic hyperthermia treatment strategies.

To determine the mechanisms by which magnetosomes induce cell death, we have performed a screening to evaluate the roles of temperature, and Fe^{2+} release in magnetic hyperthermia triggered cell-death employing A549 cell cultures as cancer models, and liposomes as membrane models. We have found that for magnetic hyperthermia with magnetosomes (157 Hz and 48 mT), a small global temperature increase ($\Delta T=2^\circ\text{C}$) is required to induce cell death, and that membrane permeability increases during magnetic hyperthermia treatment. These results may help optimise magnetosome dosages and guide the selection of co-adjuvant therapies for improved cancer treatment outcomes.

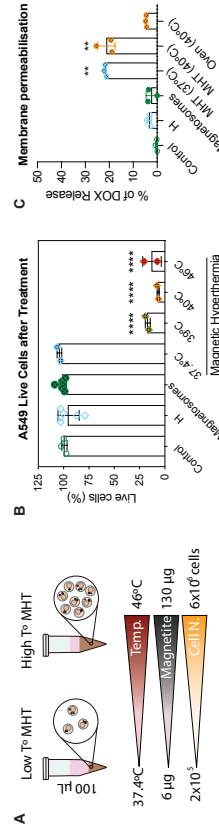


Figure 1. A. Experimental set up of the magnetic hyperthermia experiments in A549 cells. Total magnetite was adjusted by adjusting cell number, to achieve temperatures between 37°C and 46°C while maintaining magnetite concentration/cell the same. B. Live cell number 48 h after magnetic hyperthermia treatment. Differences in live cells were only observed when temperature of the sample increased above 39°C. C. Membrane permeabilisation measured in a liposomal membrane model, as the percentage of fluorophore released from the liposome.

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Improving Measurements of Magnetic Nanoparticle Heating Power

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The hysteretic properties of magnetic nanoparticles allow for heating, which can be utilised in localised cancer treatment, and clinical trials with magnetic hyperthermia have already been conducted [1]. For magnetic hyperthermia to be an efficient therapy, it is of great importance to optimise the heating power of magnetic nanoparticles. To this end, reliable quantification of the heating power is necessary to enable comparison between different candidates of particles [2,3]. A recent inter-laboratory study (RADIOMAG, 2021) found that the standard method (non-adiabatic AC calorimetry) for quantifying the heating power is subject to large systematic errors of unknown origin [2]. Across 21 participating state-of-the-art laboratories, the intrinsic loss power (field normalised heating power) displayed a systematic inter-laboratory deviation of 30–40 %. For the development of new efficient magnetic nanoparticles, the lack of consistency is problematic as it inhibits comparison of heating powers. This highlights the need for an accurate standard measurement protocol to quantify the heating power.

In this contribution, we present the importance of the sample environment in non-adiabatic AC calorimetric measurement (Fig. 1). We demonstrate how local temperature increments in the sample insulation influence the measured heating power and how the heat transfer from the sample can be analysed more directly by a new plot concept called slope curves (Fig. 1C) [4]. Additionally, we present a re-investigation [5] of the inter-laboratory data from 21 laboratories [2]. This reveals four typical instrumentation challenges: 1) Insufficient temperature resolution, 2) AC field sensitive thermometers, 3) Non-physical heat oscillations and 4) Apparent non-linear heat losses [5]. When excluding data of quantifiably insufficient measurement quality, we observe that the inter-laboratory deviation is reduced by up to 38% [5] relative to the 30–40% which was found in [2]. Based on our results, we propose a protocol to identify and avoid the identified measurement challenges and strategies on how to correctly estimate the heating power of magnetic nanoparticles [5].

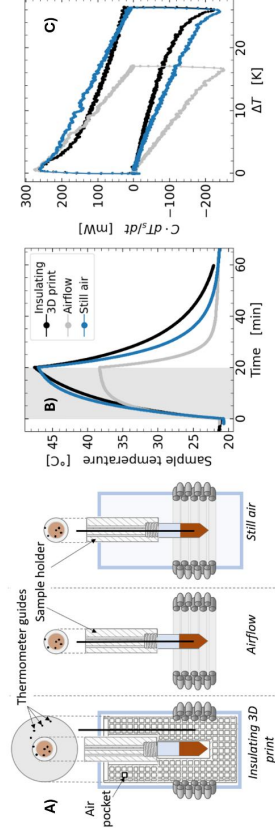


Fig 1. A) AC calorimetric setups with three different sample environments. B) Sample temperatures measured in the three different sample environments seen in the left figure. C) Data in the central plot converted into a plot of the time derivative of the temperature vs temperature change, called a slope curve [4].

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SLPcalculator: Open-Access Software for Statistically Validated SLP

Determination in Magnetic Nanoparticles

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The Specific Loss Power (SLP) is widely used to characterize the heating efficiency of magnetic nanoparticles (MNPs) subjected to alternating magnetic fields. Conventionally, SLP is extracted from calorimetric measurements by analyzing the temperature variation curve $\Delta T(t)$ using approaches such as the Initial Slope (ISM), Box-Lucas or Corrected Slope methods. However, the obtained SLP values can differ significantly depending on the chosen methodology [1]. This dispersion arises from several experimental and physical factors, including spatial temperature gradients, multiple heat dissipation pathways, and time-dependent colloidal changes during the measurement.

To reduce this strong dependence on the experimental setup, we previously introduced the Peak Analysis Method (PAM) [2]. This method estimates the SLP from the difference between the time derivatives of the $\Delta T(t)$ curve immediately before and after the field on/off maximum, where temperature inhomogeneities and competing dissipation mechanisms are largely suppressed. Since PAM relies on the determination of linear slopes, a rigorous identification of the time intervals exhibiting linear behavior is essential.

Here, we address this issue by defining linearity from a formal statistical perspective. Specifically, we implemented an F-test to compare linear and quadratic models, allowing an objective determination of the temporal windows where the system behaves linearly. This analysis was applied to the heating and cooling branches surrounding the $\Delta T(t)$ peak in repeated measurements of aqueous suspensions of dextran-coated octahedral iron oxide nanoparticles. The results reveal a well-defined and relatively narrow linear regime, underscoring the need to accurately identify this interval prior to SLP evaluation.

The same statistical approach was also applied to conventional ISM. In all cases, PAM yielded systematically higher SLP values than ISM, in agreement with previous reports indicating that ISM tends to underestimate SLP [3]. Notably, the linear region identified by the F-test is located far from the time window typically selected for ISM fitting.

To support more standardized and reproducible SLP determination, we developed **SLPcalculator.com**, an open-access and user-friendly tool that automatically computes SLP using PAM within the statistically validated linear regime. For comparison, the software also reports SLP values obtained with the conventional ISM.

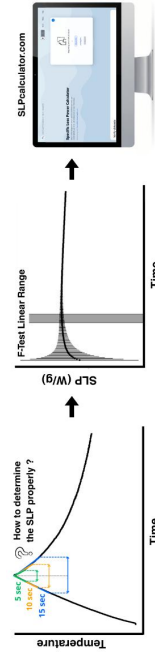


Figure 1. Schematic representation of the SLPcalculator workflow: slope fitting around the $\Delta T(t)$ peak, F-test determination of the linear fitting range, and automated SLP calculation in the web platform.

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Magnetic nanogels for combined hyperthermia and chemotherapy of prostate cancer

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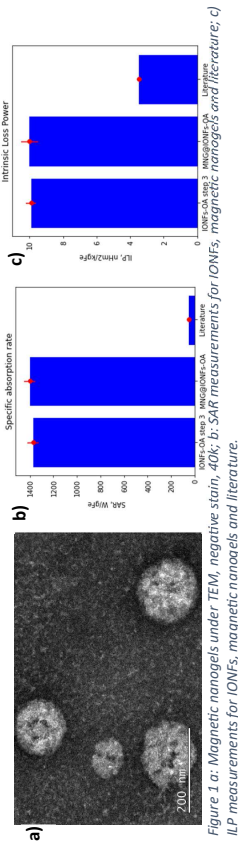
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Chemotherapy patients suffer severe side effects from the medications and hyperthermia can be an invasive treatment¹. In recent years, clinical trials have demonstrated that hyperthermia can enhance the action of chemotherapy drugs² as cancer cells are susceptible to heat¹. A combination of these therapies offers synergistic effects, potentially minimising their individual drawbacks.

Superparamagnetic iron oxide nanoflowers (IONFs) exhibit exceptional heating properties³, while nanogels—biocompatible 3D polymer networks—serve as effective carriers for drugs and other therapeutic agents. This study focuses on developing iron oxide magnetic nanogels for prostate cancer treatment, integrating hyperthermia and chemotherapy⁴.

Nanogels were synthesised using a noncovalent, electrostatically driven template polymerisation around the IONFs. Dynamic light scattering (DLS) measurements confirmed formation of the nanogels through size and surface charge measurements. In fact, the IONFs in solution have d_{DLS} = 70 nm and ζ = -23 mV, while the nanogels have d_{DLS} = 408 nm and ζ = +12 mV.



Transmission electron microscopy (TEM) imaging confirmed the nanogels' morphology, showing d_{TEM} = 363 nm (Figure 1a). Cryo-TEM confirmed presence of IONFs inside the nanogels thanks to EDS measurements. The nanogels contained 79.50% iron, as measured by inductively coupled plasma–optical emission spectrometry (ICP-OES). Magnetic characterisation via superconducting quantum interference device (SQUID) confirmed the nanogels retained the superparamagnetic properties of the IONFs. Under a magnetic field (16 kA/m, 350 kHz), the nanogels demonstrated a specific absorption rate (SAR) of 2698 W/kg_{Fe} and the intrinsic loss power (ILP) of 9.88 nHm²/kg_{Fe} (Figure 2b-2c), significantly surpassing state-of-the-art values (SAR of 47 W/kg_{Fe} and ILP of 2.8 nHm²/kg_{Fe})⁵ and hence making them ideal for biological applications³. In vitro studies showed excellent cell viability up to 100 µg/ml and efficient uptake in prostate cancer cells. Drug delivery studies showed an increased delivery under magnetic field, underscoring the potential of magnetic nanogels for non-invasive, synergistic cancer therapies.

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Catching and Counting Molecules with Buoyant Microbubbles and Magnetic Microspheres for Rapid yet Ultrasensitive Point-of-Care Diagnostics

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Rapidly detecting infectious diseases such as Covid-19 and gonorrhea could help contain outbreaks and improve treatments. Unfortunately, rapid point-of-care lateral flow assays lack sensitivity at early disease stages, while ultrasensitive assays take centralized labs hours to days to process. We recently developed an ultrasensitive rapid antigen assay that labels one epitope of an analyte molecule or cell with an antibody-functionalized buoyant microbubble and a second epitope on the same analyte with magnetic microspheres, thus forming buoyant-analyte-magnetic (BAM) sandwich complexes. A magnet captures BAM complexes while free buoyant microspheres float away without rising; removing the magnet releases the BAM complexes. These BAM complexes intensely scatter light like dust in a sunbeam and are counted by a camera, with BAM complexes proportional to analyte concentration for dilute specimens. The assay gives positive results over nine orders of magnitude of concentration, and if necessary, high concentrations can be quantified after dilution. The assay is extremely sensitive due to rapid and efficient analyte capture, and the background noise is low because opposing buoyant and magnetic forces break apart most non-specific binding. The approach has few steps, and can be performed by a paramedic on the back of a parked medical van in 3.5 minutes (spit to analysis), while retaining a remarkable analytical limit-of-detection (0.92 fg/mL for SARS-CoV-2 nucleocapsid protein spiked into PCR-negative saliva). We show examples for Covid-19, whole-cell bacteria such as *Neisseria gonorrhoeae*, and model systems with simulations and microspheres.

Opto-Magnetically Guided Monocytes for Enhanced Nanotherapy in 3D Bioprinted Tumor Models

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The clinical translation of nanoparticle-based cancer therapies remains limited by inefficient tumor accumulation and the presence of complex biological barriers. To address this challenge, we present a monocyte-mediated delivery system utilizing poly(lactic-co-glycolic acid) (PLGA) nanoparticles loaded with docetaxel partially coated by a magneto-optic nanodome-shaped Fe/SiO₂ semishell (NDs). THP-1 monocytes were used as cellular carriers due to their innate tumor-homing capabilities and high nanoparticle uptake, forming biohybrid “Trojan-horses” capable of crossing biological barriers. The NDs retained their physicochemical properties after internalization, enabling both highly efficient magnetic guidance and photothermal activation. We evaluated the magnetic and optical control, and the therapeutic performance of ND-loaded monocytes (THP1@NDs) in both transwell and in advanced 3D bioprinted cancer models that mimic the tumor microenvironment, including endothelial barriers, stromal components and colorectal cancer spheroids. Magnetically guided THP1@NDs demonstrated enhanced extravasation in transwell assays and preferential accumulation around the cancer spheroids. Upon near-infrared laser irradiation, a synergistic chemo-photothermal effect was observed, significantly reducing cancer cell viability and inducing apoptosis. In the 3D bioprinted tumor model, magnetically actuated monocytes penetrated remarkably deeper into the hydrogel matrix, achieving up to 60% viability reduction, outperforming free drug delivery, which did not cause any therapeutic effect. These findings underscore the potential of magnetically-guided immune cell-mediated nanoparticle delivery systems to overcome tumor barriers and enhance localized nanotherapy. The integration of immune-cell carriers with biomimetic 3D tumor models provides a robust platform for evaluating the next-generation of nanotherapies, representing a promising strategy to improve the efficacy and specificity of cancer treatments.

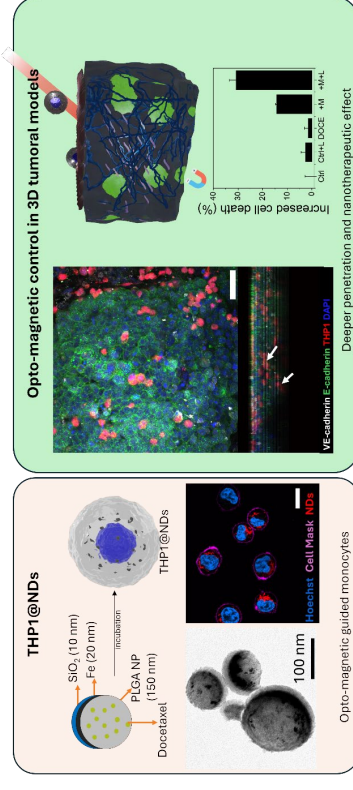


Figure: Externally guided, opto-magnetic nanoparticle-loaded monocytes efficiently infiltrate bioprinted 3D tumors. Magnetic targeting combined with photothermal activation amplifies docetaxel efficacy, enabling a highly controlled and potent cancer nanotherapy platform.

Magnetic Field-Induced Drug Delivery From Magnetic Microporous Nanocomposites Through Magnetic Nanoparticles Heating or Motion

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Metal-organic frameworks (MOFs) are promising carriers for drug delivery applications due to their large tunable porosity, structural flexibility, biocompatibility and high drug-loading capacities. Nonetheless, precise, on-demand release remains challenging. Here, we designed a magnetic field-responsive nanocomposite, termed MagZIF-8, comprising superparamagnetic iron oxide nanoparticles (IONP) coated with a ZIF-8 shell and loaded with cresyl violet, a fluorescent cytotoxic probe (figure 1). The IONPs are used to convert the high frequency alternating (AMF) or rotating low frequency (RMF) magnetic field exposure into thermal or mechanical energy, respectively, while the ZIF-8 shell serves as a carrier for the fluorescent reporter cargo, cresyl violet (CV). The particles were stabilized with a fluorescein-functionalized amphiphilic polymer that improves colloidal stability, prevents unspecific sustained release, and protects the ZIF-8 shell from premature degradation, enabling efficient intracellular uptake in cells. The aim of this study was to analyze whether AMF and RMF stimuli induced the release of the CV cytotoxic drug from the magnetic nanocomposites, triggering the death of cancer cells (figure 1).

The IONPs had a hydrodynamic diameter of 22 ± 1.92 nm, and the MagZIF-8 nanocomposites had a core-shell structure with a hydrodynamic diameter of 226 ± 8.89 nm. The IONPs, showed superparamagnetic behavior and a saturation magnetization of $73.7 \text{ Am}^2/\text{kg Fe}$; both properties were kept after being included inside ZIF-8. The MagZIF-8 nanocomposites were biocompatible on MiaPaCa-2 pancreatic cancer cells and cancer-associated fibroblasts (CAF) up to 1 pM and 72 h of incubation with main accumulation inside the lysosomes. We showed that AMF and RMF, applied using homemade miniaturized AMF and RMF setups, resulted in comparable real-time intracellular CV release inside the cells. This release — whether thermal (AMF) or mechanical (RMF) — reduces the viability of cells in 2D culture and the size of 3D spheroids composed of MiaPaCa2 and CAF cells, illustrating precise spatiotemporal control over the drug delivery process.

In conclusion, both AMF and RMF stimuli, inducing IONPs heating or motion respectively, triggered significant cargo release from MagZIF-8 nanocomposites and reduced the cell viability in 2D cell cultures and 3D tumoral heterospheroids. These results strongly highlight the potential of MOF-based advanced drug delivery nanosystems responsive to AMF and RMF actuation, paving the way for further evaluation in *in vivo* models to establish its translational relevance.

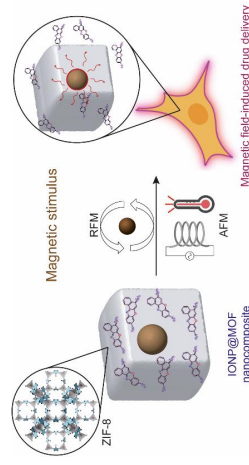


Figure 1. Schematic representation of MagZIF-8 advanced drug delivery nanosystem responsive to AMF or RMF stimuli.

Magnetic Hybrid Microdiscs as Tunable Carriers for Remote Actuation and Biomolecule Delivery

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Magnetic carriers capable of combining controlled actuation and biomolecule delivery require precise control over both structure and biological interaction. However, achieving such multifunctionality within a single platform remains challenging.

Here, we present a modular microfabrication strategy to engineer magnetic hybrid microdiscs with tunable size and composition, enabling programmable cellular behavior. By selecting the appropriate photolithographic method, microdiscs with diameters of $\sim 18 \mu\text{m}$ and $\sim 1.5 \mu\text{m}$ are fabricated, leading to distinct cellular outcomes: larger discs remain at the cell membrane, while smaller discs are efficiently internalized. The versatility and key features of this platform are schematically illustrated in Figure 1.

The fabrication approach combines photolithography with layer-by-layer assembly, allowing independent control over the inorganic thin film, polymeric multilayers, magnetic nanoparticle content, and biomolecular payload. Embedded Fe_3O_4 nanoparticles provide strong magnetic responsiveness, enabling both efficient magnetic guidance and localized heat generation under alternating magnetic fields. Importantly, the heat released by the microdiscs is spatially confined and non-cytotoxic, making the larger discs particularly suitable as surface-bound actuators for magnetothermal cellular modulation.

In parallel, the smaller microdiscs demonstrate efficient internalization with predictable exponential uptake dynamics. Their tunable cargo loading enables precise control over intracellular delivery profiles, highlighting the versatility of the platform.

Altogether, these results establish hybrid magnetic microdiscs as multifunctional and programmable carriers, where size and composition can be tailored to control cellular interaction, magnetic actuation, and delivery. These versatile carriers open new opportunities for magnetically guided and remotely controlled biomedical applications, and have recently been published in *Advanced Functional Materials*.

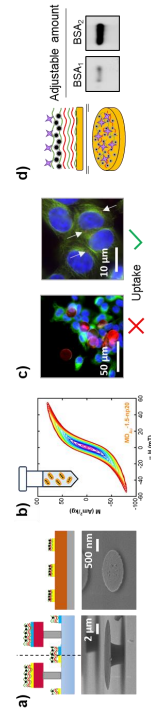


Figure 1. (a) Schematic illustration of the fabrication of hybrid magnetic microdiscs by photolithography and layer-by-layer assembly, including representative SEM images. (b) AC magnetic hysteresis loops of the microdiscs, showing their response under alternating magnetic fields. (c) Fluorescence microscopy images illustrating size-dependent cellular interaction, with larger discs remaining at the membrane and smaller discs being internalized. (d) Microdisc architecture with biomolecule loading, together with representative Western blot analysis confirming protein incorporation.

Physical aspects of field-enhanced degradation of hydrogel networks: a step closer to thrombolysis

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We report a detailed experimental and theoretical study of kinetics of degradation of calcium alginate and fibrin hydrogel networks in view of possible application to the field-enhanced thrombolysis. In our experiments, we use biocompatible single of multi-core iron oxide nanoparticles dispersed in physiological media (phosphate buffer saline or blood plasma) that are able to reversibly self-assemble into rod-like aggregates (Fig. 1-ii) under rotating magnetic fields. We inject a dilute solution of these colloids into a microfluidic channel containing either alginate or fibrine hydrogel matrix, mimicking obstructed blood vessel (Fig. 1-i). A system of four (or six) coils allows generating 2D (or 3D) rotating magnetic fields (Fig. 1-i). A special magnetic field configuration allows a symmetry breaking resulting in recirculation flows in the closed channel (Fig. 1-iv), which enhance molecular transport of a dissolution agent present in the colloid (sodium citrate for alginate hydrogel and plasmin or tissue plasminogen activator (t-PA) for fibrin hydrogel). This accelerates both the degradation rate of hydrogels (Fig. 1-v) and evacuation of the degradation products out of hydrogel. Quantitatively, under magnetic field of moderate amplitude (~10 mT) and low frequency (5 Hz), we achieve to reduce the half-life of the fibrine clot up to 50 times as compared to the passive diffusion in the absence of applied magnetic field. This is a very important field induced enhancement, as compared to 1.5-1.75-fold acceleration previously reported in literature [1,2].

From the fundamental perspective, based on multiphysics approach (aggregation kinetics, ferrohydrodynamics, convective transport) we propose experimental and theoretical correlations between the control parameters (nanoparticle concentration, colloidal state, magnetic field amplitude and frequency) and the output characteristics (aggregate size distribution, recirculation velocity profiles, clot dissolution rate) for various physicochemical formulations.

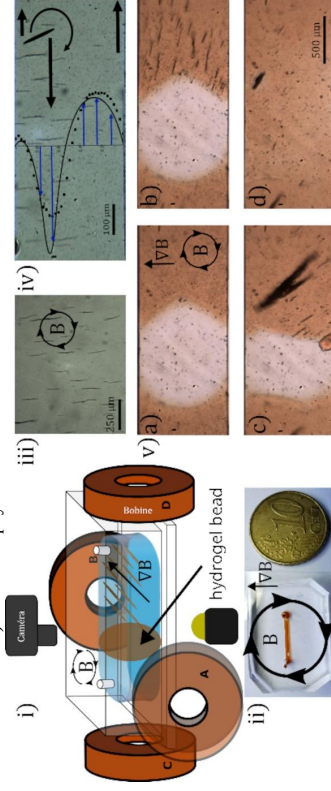


Fig. 1. The experimental system comprising 4 Helmholtz coils (i) and a microfluidic channel (ii); image of the rod-like aggregates formed in 1 min by self-assembly of magnetic nanoparticles in rotating magnetic field (iii); image of a microfluidic channel with spinning aggregates inducing a recirculation flow quantified by measured and modelled velocity profile (iv); images showing the kinetics of dissolution of a proxy clot (calcium alginate bead) due to the convective flow of a dissolving agent (sodium citrate): 0 min (a), 3 min (b), 7.5min (c), 13 min (d).

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On-Demand Magnetic Field-Responsive Nanodrug for Pain Modulation

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Neuropathic pain is a severe and often debilitating condition affecting over 600 million people globally. Despite its prevalence, current treatments rely on opioids, which pose significant risks of addiction and systemic side effects. Capsaicin, a chemical derived from chili peppers, has emerged as a promising non-opioid analgesic. Its effects are mediated through binding to the transient receptor potential vanilloid 1 (TRPV1) channel located on sensory neurons. With continuous and prolonged exposure, TRPV1 becomes desensitized, producing sustained analgesia. However, clinical use of capsaicin is limited by poor solubility, rapid degradation, and low tissue retention. To address these challenges, nanoparticle encapsulation strategies have been explored, but most rely on passive diffusion, offering minimal control over the drug release. To overcome this limitation, we developed a magnetic field-controlled delivery system for capsaicin that enables precise, repeatable, on-demand modulation of TRPV1 activity. This approach allows magnetic-field-controlled release, enabling externally tunable and targeted pain relief.

The experimental scheme is shown in Figure 1. Iron oxide magnetic nanoparticles (MNPs) were surface-functionalized via atom-transfer reverse polymerization (ATRP) to grow thermoresponsive poly (oligo (ethylene glycol) methyl ether methacrylate) (POEGMA) brushes, forming a nanoscale capsaicin reservoir. Upon exposure to an external alternating magnetic field (AMF, 27.3 mT, 250 kHz), MNPs undergo hysteresis power loss, generating localized nanoscale heat at a rate of 1077 W/g. This heat triggers a reversible thermodynamic phase transition in the POEGMA coating, resulting in a microdose release of capsaicin. A single dose of AMF-triggered release activates TRPV1 in >75% of neurons, while 3+ AMF cycles cause TRPV1 desensitization in >90% of neurons, achieving analgesic effects consistent with capsaicin's therapeutic mechanism. Importantly, when the AMF is turned off, any remaining capsaicin is re-encapsulated for subsequent release. Additionally, we observed minimal cytotoxicity in primary rat neuronal cultures.

Collectively, our findings establish POEGMA-functionalized MNPs as a viable platform for remote-controlled, repeatable, and localized neuromodulation with preserved neuronal viability. By enabling magnetically triggered, localized delivery of hydrophobic drugs like capsaicin, this technology has the potential to transform chronic pain treatment by advancing precise, nonopioid therapeutic strategies.

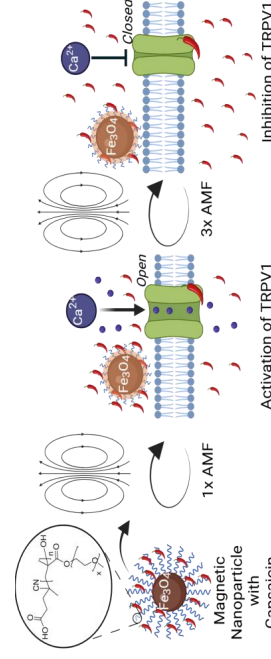


Figure 1. Magnetically-triggered nanodrug system. MNPs functionalized with thermoresponsive POEGMA release capsaicin via AMF-induced heating to modulate TRPV1 activity. The system enables both acute activation and sustained desensitization (3+ cycles) upon exposure to AMFs. Created with BioRender.

Senolytic nanoplatform to target and eliminate senescent melanoma cells

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Skin cancer, namely melanoma and non-melanoma skin cancers, are the most common types of malignancy in the Caucasian population, with a worldwide yearly increasing incidence. The therapeutic alternatives usually employed for cancer treatment can promote stress-induced premature senescence of normal and/or neoplastic cells. These senescent cells are often called zombie cells because they are resistant to cell death and their accumulation may promote tumour recurrence, metastasis or drug resistance. Moreover, they exhibit upregulated expression of heat shock proteins (HSPs), which further enhances their resistance to stress-induced apoptosis and may limit the effectiveness of conventional therapies, including hyperthermia-based approaches¹. Senolytic drugs such as quercetins are commonly used for killing senescent cells; however, they have low bioavailability and selectivity towards these cells, which can end up producing side effects. Indeed, one of the major challenges to treat senescent cells is the lack of precise markers to target them.

Here, we propose an innovative therapeutic approach to eliminate senescent cells by using a multifunctional nanoplateform based on magnetic nanoparticles (MNPs), with the final aim of inhibiting skin cancer progression (**Figure 1**). We have reported a specific alpha integrin (ITAG1) as a novel marker of drug-resistant senescent melanoma cells². Moreover, we have synthesized novel thioquercetin derivatives with improved properties against melanoma cells³.

We are currently working on the bioconjugation of the MNPs with an antibody towards ITAG1 to increase selectivity, and the functionalization of these MNPs with thiorectin derivatives. The resulting nanoplateform is being evaluated in senescent melanoma cells to assess its senolytic potential through selective targeting. Additionally, we are investigating the possibility of using magnetic hyperthermia to improve therapeutic outcomes.

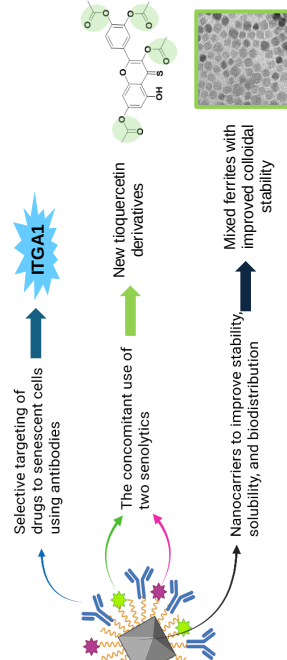


Figure 1. Multifunctional nanoplatform based on magnetic nanoparticles and their novel components.

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Polyhistidine and doxorubicin functionalized magnetic nanoparticles enhancing intracellular heating efficiency in magnetic hyperthermia

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Magnetic nanoparticles (MNPs) are powerful tools in nanomedicine for localized cancer therapy via magnetic hyperthermia. Indeed, when exposed to an alternating magnetic field, MNPs convert magnetic energy into heat, which leads to thermal damage and can enhance chemotherapeutic efficiency. Their therapeutic action, however, is often limited by endosomal entrapment and aggregation after internalization, which significantly reduces their heating capacity.¹ Overcoming this intracellular confinement is therefore crucial to exploit their potential in cancer therapy.

To address this limitation, we designed $\gamma\text{-Fe}_2\text{O}_3/\text{SiO}_2$ core-shell nanoparticles with an outer silica layer that allows versatile surface functionalization. Sulfo-betaine zwitterions were also added to the surface to promote colloidal stability and stealth. Histidine-rich peptides were then grafted onto the surface to promote endosomal escape via the proton sponge effect, enabling the nanoparticles to reach the cytosol and recover their mobility and heating efficiency.² Once in the cytosol, the disulfide bond will be cleaved via the glutathione present in larger quantities in cancerous cells, enabling the release of both the peptide and the cargo. We are currently working on further inducing cell death by adding a chemotherapeutic agent, here, doxorubicin as a cargo of the MNPs. The drug could then be directly delivered to the cytosol and will further enhance the magnetic hyperthermia cytotoxicity.

Characterizations confirmed the synthesis of monodisperse $\gamma\text{-Fe}_2\text{O}_3$ cores coated with silica shells and successful conjugation of polynhistidine peptides. Confocal microscopy studies demonstrated effective endosomal escape and cytosolic distribution of these functionalized nanoparticles in SH-SY5Y neuroblastoma cells. Magnetic hyperthermia experiments were performed on the same cell line to correlate nanoparticle localization with heating efficiency and cellular viability, providing insights into the relationship between intracellular diffusion and thermal response. Doxorubicin functionalization is validated via fluorescence spectroscopy and its efficacy on cell viability is currently being investigated.

Future work aims to include also gene silencing siRNAs. The inhibition of certain genes involved in cell defense mechanisms is expected to sensitize tumor cells to thermal damages and enhance treatment efficacy. Combining these gene-silencing effects with the localized heating could lead to a significant increase in apoptotic cell death.

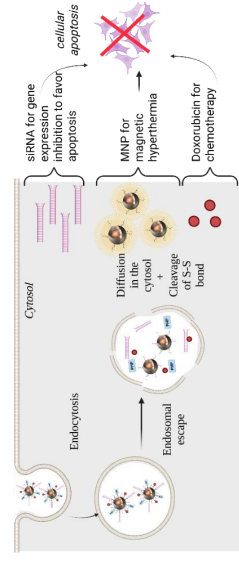


Figure: Illustration of the action of peptide functionalized MNPs for effective magnetic hyperthermia coupled to chemotherapy and gene silencing.

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MAGNETIC NANOCARGO-DELIVERY PLATFORM FOR TARGETED DELIVERY OF ANTICANCER AND ANTIVIRAL DRUG

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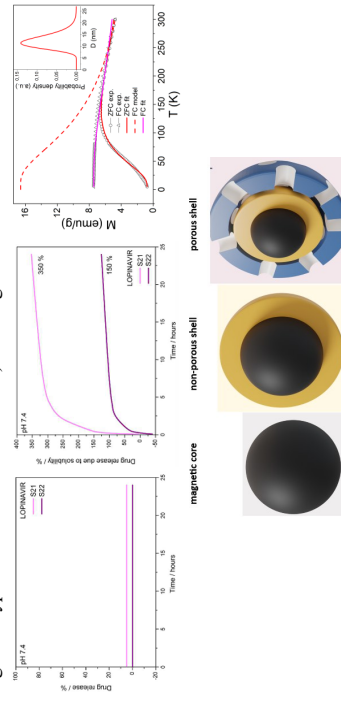
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Keywords: magnetic nanoparticles, drug delivery systems, porous silica

A nanoscale-controlled drug delivery system is an engineered device intended for the sustained release of pharmaceutically active agents to a specific location or at a specific rate or sometimes both. Magnetic nanoparticles (MNPs), typically iron oxide Fe₃O₄, coated with mesoporous silica (MSN) create a versatile, biocompatible, and magnetically guidable drug delivery system. The mesoporous silica shell provides high surface area and pore volume for loading therapeutic agents, while the magnetic core allows for external targeting and stimulus-responsive release, making them highly effective for cancer therapy. Moreover, among different drug delivery systems (DDS), which revolutionized drug delivery studies in recent years, inorganic mesoporous silica shows unique and superlative properties that make them ideal platforms to design multifunctional nanocargo systems.

In presented work, nanoparticles were composed of magnetic core with the diameter of around 10 nm and a surrounding layer of SiO₂ with a thickness of about 2 nm. Porous silica dioxide was used to create the third layer (3rd layer). The present research deals with the study of superparamagnetic nanoparticle composites based on Fe₃O₄ and nanoparticles (MNPs) with the aim of exploring their application potential for theranostics purposes. The main objective is a comprehensive study of the relaxation mechanisms of smart nanoparticle composite systems, which will enable synergy of multiple bio-applications. Our results offer a unique perspective on the creation of multi-purpose MNPs for simultaneous use in therapy (as drug carriers and magnetic hyperthermia at the same time) and diagnostics.



Characterization of nanocargo platform based on core/shell magnetic nanoparticles and analysis of magnetic properties by the proposed ZFC/FC model at relevant critical temperatures. By encapsulating Lopinavir molecules (insoluble in water) in the mesopores of prepared nanoparticles, we managed to increase its solubility by up to 350%.

Magnetothermally Activated 3D-Printed Implants for Programmable Drug Delivery

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In this work, we present an innovative approach for controlled, contactless drug delivery using 3D-printed smart implants. The system is based on a polycaprolactone (PCL) matrix containing superparamagnetic iron oxide nanoparticles (MIONPs) and naproxen as a model drug.

The resulting implants show strong magnetothermal responsiveness, which increases with nanoparticle content, reaching a specific absorption rate (SAR) of up to 132 W g⁻¹ for formulations containing 50 wt% MIONPs (310 kHz and 60 mT). This heating effect directly enhances drug release. Without a magnetic field, there is a basal drug release (<5% after 220 minutes), whereas exposure to an alternating magnetic, drug release increases by up to 20-fold after 20 min, enabling reversible ON/OFF control of therapeutic delivery (Figure 1a).

Molecular dynamics simulations reveal that magnetothermal heating reduces the viscosity of the PCL matrix by approximately 14-fold, facilitating faster drug diffusion without damaging the polymer structure.

Biological tests using HepG2 and FaDu cell lines demonstrate a dose-dependent response. An optimized formulation (LC) maintains high cell viability in HepG2 cells (87.7%), while lower viability in FaDu cells (52.3%) reflects higher sensitivity (Figure 1b). Additionally, studies in biological media show that cellular uptake promotes continuous drug diffusion through a sink effect (Figure 1c, d).

Overall, these results highlight the potential of magnetoactive 3D-printed implants as programmable and tunable platforms for personalized drug delivery.

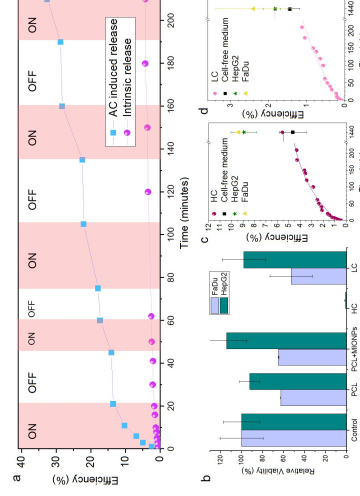


Figure 1: a) AC magnetic field induced (blue) and passive-intrinsic (pink) release efficiency. Periods of magnetic field ON are shown in pink and OFF in white; b) Cell viability for PCL, PCL + MIONPs, HC (Naproxen High-Concentration) and LC (Naproxen Low-Concentration) implant formulations; c) d) Time-dependent intrinsic drug-release efficiency measured in biological medium for HC and LC implants, together with release efficiency after incubation in cell-free culture medium, FaDu and HepG2 cell cultures.

Engineering of magnetic-based nanoplateforms for theranostic with a focus on targeting strategies

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In nanomedicine, the goal is to develop multimodal nanoparticles (NPs) to speed up targeted diagnosis, to increase its sensitivity, reliability and specificity, thereby improving disease management and patient care. Consequently, one of the major challenges in personalized nanomedicine is the development of multifunctional theranostic nanoplateforms capable of specifically targeting diseased organs in order to ensure accurate diagnosis, rapidly test different treatments, and monitor therapeutic effects through imaging. However, achieving selective and sufficient accumulation of NPs in diseased organs—at levels high enough for effective diagnosis and treatment—remains a major challenge. Most currently developed NPs accumulate, after intravenous injection, in eliminatory organs and only low amounts are internalized in tumors. For accurate diagnosis and effective treatment, active targeting of specific receptors on cancer cells using affinity ligands is therefore crucial to achieve tumor specificity.

Among the nanoparticles developed for nanomedicine, superparamagnetic iron oxide nanoparticles (IONPs) are excellent T2 contrast agents for magnetic resonance imaging (MRI) and suitably designed, they may act as imaging agent for Magnetic Particle Imaging and also as therapeutic agents through magnetic hyperthermia (MH) or photothermal (PTT) therapies. In that context, we have developed IONPs coated with an original dendron molecule (DNPs). Several *in vitro* and *in vivo* studies have demonstrated that these DNPs display antifouling properties, resulting in minimal accumulation in the reticuloendothelial system (RES). With their favorable biodistribution and bioelimination profiles, DNPs were particularly well suited for investigating affinity-based targeting strategies.

In that context, targeting ligands have been conjugated to their surface in order to develop specific contrast agents for cancer diagnosis. Initial targeting experiments showed that, after intravenous injection in a melanoma mouse model, DNPs coupled with a melanin-targeting ligand were specifically internalized by melanoma tumor cells, while exhibiting very favorable biodistribution and biokinetic properties. More recently, we investigated the targeting of head&neck and breast cancers by coupling selected targeting ligands to the surface of DNPs. These studies demonstrated the strong specificity of a GE11-like peptide for promoting the internalization of large amounts of DNPs into cancer cells [1-3]. *In vitro* and *in vivo* experiments demonstrated further that the presence of a spacer between the targeting ligand and the nanoparticle surface was crucial to significantly enhance cellular uptake. The coupling method of targeting ligands, their grafting yield and their availability at the surface of DNPs were important issues to face.

Then, IONPs with different sizes and shapes have been designed by using the thermal decomposition method to evaluate their potential to combine different therapeutic modes. We have tuned different synthesis parameters and IONPs with different shapes were thus synthesized and dendronized [4-6]. The effect of the NPs size, shape and defects on MH and PTT has been investigated allowing to establish the optimal NPs design to combine therapies [1,6].

The rational design of IONPs as imaging and therapeutic agents, together with the implementation of effective targeting strategies, is essential to address the current need for better-performing nanoplateforms in nanomedicine. Such a smart approach, once translated into clinical practice, could have a significant impact on disease management by improving patient survival and quality of life.

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Measurement uncertainty analysis of a one-dimensional Magnetic Particle Spectrometer

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Magnetic Particle Spectroscopy (MPS) has emerged as an important technique for characterizing magnetic nanomaterials for a wide range of biomedical and life-science applications, including tracer optimization for Magnetic Particle Imaging, quantitative immunoassays, pathogen detection, cell tracking, magnetic hyperthermia, and environmental- or viscosity-responsive multi-contrast readouts. As a comparatively novel technology with predominantly lab-specific implementations, MPS faces limitations in terms of standardized workflows, currently hindering compatibility and reproducibility between different devices and studies.

The presented work addresses this gap through a meticulous analysis, classification and quantification of the predominant sources of measurement uncertainty for a custom-built one-dimensional MPS (Fig. 1 left). To enable the translation of these analyses to other MPS devices, the establishment of a structured workflow is proposed. Once implemented, it will classify measurement errors as either absolute or relative, including contributions from electronic and thermal noise, external interferences, drive-field nonidealities (amplitude/phase stability, spectral purity), calibration inaccuracies, and user-dependent sample handling such as vial positioning. A model incorporating all these factors enables accurate assessment of MPS measurements, which is particularly important for low concentration samples or when detecting small signal changes, as in antibody binding experiments.

As a first step towards this goal, we analyzed the absolute error introduced by internal and external interferences for 1000 individual measurements, characterizing the absolute detection limit of the investigated device. Mapping this noise floor into the equivalent magnetic moment for an acquisition of 1 s with a sinusoidal excitation at 20 mT and 25 kHz results in a detection limit of 300 pAm² at an SNR of 5 (Fig. 1 right). This is equivalent to a concentration of the iron-oxide tracer Resotran (Ferucarbotan) of 125 ng_{Fe}/ml at the standard sample volume of 500 µl.

When extended to all error types and applied consistently, this approach should advance the reliability, reproducibility, and cross-lab comparability of MPS, strengthening its utility across medical and biological applications for establishing it as a characterization tool for magnetic materials.

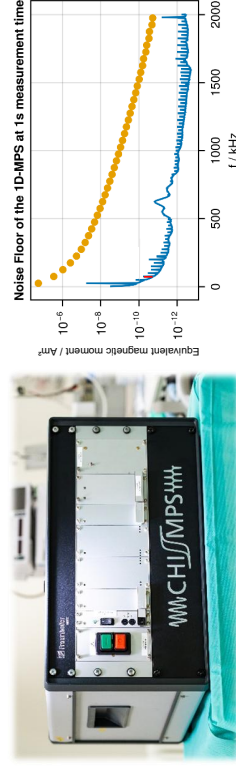


Fig. 1: Left: Analyzed one-dimensional tabletop MPS. Right: Noise floor (blue) of the MPS at a measurement time of 1 s determined from 1000 individual measurements with the third harmonic marked in red. The odd harmonics of 500 µl Resotran at 1 mg/ml are shown as reference (orange).

Systematic Analysis of Parameters Affecting Colorization Performance for Magnetic Particle Spectroscopy Applications

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Colorization of magnetic nanoparticles (MNPs) has been of key interest for multiplexed biosensing and targeting applications in magnetic particle spectroscopy (MPS). Herein, we present a systematic analysis of different parameters in play affecting the colorization performance for such practical applications. Three commercially available multicore MNPs DSPIO, SPG0050, and SC0102 were used for the colorization experiments utilizing a single-frequency MPS system. Firstly, experiments were conducted to investigate the dependence of colorization error on the excitation frequency and field amplitude, as presented in Figure (a) and (b) respectively. It was observed that MPS operation at larger excitation frequency/ field amplitude resulted in better colorization predictions, which could be attributed to SNR improvement. Thereafter, experiments were also carried out investigating the effects of utilizing single harmonic information at varying excitation conditions (3rd harmonic information recorded for varying excitation frequency or field amplitude) vs using multiple harmonic information obtained for a single excitation condition (3rd and 5th harmonic information recorded for a fixed excitation frequency of 5 kHz and field amplitude of 200 Oe) for the colorization application. It was found that the best colorization predictions were achieved by utilizing the 3rd harmonic information alone, collected for varying excitation frequencies as noted in Figure (c). These observations provide valuable insights for the future design and applications of magnetic colorization in biosensing applications.

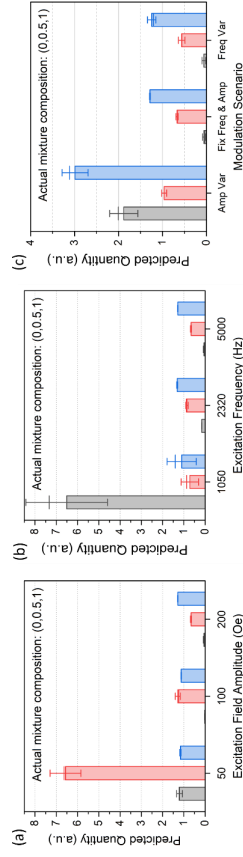


Figure. Dependence of colorization prediction on the excitation frequency and amplitude has been presented in (a) and (b) respectively for a mixture of 3 MNPs. Use of a higher excitation frequency or field amplitude results in better SNR performance and thus a better colorization prediction. (c) Performance of colorization prediction utilizing three scenarios (1) using 3rd harmonic information at varying field amplitudes of 50 Oe, 100 Oe, and 200 Oe for a fixed excitation frequency of 5 kHz; (2) utilizing 3rd and 5th harmonic real and imaginary components for the excitation frequency of 5 kHz and field amplitude of 200 Oe; (3) using 3rd harmonic components at varying excitation frequencies of 1.05 kHz, 2.32 kHz, and 5 kHz, whilst maintaining a constant field amplitude of 200 Oe.

1D Reconstruction of Magnetic Nanoparticles in an Unshielded Environment Using OPM-Based Magnetorelaxometry

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Magnetic hyperthermia is a potential cancer treatment in which magnetic nanoparticles (MNP) are delivered to a tumor site to generate heat under an external magnetic field. The resulting temperature increase can destroy cancer cells. To monitor the treatment, analyze the temperature, and detect the distribution of the particles, accurate quantification of MNPs is important. One promising technique for this purpose is magnetorelaxometry imaging (MRXI) [1]. However, performing MRXI in an unshielded environment, which represents real clinical conditions, is challenging due to high magnetic interference.

This work focuses on noise reduction of MRX signals in unshielded environments and on 1D MRX imaging (MRXI). Our unshielded setup consists of three optically pumped magnetometers (PPMs, from Twinleaf LLC, NJ, USA), an excitation coil, and a 1D sample holder. The sensors were used with a sensor-to-sensor distance of 3.5 cm. The nanoparticle sample consists of 12 mg Fe of Perimag[®] nanoparticles (plain, micromod, Germany) immobilized in an ellipsoidal gypsum block with dimensions of 3 cm x 2 cm x 2 cm. By placing the nanoparticle sample sequentially in each voxel and using first-order gradiometer signals along with noise reduction techniques, an experimental lead-field matrix was constructed. This matrix was then used to reconstruct the nanoparticle distribution by solving the associated inverse problem.

This setup demonstrates the feasibility of reconstructing the 1D distribution of MNPs in an unshielded environment. The limitations of the setup are currently being investigated.

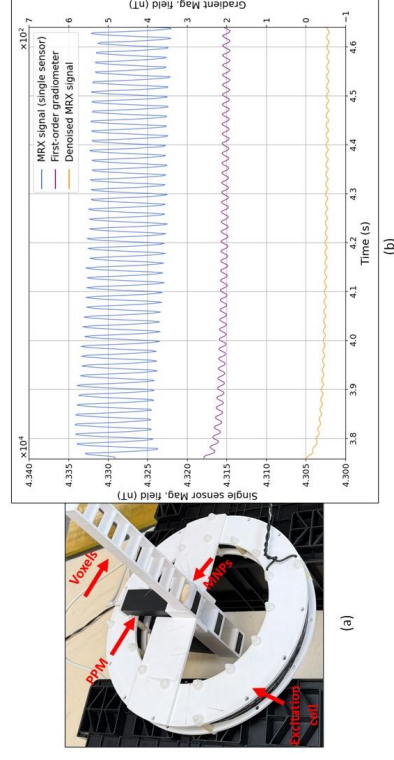


Figure. (a) Experimental setup. (b) MRX pulse signals from a single sensor, the corresponding first-order gradiometer signal obtained from two sensors, and after noise reduction steps.

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Simultaneous High-Frequency Magnetometry and AC Calorimetry for Magnetic Nanoparticle Characterization

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Magnetic nanoparticles (MNP) have seen increased use in applications that employ high-frequency alternating magnetic fields, a notable example being magnetic hyperthermia. This technique relies on exposing MNP to alternating fields with amplitudes of tens of mT and frequencies in the hundreds of kHz. Characterization of MNPs for such systems has commonly been done using static methods, such as vibrating sample magnetometry to directly determine magnetic properties, or indirect dynamic techniques such as AC calorimetry to determine the heating power. However, recently several studies have demonstrated high-frequency AC magnetometry on MNPs at lower fields using magnetic particle spectroscopy[1] and at larger fields using a loop tracer[2].

A loop tracer works in a similar fashion to an AC susceptometer with a pick-up coil positioned inside an excitation coil driving an alternating magnetic field (Fig. 1a). The pick-up coil is wound to produce zero signal in the absence of a sample; inserting a sample then induces a voltage from which the magnetic moment can be inferred. For loop tracers, the applied fields are typically large (<100 mT) and at high frequencies (<1 MHz), often requiring a water-cooled excitation coil and a reduced number of windings in the pick-up coil to limit heat dissipation.

In this talk, we present an easily constructable loop tracer that can be retrofitted onto an existing AC calorimetry setup[3]. This design enables the loop tracer to operate simultaneously with the AC calorimetry system, allowing direct comparison between the two techniques and measurements of hysteresis loops at elevated temperatures as the sample heats. The loop tracer is shown to work in the frequency range 160-922 kHz with maximum applied fields of 18-46 mT, depending on frequency.

We present a series of measurements on an iron oxide nanoflower sample, showcasing high reproducibility in the measured magnetic properties. Finally, we show that the system exhibits excellent stability for extended measurements, providing unique insight into the temperature evolution of the sample's magnetic behavior, as illustrated in Fig. 1b.

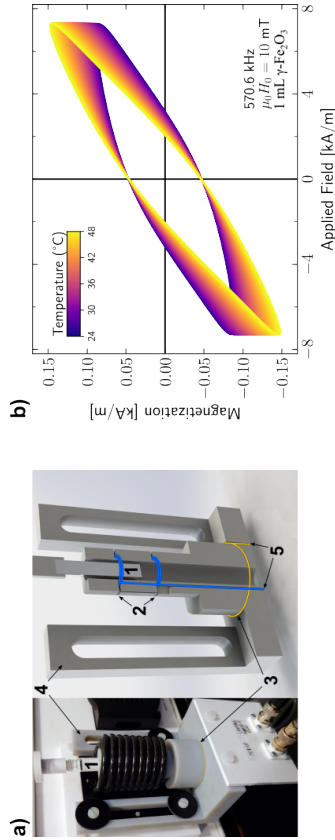


Figure 1: a) Photo of the loop tracer installed in the excitation coil alongside a cut view of the loop tracer. 1: Sample vial, 2: Pick-up coil, 3: Field coil, 4: Mounting rails, 5: Wire channels. b) Temperature evolution of the hysteresis curves for the iron oxide sample measured in the loop tracer.

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Interpreting Magnetic Particle Spectroscopy Through Hierarchical Modeling of Interacting PEG-Coated Iron Oxide Nanoparticles

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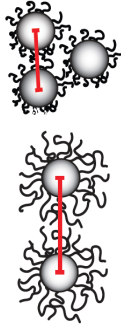


Figure 1: Proposed nanoparticle spacing dependence on ligand molecular weight

Magnetic particle spectroscopy (MPS) has emerged as a promising technique for characterizing magnetic relaxation dynamics and enabling sensitive magnetic carrier-based diagnostics. However, accurate interpretation of harmonic signals requires both well controlled colloidal behavior in aqueous and complex media as well as statistical models that appropriately represent experimental variability. In practice, MPS measurements often exhibit structured fluctuations arising from a variety of factors such as nanoparticle dynamics, thermal drift, mechanical components, etc. This variability challenges the assumptions of stationary and homoscedastic noise that underlie conventional least squares (LS) approaches. In this work, we investigate the relationship between interparticle interactions, signal variability, and statistical interpretation in MPS using 22 nm iron oxide nanoparticles (IONPs) functionalized with 20 kDa poly(ethylene glycol) of varying molecular weight. Changes in PEG length modulate interparticle spacing and aggregation behavior, providing a tunable platform to study magnetic coupling and relaxation dynamics of aggregated systems. Structural and magnetic properties are characterized through small angle X-ray scattering (SAXS), vibrating sample magnetometry with first-order reversal curves (FORC) analysis, AC susceptibility and MPS.

Repeated MPS measurements under identical conditions reveal substantial structured variability consistent with a non-stationary measurement process. Transformations commonly used to normalize mass loading effects, including harmonic ratios, redistribute variance without resolving the underlying variability. To address this limitation, we implemented a hierarchical mixed effects model to partition within-run and temporal sources of variation while providing confidence estimates that reflect the observed variance structure across observation levels. In parallel, we introduce a sampling framework for determining adequate measurement protocols for reliable MPS analysis. Together, these findings establish a combined experimental and statistical framework for interpreting MPS signals in interacting nanoparticle systems, advancing quantitative and reproducible analysis of magnetic carriers for biomedical sensing applications.

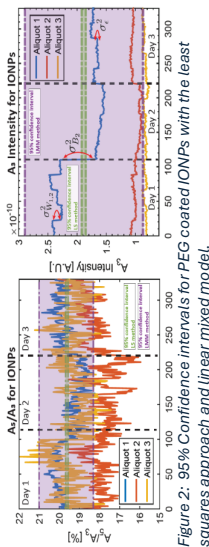


Figure 2: 95% Confidence intervals for PEG coated IONPs with the least squares approach and linear mixed model.

Dynamic Magnetic Response of Magnetic Multicore Particles: Competing Anisotropies

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Recently, it has been found that multicore architecture can significantly enhance magnetic losses and modify relaxation spectra compared to single-core particles, even when the overall particle size is comparable [1]. This happens because of additional internal degrees of freedom: magnetic interactions between the cores, correlations mediated by the surrounding matrix, and multiple relaxation mechanisms operating on distinct length and time scales [2]. However, most of the existing work has focused on spherical multicores, leaving the combined effects of shape anisotropy and multicore structure largely unexplored.

In this work, we have systematically investigated the dynamic magnetic response of multicore magnetic ellipsoids, with a particular emphasis on the role of particle shape in combination with internal magnetic interactions. Using coarse-grained Brownian dynamics simulations coupled with a microscopic description of Néel relaxation at the level of individual cores [3], we were able to resolve the interplay between Brownian rotation, internal magnetic anisotropy, and dipolar inter-core coupling.

Our modelling approach treated each multicore particle as a rigid ellipsoidal cluster of interacting magnetic grains, incorporating both dipole-dipole interactions and uniaxial magnetocrystalline anisotropy. The dynamics were captured through a hybrid scheme combining stochastic rotational motion of the entire particle with Landau-Lifshitz-Gilbert-type dynamics for the individual core moments. The dynamic susceptibility spectra were obtained via the fluctuation-dissipation theorem from the autocorrelation function of the total magnetic moment, employing a robust multi-exponential reconstruction method to resolve the underlying relaxation modes.

Particle elongation plays a fundamentally different role depending on the interaction regime. In the absence of internal degrees of freedom, it simply rescales the Brownian relaxation time, shifting the susceptibility peak towards lower frequencies. However, with finite anisotropy and dipolar interactions, the behavior becomes more complex, leading to spectral broadening and the emergence of multiple relaxation modes. For strongly interacting cores, elongation promotes slow collective relaxation processes, shifting spectral weight to lower frequencies and slowing the overall magnetic response. This is linked to enhanced alignment of core magnetic moments along the major axis of the ellipsoid. Consequently, particle shape affects both external rotational dynamics and the internal magnetic structure of multicore systems. Additionally, elongation increases the static susceptibility, in contrast to expectations for single-core anisotropic particles [4]. This highlights the role of internal dipolar correlations, which are amplified by geometrical confinement and not fully captured by mean-field models at strong coupling. Overall, the dynamic magnetic response arises from a complex interplay of particle shape, anisotropy, and inter-core interactions.

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Magnetic Particle Imaging and Functional Hydrogels for Micro- and Nanorobotics

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Micro- and nanorobots can be magnetically guided to a target in the body and enable the local administration of therapeutics or thermal treatment. Various materials and shapes are being developed for this purpose that are specially tailored to their respective medical application, are biocompatible or biodegradable and react to stimuli. Tomographic real-time visualization is essential for the precise and safe control of micro- and nanorobots. For this purpose, magnetic particle imaging (MPI) can be used for the tracking of micro- and nanorobots. In addition to its advantages of three-dimensional imaging, high acquisition rates, and the absence of ionizing radiation, it also enables functional imaging of parameters such as temperature and the viscosity of the surrounding medium. This capability, known as multi-contrast or multi-color MPI, allows not only the tracking of micro- and nanorobots but also provides valuable information about their local environment.

For biomedical applications, pH is a valuable indicator, as it often changes at sites of inflammation or in the vicinity of tumorous tissue. I will present a method for resolving the pH with multi-contrast MPI using a pH-responsive, magnetically functionalized hydrogel [1]. One potential application of this approach is monitoring pH levels within the urinary tract, where decreased pH can contribute to the formation of kidney stones. I will introduce a soft magnetic miniature robot designed to dissolve kidney stones by locally modifying the pH through an onboard enzymatic reaction [2].

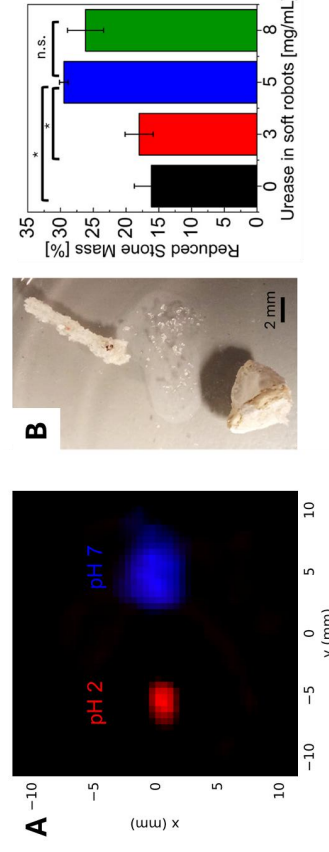


Figure: A) Multi-contrast MPI of a magnetic hydrogel in solution of pH 2 and pH 7. Taken from [1] B) A soft magnetic robot and a kidney stone (left) the magnetic micro-robot can reduce the mass of the kidney stone by changing the pH through the enzymatic reaction of loaded urease (right). Taken from [2]

[1] B. Kluwe et al. Multi-contrast magnetic particle imaging for tomographic pH monitoring using stimuli-responsive hydrogels. *Commun Eng* (2026). DOI: 10.1038/s44172-026-00586-8

[2] A. Khabbazi et al. Kidney Stone Dissolution By Tetherless, Enzyme-Loaded, Soft Magnetic Miniature Robots. *Adv. Healthcare Mater.* (2025). DOI: 10.1002/adhm.202403423

Reference measurement site to characterize magnetic nanoparticles employed in biomedical applications

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Magnetic nanoparticles (MNPs) have been utilized as a promising tool in several biomedical applications such as heat generators in magnetic hyperthermia, as nanocarriers in drug delivery, and as contrast agents in magnetic resonance imaging. The annual economic importance of MNPs based biomedical products from European companies alone amounts to more than 2 billion €. Therefore, due to the biomedical applications of MNPs in humans and economic importance an accurate magnetic measurement of MNPs and a reliable quality control of the magnetic characteristics of MNP samples such as the magnetic moment (μ_m) are required.

A systematic investigation of the measurement for the magnetic moment of MNP suspensions using a commercial DC superconducting quantum interference device (SQUID) magnetometer (Quantum Design, MPMS-XL), showed several sources of measurement uncertainty (contributions from sample holder, sample container, sample positioning inside the detection coil system and the effects of sample geometry) which must be quantitatively be taken into account in the data evaluation.

For accurate quantitative measurements, the magnetometer itself is linked into metrological measurement chains which are traceable to the SI unit system. We have identified the following three key steps:

First, the magnetometer is calibrated to SI-units. The temperature (T) display of the magnetometer is calibrated using a reference thermometer, the magnetic field (H) and the measured magnetic moment are calibrated using certified reference materials. Specifically, a Pt cylinder (NIST SRM 764a) and Ni sphere (NIST SRM 772a) are used. After the calibration, the display values of the magnetometer for H , T and μ_m are in SI-units with a known uncertainty.

Second, the absolute magnetic moment of uncertainty influences is determined through a series of independent background measurements without the MNP sample. This enables for the evaluation of both the absolute value and the uncertainty of the background influences affecting the measurement of the sample.

Finally, the field and temperature dependent magnetic moment of an MNP sample and its uncertainty is determined under consideration of all previous determined measurement influences, resulting in a fully traceable and uncertainty-evaluated measurement. The combination of the calibration results and the determined uncertainties follow the methodology laid out in the Guide to the expression of Uncertainty in Measurement.

For the determination of the sample's mass magnetization M , also the mass of the sample must be determined. This follows standard procedures and is out of scope of the present work.

Real-time, rapid optical imaging method for single magnetic nanoparticles

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In the microscopic view of life sciences, in situ real-time capture of individual proteins and single neural electrical signals is the key to understanding the essence of life activities, especially the mechanism of neural information transmission. It is among the cutting-edge topics at the intersection of life sciences and artificial intelligence. Magnetic nanolabeling technology provides a new tool for this exploration due to its unique electromagnetic dynamic behavior. It is expected to overcome the inherent defects of traditional fluorescent labeling methods such as weak signal, easy photobleaching, and limited time resolution, and achieve long-term, high-speed dynamic tracking of biomolecules. However, classical magnetic particle imaging (MPI) technology can only detect collective signals of hundreds or thousands of particles, making it difficult to achieve in-situ characterization at the single particle level. How to overcome the bottleneck of time, as well as the spatial resolution at the scale of single magnetic nanoparticles is the core challenge currently faced in microscopy.

In response to this challenge, this abstract combines the ultra sensitive optical detection capability of interferometric scattering microscopy (iSCAT) with magnetic field manipulation technology to successfully develop a new method for real-time tracking of single magnetic nanoparticles in liquid phase environment. In the experiment, a magnetic field gradient was used to guide the directional displacement of 30 nanometers magnetic particles in the solution, while real-time observation was performed using iSCAT. By utilizing the extremely high spatiotemporal resolution of iSCAT, the microscopic motion trajectory of a single magnetic nanoparticle has been clearly observed for the first time.

This method lays the key technological foundation for labeling and tracking individual proteins in complex biological environments, as well as real-time sensing of local electromagnetic field changes. It is expected to be directly used to detect the most subtle electromagnetic signals in life processes such as neural activity, using magnetometers and neuronal electromagnetic signal imaging.

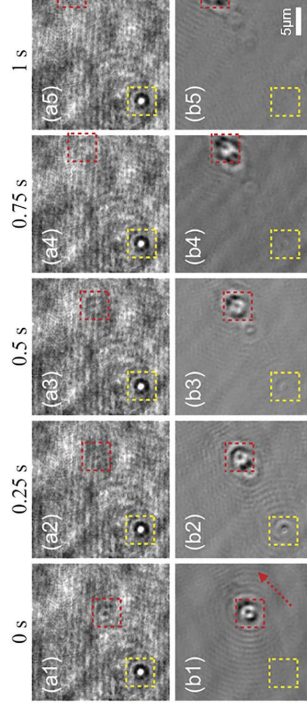


Figure 1. Comparison of experiment results between 30 nm Fe_3O_4 particles and 30 nm gold nanoparticles. (a) Raw images. (b) Images after spatial filtering. Among them, the direction of the gradient magnetic field is shown in b1. Only Fe_3O_4 particles move along the direction of the gradient magnetic field.

Magnetic molecular nanorulers for resolving conformational changes in nucleic acids at sub-nanometer spatial resolution

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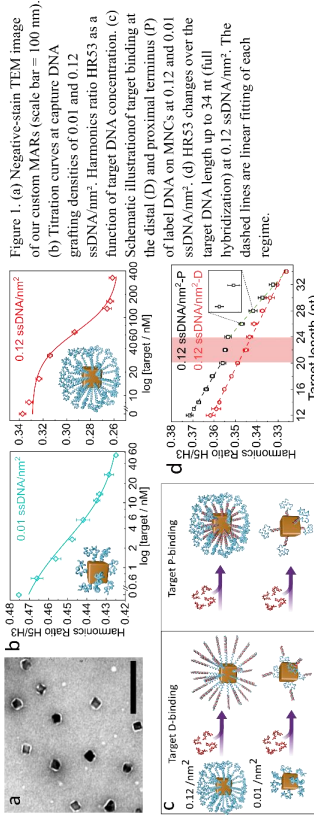
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Resolving conformational changes in nucleic acids and proteins is fundamental to deciphering the development of diseases such as Alzheimer and cancer, and is helpful for their early-stage diagnosis. While established molecular nanorulers utilizing optical modalities such as Förster resonance energy transfer (FRET) represent the current benchmark for detecting conformational changes, they are constrained by optical background interference and have a limited dynamic range (≈ 10 nm for FRET). In contrast, magnetic methods can bypass optical noise coming from opaque biological environments, expanding the analytical landscape for mapping sub-nanometer conformational changes.

Here, we propose DNA-labelled magnetic nanocubes (MNCs) with hydrodynamic sizes < 40 nm and engineered magnetization dynamics as magnetic molecular nanorulers (MARs) (Fig. 1a). We functionalized the MARs at different ssDNA grafting densities and investigated how their Brownian relaxation dynamics change upon adding complementary ssDNA strands. DNA hybridization on MARs is monitored using magnetic particle spectroscopy (MPS) and calculating the MPS harmonics ratio $H5^*/H3^d$ (HR53), which decreases when the Brownian relaxation of MARs slows down.

The MARs show tunable dynamic range and response window depending on the ssDNA grafting density (Fig. 1b). At low grafting density (LD), the dose-response curve shows two orders of magnitude dynamic range, while at high grafting density (HD) the MARs exhibit a sharp response, yet over a narrow range of target DNA concentration (Fig. 1b). Based on our previous findings¹, we know that ssDNA strands are coiled on MARs at LD and whereas are brushed at HD. This inspired us to investigate how the target binding position affects the response of MARs at different DNA grafting densities (Fig. 1c). At HD, while binding position affects the response of MARs at different DNA grafting densities (Fig. 1c). At HD, while distal binding (D-binding) can be fitted by a single linear function, proximal binding (P-binding) has to be fitted by two separate linear functions, indicating a target binding site-dependent response of MARs: the regime up to 20 nt mirrors the D-binding trend, followed by a sharper attenuation from 24 nt up to full hybridization (Fig. 1d pink marked). We deduced that the length of the brushed layer is between 20-24 nt (i.e. 25-29 nt considering 5 nt spacer). Moreover, the MARs can resolve conformational changes caused by 2 base pairs (≈ 0.68 nm) (Fig. 1d inset). More data on resolving other DNA and RNA motifs using our MARs will be presented and discussed at the conference.



[1] A. Lak et al., Nanoscale 16, 7678-7689 (2024).

QCM Sensing the Magnetically Driven Motion of Particles for Biomolecular Analysis

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To characterize biomolecules and understand biochemical processes, multiple parameters rather than a single parameter are needed to be assayed and synchronously traced over time. In current technologies, one assay usually tells one parameter and the evaluation of multiple parameters requires multiple assays with distinct instrumentation principles and schemes.

It is a common knowledge that the intrinsic properties of an object will substantially influence its motional behaviors. This suggests that the motional signal of biomolecules will contain multi-parametric information and multiple parameters are possible to be synchronously detected from it.

When biomolecules are conjugated with magnetic beads the biomolecules can be operated with magnetic fields. If the applied magnetic fields are dynamic, the magnetic beads carrying biomolecules will be in motion due to magnetic relaxation. Optical imaging is one of the most essential tools to acquire motional signal. However, state-of-art microscopical imaging of biomolecules still suffers from problems such as resolution, sensitivity, speed, and penetration depth.

QCM is one of the most used sensors in bio-chemical assays. Whether in the initial Sauerbrey equation or in the commonly used BVD model for characterizing QCM sensing performances, the underlying piezoelectric quartz is taken as possessing linear mechanic performances. However actually quartz possesses mechanic nonlinearity. From the nonlinearity, when a QCM is electrically excited and oscillating at ω_q , the motion equation at the loading surface is

$$\rho t_q \frac{\partial^2 u(t)}{\partial t^2} + (\xi_0 + \xi_1 S(t)) \frac{\partial u(t)}{\partial t} + (C_0 + C_1 S(t)) \frac{\pi^2}{t_q} u(t) = F_0 e^{i\omega_q t} \quad (1)$$

where $u(t)$ the displacement, ρ is the density of quartz, t_q the thickness, ξ_0 and ξ_1 are the surface damping due to the QCM loss and the loaded surface friction, C_0 and C_1 are the second and third elastic coefficients, and $S(t)$ is the strain caused by the action force of the sample to QCM. If $S(t)$ is harmonic with frequency ω , the solution to the nonlinear differential equation (1) is

$$u(t) = (Ae^{i\omega t} + Be^{-i\omega t} + C)e^{i\omega_q t} \quad (2)$$

where A,B,C are constants determined by the coefficients in equation (1).

Expression (2) shows that when the oscillating QCM is subject to harmonic force and induced harmonic strain $S(t)$, the harmonic strain will modify its oscillation and the output of QCM is an AM waveform rather than a mono tone. By demodulating the output, it is ready to obtain $S(t)$.

When magnetic beads or magnetically labelled biomolecules are contained in a liquid sample, under dynamic magnetic excitation they get to rotate due to magnetization and magnetic relaxation. During rotation, friction occurs between the magnetic particles and base liquid. The friction will be transferred to the QCM and cause the strain. So the strain is the results of magnetic particle motion and fully reflects the motion. Thus the strain $S(t)$ can be taken as the motional signal of the particles.

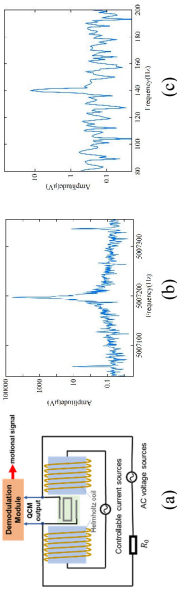


Fig. (a) Schematic of QCM sensing motion of magnetic particles, (b) Spectra of QCM output and the demodulated motion

Fig. (a) shows the schematic of QCM sensing magnetically excited motion of magnetic particles. Fig. (b) demonstrates the output spectrum of QCM loaded with magnetic particles excited with an alternative field at 70Hz. Fig. (c) presents the particle motional spectrum demodulated from the QCM output. Due to the quadratic effect of magnetization, the particles are rotating at frequency of 140Hz.

Once motional signals of biomolecules are acquired, it is ready to analyze the parameters. The parameters such as biomolecular concentration, hydrodynamic radius, elasticity, viscosity and viscosity of base liquid have been detected from the motional signal of magnetically labelled biomolecules and all the parameters are analyzed and detected from a single sample loaded on QCM in one assay only provided the magnetic excitation takes on variable waveforms to make the parameters better emerge in distinct motional modes.

synomag®-pro – The Benchmark for Theranostics

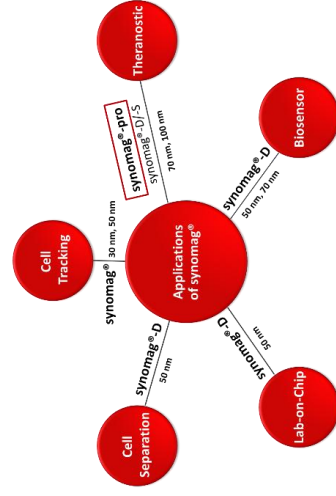
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The characterization of magnetic nanoparticles (MNPs) according to international standards is the prerequisite for comparison of different MNPs with respect to their physico-chemical and application-specific properties.

While ISO norms for size determination and surface characterization using DLS or TEM have been established for several years, magnetic properties such as saturation magnetization (M_s), magnetic susceptibility (χ), or intrinsic loss power (ILP) were determined on a wide variety of systems, some of which are even custom-built. For the standardization and the harmonization of magnetic measurements, two European Projects NanoMag and MagNaStand were launched. Their results were implemented into ISO 19807-1, which specifies the methods to determine the properties of MNP suspensions.

The specific magnetic properties of synomag® particles were used as a benchmark in the development of standardized methods for magnetic particle characterization including round-robin tests among various European standardization institutes and universities. Synomag® is the state-of-the-art MPI tracer composed of multicore maghemite nanoparticles with characteristic "nanoflower" morphology¹ and is available with two hydrodynamic core diameters of 30 nm and 50 nm, respectively. Different end-use specific coatings are represented in the product lines synomag®-D, synomag®-S and synomag®-pro (Figure 1).

Here, we want to introduce synomag®-pro², which combines the established magnetic properties of synomag®-D for MPI and hyperthermia applications with essential requirements for life science research. The aqueous synomag®-pro suspension is isotonicity formulated and autoclaved to ensure high biocompatibility and low endotoxin level.³



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2. For research use only (RUO), not for therapeutic, diagnostic or human use.
3. P. Stoer, B. Kunkel, V. Khaimov, T. Stahnke, S. Großmann, *International Journal on Magnetic Particle Imaging LMPI* **2024**, 10.

Dendronized iron oxide: Superspio20® as MPI tracer and magnetic hyperthermia agent

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Abstract

The rise of MPI technology has led to the growing development of equipment requiring the use of an optimized magnetic tracer for increased sensitivity and resolution. In addition, MPI technology paves the way for truly targeted tumour treatment using the field free point approach for focused magnetic hyperthermia. The need for a theranostic tracer is therefore essential for further preclinical and clinical development. Among the many methods of synthesizing nanoparticles, thermal decomposition is the method of choice for perfect control of the size, distribution, shape and composition of nanoparticles. Mastery of this method has led to the development of SuperSpio20, a dendronised iron oxide nanoparticle whose 20 nm iron oxide core has a first-order MPI signal (figure1) and optimized heat release for focused mild hyperthermia (figure2). The controlled dendronized coating maintains a hydrodynamic diameter of less than 35 nm, allowing intravenous injection. This design also allows the labelling of therapeutic cells without the need for a transfection agent for the development of MPI-tracked cell therapies.

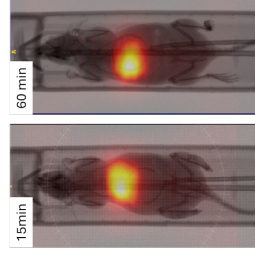


Figure 1 - In vivo detection of SUPERSPIO with MPI. Representative images of MPI signal merged with the CT images in mice taken 15 min and 60 min after IV injection of 400 µg of SUPERSPIO20.

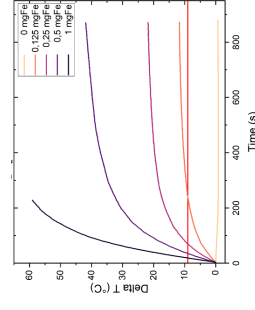


Figure 2 - Delta of temperature for different mass of iron obtained at 340 kHz and 16 mT on the Hyper focalized magnetic hyperthermia apparatus

Tuning Core Size of Iron Oxide Magnetic Nanoparticles in Liposome-Based Nanoreactors: An In Situ Approach

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Magnetoliposomes that integrate liposomal nanocarriers with superparamagnetic iron oxide nanoparticles are attractive magnetic carriers for drug delivery, imaging, and actuation. Yet most syntheses rely on the encapsulation of magnetic nanoparticles, which limits encapsulation efficiency, often requires surface modification, and which complicates the scale-up. We present a microfluidic in situ synthesis route in which liposomes act as nanoreactors for iron oxide formation, allowing us to systematically relate transport-limited precursor supply to crystal growth and magnetic response. Liposomes (~110 nm, PDI ≈ 0.1, ζ ≈ -30 mV) are produced in a caterpillar micromixer and used to encapsulate iron salt solutions. Intraluminal precipitation is initiated by base diffusion across the bilayer. We compare (A) direct coprecipitation from $\text{Fe}^{2+}/\text{Fe}^{3+}$ with (B) a two-step route involving partial oxidation of encapsulated Fe^{2+} prior to precipitation. Cryogenic TEM shows clustered 6-9 nm cores for route A, whereas route B yields predominantly single 11-12 nm cores per vesicle, reflecting a better separation of nucleation and growth under nanoscale confinement. Magnetic particle spectroscopy confirms superparamagnetic behavior with $A_5/A_2 \approx 18\text{--}23\%$ and reveals a dependence of the harmonic spectra on core size and iron loading. Preliminary X-ray diffraction measurements are being conducted to assess crystallinity and phase composition; future work will correlate these structural parameters with the MPS response. Overall, the study demonstrates a scalable platform for preparing and characterizing magnetic lipid nanoparticles and shows how diffusive control over precursor supply can be exploited to tune magnetic core structure and performance for MPI, hyperthermia, and other magnetic carrier applications.

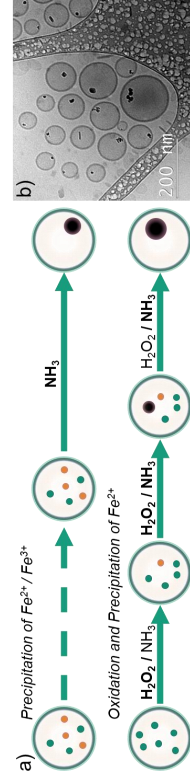


Figure 1 a) General procedure of magnetoliposome production by precipitation or prior oxidation and b) Cryo-TEM of in situ produced magnetoliposomes via oxidation.

Controlled Solvothermal Growth of Iron Oxide Nanorods with Tunable Size and Magnetic Properties for applications in Biomedicine

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Do we need more new magnetic nanoparticle formulations? While a large part of the scientific community is designing new systems based on multifunctional nanoparticles (i.e. by integrating additional domains into the magnetic core or by encapsulating magnetic nanoparticles within organic/polymeric capsules or immune cells) there is another strategy that has remained largely unexplored which is the use of anisotropic nanoparticles.

In recent years, anisotropic morphologies such as nanorods have attracted growing attention within the magnetic iron oxide community due to their directional properties and their potential for a wide range of applications. [1] However, synthesizing these nanorods across a broad size range while maintaining good crystallinity and desirable magnetic properties remains a significant challenge. The cubic crystal symmetry of magnetite/maghemite and their large specific surface area are major barriers to the controlled growth of iron oxide nanorods.

By adjusting specific parameters within a solvothermal synthesis approach [2], it is possible to obtain magnetic iron oxide nanorods ranging from 12 to 400 nm in length, with aspect ratios between 2 and 20 (Figure 1). The potential use of these nanorods in diverse biomedical applications such as NMR, magnetic hyperthermia, photothermal, and in-situ temperature sensing, will be demonstrated. The versatility of this synthesis platform may facilitate the development of oxide nanorods for a wide variety of technological and biomedical applications.



Figure 1. TEM images of magnetite nanorods using different ratios of oleic acid and sodium oleate.

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Magnetic CeO₂-Based Nanocomposites: Influence of the Synthesis Route on Structure, Morphology and Bioactivity

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Recently, nanotechnology has advanced the development of inorganic nanoparticles (NPs) for biomedical applications. These NPs exhibit diverse properties (magnetic, catalytic, sorption, etc.), making them attractive for therapeutic and diagnostic purposes. Of particular interest are materials capable of neutralizing reactive oxygen species (ROS), which play a key role in oxidative stress and the progression of oncological, neurodegenerative, and other pathological conditions. To achieve effective therapy, it is crucial to develop multifunctional materials combining several useful properties. A promising strategy is the design of composite nanomaterials with two or more components, allowing the integration of multiple functionalities, enhancing chemical and colloidal stability, and generating synergistic interactions that can boost existing functions or create new ones [1].

In this study, a series of Fe₃O₄@CeO₂ nanocomposites (NCPs) were developed using two methods: deposition of CeO₂ onto the Fe₃O₄ surface with defined “shell” thickness and “layer-by-layer” growth of CeO₂. This allowed the formation of “core@shell”-like structures with partial or uniform coverage of the magnetic core. The optimized arrangement of redox-active centers Ce³⁺/Ce⁴⁺ and Fe²⁺/Fe³⁺ provides a basis for enhanced and controllable biofunctionality.

The study demonstrated that increasing the CeO₂ content alters the surface chemical state of the composites and the Fe²⁺/Fe³⁺ ratio, enhancing active redox interactions. This leads to an increase in enzyme-mimetic and anti-amyloid activity, which in Fe²⁺- and Ce³⁺-enriched composites exceeds the activity of individual CeO₂ NPs by several times [2]. The morphology of the composites determines the accessibility of active sites and the efficiency of biocatalytic processes, while the synergy of redox pairs ensures continuous regeneration of active centers and rapid ROS decomposition. Within the framework of comprehensive investigations, a potential mechanism for this synergistic enhancement of bioactivity was proposed (Fig. 1). Furthermore, the nanocomposites retain the ability to generate heat under an alternating magnetic field, making them promising for controlled magnetic hyperthermia and potential enhancement of antioxidant tissue protection. Thus, the developed Fe₃O₄@CeO₂ NCPs demonstrate multifunctionality, controllable morphology, and synergistic bioactivity, making them promising candidates for new therapeutic strategies in biomedicine.

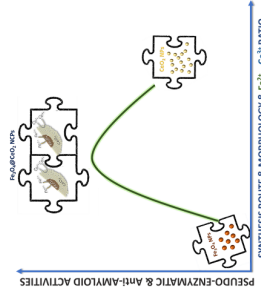


Figure 1. Schematic representation of the synergistic enhancement of bioactivity in magnetic Fe₃O₄@CeO₂ NCPs.

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Acknowledgement: This work was supported by the NATO Science for Peace and Security Programme (Grant ID C8914), the Ministry of Education and Science of Ukraine (grant No M/6-2026) and MVTs SK-TW SupraSight.

Novel Magnetic Nanohybrids Coated with Peptides to Cross the human Blood-Brain Barrier and to Target Neuronal Mitochondria

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Given the global increase in life expectancy, the prevalence of neurodegenerative diseases—particularly Alzheimer’s disease, which accounts for 60–70% of dementia cases—has risen dramatically.¹ Oxidative stress, driven by mitochondrial dysfunction, is a central pathophysiological mechanism in these disorders, underscoring the urgent need for targeted therapeutic strategies.²

To address this challenge, we designed hybrid nanoparticles (HyNPs) capable of crossing the blood-brain barrier (BBB) and selectively targeting neuronal mitochondria to deliver antioxidant compounds. Our HyNPs consist of superparamagnetic iron oxide nanoparticles (SPIONs)³ – T2 contrast agent for *in vivo* brain localization – coated with a heterobifunctional polyethylene glycol (PEG), further functionalized *via* click chemistry with peptides.⁴ The latter have been chosen to allow BBB crossing, mitochondrial targeting, and direct antioxidant activity. To enable HyNPs tracing, peptides were labeled with fluorescent probes.

The synthesis of these HyNPs followed a stepwise approach: i) metal-phosphate interaction for core stabilization, ii) amide bond formation for polymer conjugation, and iii) click chemistry for peptides attachment (Figure 1). Each intermediate was purified and characterized using dynamic light scattering (size distribution), thermogravimetric analysis (organic coating quantification), and X-ray photoelectron spectroscopy (chemical composition and bonding).⁵ *In vitro* evaluations were conducted using a human BBB model, where HyNP translocation and toxicity were quantified by fluorescence. Intracellular localization and mitochondrial colocalization will be assessed by conventional and superresolved fluorescence microscopy.

This presentation will highlight (i) the synthesis optimization with a proof of effective coupling at each step through multiple characterizations, (ii) the BBB crossing efficiency, through a kinetic analysis of HyNP translocation, and cytotoxicity assessment using an *in vitro* human BBB model, and (iii) the mitochondrial targeting by evidence of colocalization and preliminary data on oxidative stress reduction in cellular models. Our results demonstrate the potential of these magnetic multifunctional nanocarriers, as a promising platform for neurodegenerative disease therapy, with a focus on Alzheimer’s disease.

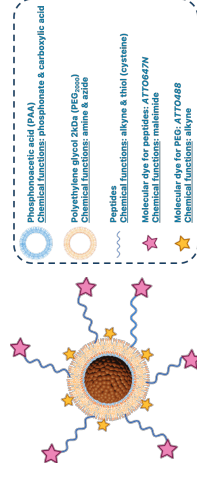


Figure 1: Scheme of the nanohybrid made of SPIONs pre-functionalized with a biocompatible polyethylene glycol (PEG) and functionalized with peptides and labelled with dyes for intracellular tracking

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Continuous-flow microwave polyol synthesis enables scalable production of metallic nanoparticles

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The microwave-assisted polyol method provides a flexible approach for synthesizing metallic nanoparticles, such as Fe, Ni, and Cu, with precise control over size and shape via capping agents [1], (Figure 1). These nanoparticles' small dimensions are well suited to inkjet printing, while their low surface oxide content is expected to improve interparticle connectivity during low-temperature sintering, resulting in superior electrical conductivity in printed structures. Simultaneously, research is focused on scaling the process by adapting it from batch to continuous microwave reactors, targeting gram-per-hour production rates [2]. For magnetic nanoparticles, novel uses as thermally activated agents under alternating magnetic fields are being explored, particularly for their promising role in electrocatalysis [3].

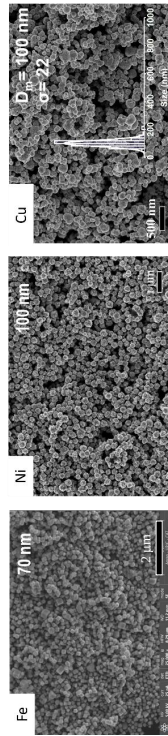


Figure 1. SEM micrographs of Fe, Ni and Cu produced by polyol synthesis

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Invited talk

Reflections on Academic Entrepreneurship:
Translational Research and Commercialisation
(Without Quitting the Day Job)

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The speaker will offer some reflections on a 40-year academic career which has latterly featured some excursions into translational research and commercialisation.

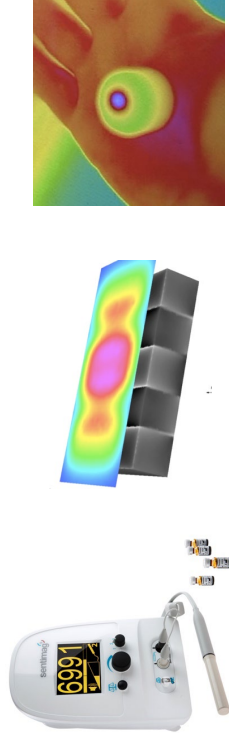


Figure 1. Representative images, from left to right, related to magnetic sensing (with Endomagnetics Ltd), magnetic actuation (with MediSieve Ltd), and magnetic thermotherapy (with Resonant Circuits Limited).

Vectorization of functionalized IONPs with β -amyloid-targeting ligands to obtain specific MRI contrast agents for the detection of Alzheimer's disease

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The detection of senile plaques (SP), one biomarker of Alzheimer's disease (AD), using imaging techniques such as magnetic resonance imaging (MRI), requires the use of contrast agents (CAs) bearing targeting ligands that provide specificity to β -amyloid (β A) peptide fibers, the main component of SP. The Amylovis molecule has shown a proven affinity for the β A peptide and is thus a promising targeting ligand of SP. Therefore, the objective of the work was to couple the β A-related target ligand at the surface of functionalized (poly(acrylic acid) (PAA) and dendron (DD), see Figure A) iron oxide nanoparticles (IONPs), well-known T2 MRI CAs and to then validate their targeting efficiency on β A fibers. Dendronized IONPs were obtained by thermal decomposition method and water transfer by a ligand exchange procedure, while IONPs coated with PAA were obtained in situ by coprecipitation method. Thus, different amounts of Amylovis have been coupled to coated IONPs by a carbodiimide reaction (Figure A) to develop two specific MRI CAs for the molecular diagnosis of AD. A procedure to quantify the amount of grafted targeting ligand has been established. The Amylovis coupling was shown to preserve the colloidal stability and relaxivity properties of these vectorized MRI CAs. The fibrillation of β A, used to mimic SP and to ascertain the targeting efficiency, has been followed by fluorescence and the effects of Amylovis and dendronized IONPs bearing or not Amylovis on the fibrillation process has been analyzed. Then, the targeting efficiency of IONPs bearing Amylovis or not was studied by putting the functionalized IONPs bearing or not Amylovis in contact with β A fibers and observing the interactions by TEM experiments. All these tests have confirmed stronger interactions between fibers and IONPs when Amylovis is bound to the surface of CAs, compared to non-grafted CAs (Figure B). The results showed thus strong potential for these targeted MRI CAs for early and specific diagnosis of AD.

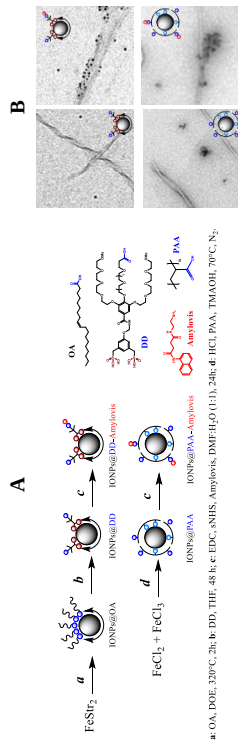


Figure. (A) Scheme of the synthesis of coated IONPs bearing Amylovis. (B) TEM images of β A fibers and functionalized IONPs bearing or not Amylovis.

Keywords: Iron oxide nanoparticles, β A related targeting ligand, Amyloid fibers, MRI contrast agents, Alzheimer's disease

Superferromagnetic Disk Particles for Magnetic Particle Imaging and Magnetic Particle Spectroscopy

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Magnetic Particle Imaging (MPI) maps the distribution of magnetic nanoparticles by detecting higher-harmonic signals that arise from their nonlinear magnetization response to an applied oscillating magnetic drive field. Conventional tracers, typically superparamagnetic iron oxide nanoparticles (SPIONs), exhibit a Langevin-type magnetization curve with a moderate susceptibility and saturation magnetization, inherently limiting their MPI signal generation [1]. Recent studies have demonstrated that the MPI signals provided by superparamagnetic (SP) particles can be enhanced by orders of magnitude if they are employed in a superferromagnetic (SF) state, induced, e.g., by dipolar coupling in linear chains [2] or by quantum mechanical exchange interactions in higher-dimensional arrangements [3].

In our work, we apply a top-down approach to fabricate magnetic disk nanoparticles (MDP) with diameters down to ≈ 200 nm from discontinuous metal-insulator multilayers (DMIMs). In these MgO/Fe DMIMs, a magnetic film of low nominal thickness forms a discontinuous layer, consisting of SP islands. Quantum mechanical exchange interactions between the metal islands induce a SF state. The MDP particles show a highly nonlinear (in-plane) magnetization response, generating higher-harmonic signals that exceed those of SPIONs (Perimag) by several orders of magnitude, translating directly into higher signal-to-noise ratio and improved spatial resolution. Due to a pronounced shape anisotropy, signal generation is strongly suppressed for out-of-plane excitation fields. In suspension, the MDP align themselves to the applied excitation field, ensuring a strong signal generation.

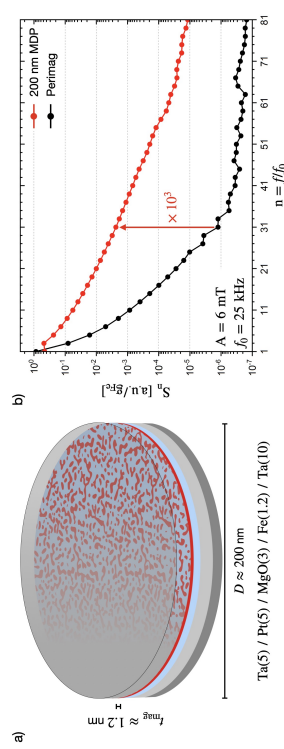


Figure 1: a) Schematic representation of fabricated disk-shaped DMIM particles featuring the multilayer structure and the discontinuous nature of the magnetic layer. b) Magnetic particle spectra for the MDP as well as Perimag in suspension measured with a drive field amplitude of $A = 6$ mT and a frequency of $f_0 = 25$ kHz. The MDP particles outperform Perimag by more than 3 orders of magnitude in terms of signal amplitude.

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Carbon-Coated Magnetite in Cancer Therapies: Challenges and Perspectives

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Generally, when magnetite nanoparticles are coated or functionalized with small organic molecules or polymers such as citric acid or dextran, their surface chemistry can be relatively well predicted and controlled. However, what happens if these molecules do not directly attach to the surface of NPs but decompose during synthesis? Here, we introduce and explain an approach that uses controlled thermal decomposition of organic modifiers to generate carbon-coated magnetite nanoparticles. Coating Fe₃O₄ NPs with a carbon-based shell has been shown as a promising method for photothermal-chemodynamic therapy [1]. Conversely, modification of the chemical composition of carbon-based shells can induce reductive stress [2], and synthesis within magnetite flower-based chains (Fig. a and b) may improve the efficiency of magnetic hyperthermia [3]. Nonetheless, there are many challenges in synthesizing and controlling the carbonaceous coating. First, the shell's chemical composition depends on the precursor used, which also affects magnetite crystallization. Second, the medium influences the types of functional groups and the hydrophilicity (Fig. c). Lastly, particle aggregation can happen spontaneously, complicating one-pot and one-stage synthesis methods. In this research, we compare various methods for preparing carbon-coated Fe₃O₄ NPs, discuss their benefits and drawbacks, and highlight the most promising biomedical applications identified through our work—focusing on magnetic hyperthermia, magnetic particle imaging, and cancer treatment via reductive-stress-mediated cytotoxicity.

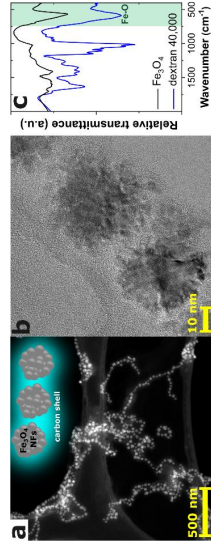


Figure. (a) High-angle annular dark-field scanning transmission electron microscopy and (b) transmission electron microscopy images of carbon-coated chains of Fe₃O₄ NPs with an inset showing the proposed model of the structure. (c) Comparison of Fourier transform infrared spectra of the pure dextran 40,000 and the carbon-coated chains of Fe₃O₄ NPs synthesized during dextran decomposition.

Acknowledgements

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Pressure-Controlled High Temperature Continuous-Flow Synthesis of Iron-Based Nanoparticles: From Metastable Phases to Au–Iron Heterodimers

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For nearly half a century, nanomaterials such as iron oxides, iron carbides, and Au–iron oxide nanoparticles (NPs) have been extensively investigated because of their unique properties, making their synthesis a major focus of contemporary nanomaterials research. Nevertheless, the batch production of these NPs in large quantities, while retaining fine control over crystalline phase, size, and shape, remains highly challenging. Millifluidic synthesis, in which reagents are continuously delivered through a millimeter-scale reactor, represents a powerful alternative to conventional batch methods. Beyond the inherent advantages of continuous processing for scale-up, flow synthesis can also address key limitations of batch production by improving control, reproducibility, and reaction uniformity.

In this work, we report the large-scale continuous-flow synthesis of iron-based nanoparticles through the thermal decomposition of iron pentacarbonyl in octadecene in the presence of oleylamine and oleic acid. We demonstrate that nanoparticle formation under flow conditions differs markedly from that observed in batch synthesis. In particular, we show that the application of pressure is a key parameter for triggering precursor decomposition and promoting the nucleation and growth of iron-based nanoparticles. At high pressure, alongside spherical nanoparticles, anisotropic nanostructures with diverse morphologies, including rods and star-like particles, were obtained at the end of the synthesis. High-resolution TEM and selected-area electron diffraction suggest that these anisotropic nanoparticles form through the oriented attachment of spherical nanoparticles acting as building blocks, likely facilitated by the flow direction. Beyond iron oxide nanoparticles, the process also enables access to air-sensitive phases that are difficult to obtain in bulk, including iron(0) and iron carbide nanoparticles, as evidenced by X-ray diffraction (XRD), X-ray absorption spectroscopy (XAS), and extended X-ray absorption fine structure (EXAFS). Mechanistic aspects were also investigated, particularly the carbon source involved in the formation of iron carbide NPs, using nuclear magnetic resonance (NMR) and mass spectrometry (MS). Finally, we show that the slow decomposition of the iron precursor under high-temperature flow conditions can be advantageous for inducing and controlling the heterogeneous nucleation of magnetic iron-based domains on preformed metallic seeds such as gold nanoparticles. Using this approach, magnetic iron–gold heterodimers, which combine magnetic and plasmonic properties within a single nanostructure and remain highly challenging to produce in large quantities, can be synthesized in continuous flow.

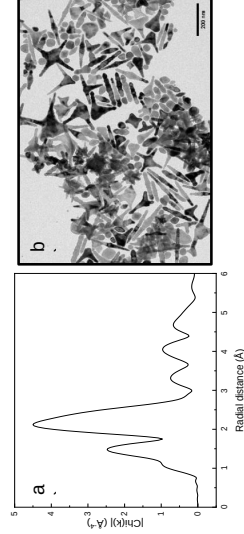


Figure. (a) EXAFS pattern of iron carbide NPs, (b) TEM micrographs of iron-based NPs synthesized with the pressurized millifluidic system

In-Depth Investigation of the Magnetically Related Properties of Iron Oxide Nanospheres

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Iron oxide nanoparticles (IONPs) are increasingly employed as magnetic carriers in a wide range of biomedical applications, including imaging, drug delivery, and magnetic hyperthermia [1,2]. More recently, advances in synthesis have enabled improved control over particle size and dispersity, shifting current challenges toward surface functionalization, colloidal stability, and the understanding of interparticle interactions in complex media [3,4]. However, the controlled synthesis of iron oxide nanoparticles at the gram scale is a relatively recent development [5], and significant challenges remain in achieving precise characterization of their composition, their colloidal state and their magnetic properties. To address these needs, we have adapted an existing solvothermal method [5] to obtain monodisperse spherical IONPs of controlled size (Figure 1a,b). From those objects, acting as core for further materials, we developed a nano-object based on those IONPs covalently functionalized with a novel fluorescent catechol ligand, Nitro-DOPA-FITC. The nanoparticles are first transferred to the aqueous phase, followed by surface grafting of the Nitro-DOPA-FITC ligand, resulting in a nano-object both fluorescent and magnetic (Figure 1c,d). The colloidal state was primarily investigated using SAXS-WAXS analysis performed at the SOLEIL synchrotron. These experiments revealed a narrow size distribution (polydispersity index ~6%) for the obtained spherical particles, as well as the possible presence of nanoparticle chains in solution (Figure 1e). The magnetothermal properties were analysed using several methods, including dynamic susceptibility, dynamic hysteresis, and direct temperature measurements under an AC magnetic field. These analyses revealed an outstanding specific loss power (SLP) value of approximately 700 W/g at 307 kHz for those magnetic and fluorescent nanoparticles.

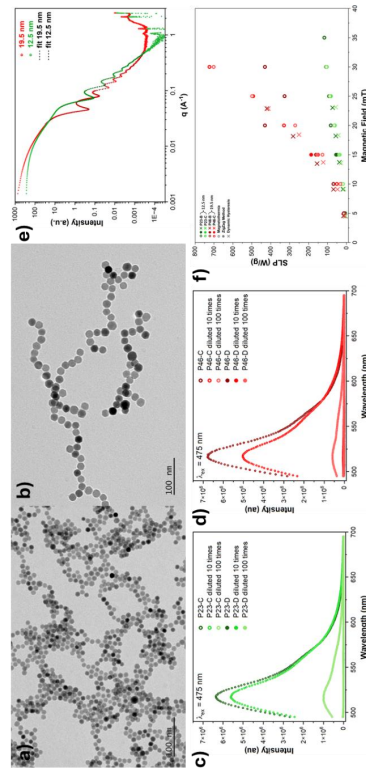


Figure 1: (a,b) TEM images of functionalized spherical IONPs with NitroDOPA-FITC of (a) 12.5 nm and (b) 19.5 nm; (c,d) Fluorescence spectra of (c) 12.5 nm and (d) 19.5 nm IONP-NitroDOPA-FITC excited at 475 nm in H₂O; (e) SAXS-WAXS measurements performed at SOLEIL synchrotron of 12.5 nm (green) and 19.5 nm (red) IONP-NitroDOPA-FITC. The respective fit obtained by SasView are in black dash; and (f) the calculated SAR measured at 307 kHz in function of the applied alternative magnetic field of 12.5 nm (green) and 19.5 nm (red) IONP-NitroDOPA-FITC.

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Magnetothermal-Triggered Response and Self-Healing of Recyclable and Reprocessable Nanocomposites for Actuation Systems

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The field of stimuli-responsive soft materials is rapidly evolving, particularly with recent advances in the design and fabrication of magnetic soft materials. By incorporating superparamagnetic nanoparticles (MNPs) into an elastic polymer matrix, materials with rapid and fully reversible mechanical responses to magnetic fields can be created, making them highly suitable for the development of flexible, remote-controlled soft robots. However, conventional crosslinked elastomer materials often lack reprocessability and recyclability, limiting their lifespans, especially when subjected to repeated mechanical stress. These limitations can be overcome by using vitrimers as the elastic matrix. Vitrimers are dynamically crosslinked polymers that can be reshaped at high temperatures and offer valuable features such as self-healing and shape memory. The dynamic mechanical properties of the material can be tailored for specific applications by adjusting parameters such as the building blocks, crosslink density, amount and size of MNPs, and the manner in which the particles are integrated into the matrix.

In this work, we present a magnetic elastomer containing 5 wt% Co_{0.7}Fe_{2.3}O₄-MNPs ($x = 0.42 - 0.49$) of different sizes (Figure 1a). Precise size control of the MNPs between 3 and 22 nm was achieved via a hydrothermal approach in the presence of acetoacetylated D-sorbitol (SxAcAc with x denoting the mean number of acetoacetate groups), depending on the concentration of the capping agent. The dynamic nature of the materials is provided by the vinyllogous urethane bonds formed upon mixing SxAcAc with the commercially available trifunctional amine Jeffamine T403. This allows network reshuffling without a catalyst at temperatures above 40 °C. The resulting composites could be molded into the desired shape and directly used. More complex structures can be readily created by welding the pure matrix material and the nanocomposite to fabricate defect-free structures with more complex deformation behavior. Moreover, the magnetic properties and thermoreversibility can be conveniently combined using alternating magnetic fields (AMF) to induce localized heating and trigger self-healing or reshaping of the material (Figure 1b). For example, a composite containing 8 nm-sized MNPs, which is exposed to a frequency of 142.70 kHz and a field amplitude of 36 mT, reaches a temperature rise of up to 112 °C (Figures 1c and d). Still, after 9 months of aging on air and five heating/cooling cycles, the material's heating performance remains consistent.

Additionally, the recyclability of the material was investigated to demonstrate full mechanical reprocessability without magnetic particle segregation via heat compression. The composites' solvent resistance and cobalt retention in various immersion solutions were demonstrated, enabling their safe use, especially in solid-gas environments. Additionally, the closed-loop chemical recycling of the composites using 0.5 M acetic acid was investigated, showing that the dissolved matrix and the MNPs can be easily separated using a permanent magnet. A reformulation of the prune matrix after removal of acetic acid and water, as well as the recovery of MNPs without altering their morphological and magnetic properties, were achieved.

We demonstrated that smart magnetic elastomers can be easily fabricated using dynamic polymer networks, known as vitrimers, which exhibit rapid mechanical responses to magnetic and temperature-dependent shape memory and self-healing properties that can be remotely triggered via magnetic heating using alternating magnetic fields.

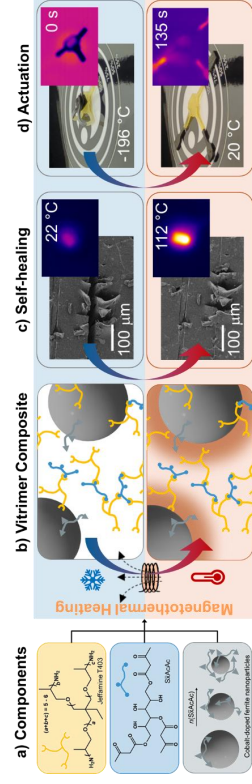


Figure 1: a) Schematic of the single components of the system and b) the resulting magnetic vitrimer nanocomposite, whose dynamic nature can be triggered magnetothermally by inducing a temperature increase above the glass transition temperature using an AMF. Due to this temperature increase of up to 112 °C (36 mT, 142.70 kHz), c) self-healing and d) reshaping properties of the composites are demonstrated. Reshaping is achieved three times faster than without applying an AMF.



Poster Sessions Tuesday, May 26 - No. 1 - 53 Wednesday, May 27 - No. 54 - 107				
	First Author	Title	City, Country	Corresponding Author
1	Agaesse, Angela	Magnetic Hyperthermia and Mechanical Ablation Induce an Anti-Tumor Immune Response in Pancreatic Ductal Adenocarcinoma	Toulouse, France	Agaesse, Angela
2	Altuna Ruiz de Eguino, Amaia	Magnetic Bead Redispersion: The Often Overlooked Control That Shapes Automated Chemiluminescent Assay Outcomes	Church Stretton, UK	Altuna Ruiz de Eguino, Amaia
3	Antal, Iryna	Amino Acid-Functionalized Magnetic Nanoparticles with Enhanced Colloidal and Relaxivity Properties for MRI Applications	Kosice, Slovakia	Antal, Iryna
4	Arik, Feyzanur	Positively charged Gold-Iron Oxide Nanoparticles for Immune Therapy	Tübingen, Germany	Arik, Feyzanur
5	Armenia, Ilaria	Magnetic-Chitosan Nanocarriers for CRISPR/Cas9 Delivery in Hermetia illucens	Varese, Italy	Armenia, Ilaria
6	Bär, Sebastien	MPI guided soft magnetic fluid hyperthermia using antibody-conjugated MNPs allows Blood-Brain Barrier opening in the rat	Freiburg im Breisgau, Germany	Bär, Sebastien
7	Barutiak, Michael	UV-C Activated APTES Functionalization of Fe ₃ O ₄ Magnetic Nanoparticles for RNA Separation	Kosice, Slovakia	Barutiak, Michael
8	Bikulov, Timur	Decoupling interaction and viscous effects in nonlinear responses through direct partition function evaluation	Jülich, Germany	Bikulov, Timur
9	Boelens, Peter	Characterization of citric acid coated magnetic nanoparticles attachment to Y2O3:Eu for recycling applications	Dresden, Germany	Boelens, Peter
10	Boulant, Lou	Fibrin matrices dissolution enhanced by self-assembling magnetic colloid's actuation	Nice, France	Boulant, Lou
11	Buhne, Maria-Josephina	Continuous Coagulation Monitoring of Human Blood via Magnetic Particle Spectroscopy	Lübeck, Germany	Aderhold, Eric
12	Cam, Necda	Tuning field amplitude to minimise heat-loss variability in magnetic hyperthermia	Santiago de Compostela, Spain	Cam, Necda
13	Caoure, Elisa	Innovative detection of biological targets using a magnetic sensor-based biochip prototype for future early diagnosis	Saclay, France	Caoure, Elisa
14	Casas, Enric	Design of Anisotropic Magneto-Opto-Mechanical Nanocapsules for Cancer Treatment	Bellaterra, Spain	Casas, Enric
15	Chen, Dongyu	Intelligent Multiparametric QCM Detection of Magnetically Labeled Molecules	Beijing, China	Chen, Dongyu
16	Chwiej, Joanna	Spectroscopic study of cellular uptake, metabolism and systemic effects of ⁵⁷ Fe-labeled iron oxide nanoparticles	Krakow, Poland	Chwiej, Joanna
17	Ciuraszkiewicz, Agnieszka	Starch Makes The Difference: Surface-Engineered Magnetite Nanoparticles For Improved Magnetite Hyperthermia Effect	Gliwice, Poland	Ciuraszkiewicz, Agnieszka
18	Dibdiakova, Katarina	Cytotoxicity and MRI Relaxometry of Iron Oxide Nanoflowers in Neuronal Cells	Martin, Slovakia	Dibdiakova, Katarina
19	Drab, Jiri	SPIO nanoparticles as promising drug carriers for neurodegenerative disease treatment	Olomouc, Czech Republic	Drab, Jiri
20	Dupuis, Vincent	Investigation of dynamic hysteresis in Hard-Soft binary ferrofluids: dimers and short chains	Paris, France	Dupuis, Vincent
21	Ehsandoost, Afsaneh	Stiffness-Dependent Magnetic Responses in MNP-Loaded 3D-Printed Hydrogels	Darmstadt, Germany	Ehsandoost, Afsaneh
22	Engelmann, Ulrich	In-silico Investigation of Interacting Magnetic Nanoparticle Response in Physiological Environments Using Single- and Dual Frequency MPS	Jülich, Germany	Engelmann, Ulrich
23	Exposito, Laurie	Encapsulation of a poorly water-soluble anti-cancer drug in ultra-magnetic liposomes for its controlled and locoregional release	Paris, France	Menager, Christine
24	Fabriciova, Zaneta	Shape-Dependent Magnetic Properties of CoFe ₂ O ₄ Nanoparticles for MRI Applications	Kosice, Slovakia	Fabriciova, Zaneta
25	Failde, Daniel	Optimizing Magnetic Hyperthermia Performance under Safety Limits	Barcelona, Spain	Iglesias, Oscar
26	Feoktystov, Artem	Insights into internal magnetic structure of iron oxide nanoparticles: a combined small-angle neutron scattering and magnetometry study	Garching, Germany	Feoktystov, Artem
27	Gallo-Cordova, Alvaro	Magnetic hyperthermia in focus: emerging non-cancer applications of magnetic nanoparticles	Madrid, Spain	Gutierrez, Lucia
28	Gandarias, Lucia	Engineering HER2-targeted magnetosomes displaying immunotherapeutic proteins to enhance radiotherapy efficacy in solid tumors	Saint Paul lez Durance, France	Preveral, Sandra
29	Giang, Trang Ngan	Photothermal and phototherapeutic effects induced by gold/iron oxide nanoparticles to facilitate the penetration of anticancer agents	Ecully, France	Giang, Trang Ngan
30	Gigoux, Veronique	Magnetic field-responsive bioMOF drug delivery nanocomposite based on Bi (III)-ellaglate SU-101	Toulouse, France	Gigoux, Veronique
31	Grossrieder, Tim	Low Frequency Inductive Sensing of Magnetic Microrobots	Zürich, Switzerland	Christiansen, Michael
32	Guo, Dongdong	Magnetic Nanoflower-Mediated Hyperthermia Activates Concurrent Apoptosis and Ferroptosis on Prostate PC3 and Melanoma DX3 cells	London, UK	Thanh, Nguyen

33	Habermann, Sebastian	Hydrogel-Based MPS-Sensor for the Visualization of Microenvironmental Changes and Identification of Pathological Conditions	Zürich, Switzerland	Herrmann, Inge
34	Hadadian, Yaser	UV-Vis spectroscopy of turbid dispersions containing magnetic nanoparticles and drugs	Berlin, Germany	Hadadian, Yaser
35	Hanson, Lise	Revealing the temperature inside induction-heated magnetic nanoparticles and their surroundings - hotspots defied	Kgs. Lyngby, Denmark	Hanson, Lise
36	Haq, Siraj	Monte Carlo-Based Cone Angle Approach for Torque Analysis in Hybrid BD-KMC Simulations of Magnetic Nanoparticles	Santiago de Compostela, Spain	Haq, Siraj UL
37	Herrera Aquino, Rafael	Sustainable Valorization of PET Nanoplastics: Integrated Magnetic Harvesting and Upcycling via Mesocrystalline Iron Oxide Nanoflowers	Madrid, Spain	Herrera Aquino, Rafael
38	Hrubovcak, Pavol	Interactions of silica-coated magnetic nanocarriers with cell membranes	Kosice, Slovakia	Hrubovcak, Pavol
39	Hu, Xinkai	Magnetic Hyperthermia for Chemo-Thermal Therapy via Intracellular GSH-Responsive Prodrug Release	London, UK	Thanh, Nguyen
40	Imhoff, Eric	A High-Throughput Thermal Decomposition Synthesis Platform for Optimizing Magnetic Nanoparticles	Gainesville, FL, USA	Rinaldi-Ramos, Carlos
41	Jaiswar, Ankur	Hybrid Magnetic Nano/Micro-swimmers with Integrated Theranostics for Targeted Biomedical Applications	Bangalore, India	Jaiswar, Ankur
42	Jedinak, Valentin	BSA-Coated Magnetic Nanoparticles for Betulinic Acid Delivery and Hyperthermia	Kosice, Slovakia	Jedinak, Valentin
43	Jefremovas, Elizabeth	Engineering intra-particle spin disorder to tailor heat generation	Luxembourg	Jefremovas, Elizabeth
44	Jones, Iestyn	High Magnetisation Magnetite Particles for Biomedical Applications	Bangor, UK	Jones, Iestyn
45	Khmara, Iryna	Poly-L-Lysine Functionalized Iron Oxide Nanoparticles: Single-Core vs Nanoflower Structures for potential MRI, Hyperthermia, and theranostic applications	Kosice, Slovakia	Khmara, Iryna
46	Kianpour, Mehrnoosh	Drug-Coated Magnetic Microrobots as a Targeted Drug Delivery Platform for Cancer Drug Studies	Colchester, UK	Kafash Hoshlar, Ali
47	Klein, Stefanie	Magneto-Plasmonic Nanoparticles for X-ray triggered cancer therapy	Tübingen, Germany	Klein, Stefanie
48	Kluwe, Bruno	Setup for dynamic control of magnetic particle concentration enabling versatile measurement applications	Berlin, Germany	Kluwe, Bruno
49	Kosch, Olaf	Determination of unique pure system functions for Color- Magnetic Particle Imaging of cellular states	Berlin, Germany	Kosch, Olaf
50	Kralj, Slavko	Magneto-Mechanical Remodelling of Bacterial Biofilms Using Bimodal Chemo-Mechanical Nano- Microrobots	Ljubljana, Slovenia	Kralj, Slavko
51	Kubovcikova, Martina	Development of Amino-Functionalized Magnetic Nanoparticles for Theranostic Applications	Kosice, Slovakia	Kubovcikova, Martina
52	Kurokawa, Ryosuke	Blood Coagulation Testing using Magnetic Nanoparticles Measured by HTS-SQUID System	Okayama, Japan	Kurokawa, Ryosuke
53	Lafuente, Aritz	Opto-Magnetically Guided Monocytes for Enhanced Nanotherapy in 3D Bioprinted Tumor Models	Barcelona, Spain	Lafuente, Aritz
54	Löffler, Marcus	3D-printed anatomic and geometric phantoms for platform-independent Magnetic Particle Imaging	Zwickau, Germany	Löffler, Marcus
55	Lünne, Kai	Towards a scaled-up, integrated system for Magnetic Particle Imaging and localized Hyperthermia for theranostic applications	Braunschweig, Germany	Lünne, Kai
56	Lyu, Weiming	Synthesis of cobalt ferrite magnetic seed nanoparticles for magnetoelectric system	London, UK	Nguyen, Thanh
57	Ma, Yunn-Hwa	Tannic Acid-Coating Augments Nanoparticle Uptake by Laminin Receptor-Mediated Endocytosis: Implication in Tumor Targeting	Tao-Yuan, Taiwan	Ma, Yunn-Hwa
58	Maisuradze, Anano	Flame-made Superparamagnetic Iron Oxide Nanoparticles for Non-invasive Diagnosis of Inflammatory Bowel Disease	Uppsala, Sweden	Maisuradze, Anano
59	Marsalin, Akash	Structural Engineering of Fe3O4 Mesocrystals for Enhanced Magneto-Optical Cancer Therapy	Chennai, India	Mani, Rajaboopathi
60	Matskevich, Natali	AI/ML-driven in vitro Platform for Quantification of Nanoparticle Transport Efficiency Across Biological Barriers	Prague, Czech Republic	Matskevich, Natali
61	Matsuki, Kenjiro	Improved Thermal Management for Stable Continuous Measurement in Magnetic Particle Spectroscopy	Hyogo, Japan	Matsuki, Kenjiro
62	Mefford, Thompson	Influence of interparticle spacing on AC magnetic losses in magnetic nanoparticle assemblies	Clemson, SC, USA	Mefford, Thompson
63	Molcan, Matus	Disruption of Amyloid Fibrils by Nanoparticles: Effect of Pulsed and Rotating Magnetic Fields	Kosice, Slovakia	Molcan, Matus
64	Nagy, Lubos	Biomolecule-functionalized CoFe2O4 nanoparticles: Balancing high heating efficiency with improved cellular safety	Kosice, Slovakia	Nagy, Lubos
65	Nahar, Tasmin	Development of magnetic force biotechnology for neural regeneration	Keele, UK	Nahar, Tasmin
66	Nistor, Mirela	Development of Theranostic Magneto-Microemulsion Platforms Based on Mn-Doped Magnetite Nanoparticles for Doxorubicin Delivery	Iasi, Romania	Dragoi, Brindusa
67	Novak, Ekaterina	Effects of Mixing Hard and Soft Magnetic Nanoflowers: Theory and Simulations	Ekaterinburg, Russia	Novak, Ekaterina
68	Nozka, Aniela	Development and validation of magnetic particle imaging-guided modeling and comparison with magnetic fluid hyperthermia in 3D printed mouse phantoms	Gainesville, FL, USA	Rinaldi-Ramos, Carlos
69	Nucci, Giulia	Repurposing mild magnetic hyperthermia for rapid intracellular labelling of immune cells for tracking applications	Genova, Italy	Nucci, Giulia Eugenia Paola
70	Ozkahraman, Bengi	pH-Responsive Magnetic Iron Oxide Nanogels of Seed-Nanoflower-Chitosan for Cancer treatment	Corum, Turkey	Ozkahraman, Bengi
71	Palacios-Alonso, Pablo	Predictive Magneto-Hydrodynamic Simulations of Ferrofluids for Biomedical Applications	Madrid, Spain	Palacios-Alonso, Pablo
72	Pansegrau, Kerstin	Towards Magnetorelaxometry-Based Real-Time Remote Magnetic Nanoparticle Thermometry for Thermotherapy Applications	Hall in Tirol, Austria	Pansegrau, Kerstin

73	Patel, Tushar	Dual-Session Magnetic Fluid Hyperthermia Induces Complete Regression of Hetero-Multicellular Stroma-Rich Breast Cancer Spheroids with Predominant Apoptotic Cell Death	Changa, India	Patel, Tushar
74	Payan, Sandy	Chemical coupling of biological magnetosomes with amine-functionalized antibody conjugates to improve immuno-associated cancer therapy	Saint-Paul-Lez-Durance, France	Sandra, Preveral
75	Pei, Peggy	Complex-Weighted Differential Harmonic Extraction in Magnetoresistance Sensor-Based Magnetic Particle Spectroscopy	Kiel, Germany	Pei, Peggy
76	Phan, Minh Duy	Design, fabrication, characterization and modeling of additive manufactured devices using novel magnetic nanoinks for label-free magnetic cell fractionation	Lubbock, TX, USA	Gomez-Pastora, Jenifer
77	Pillarova, Paula	Design of Amino-Modified PLA Nanospheres as a Promising Platform for Nitric Oxide Delivery	Kosice, Slovakia	Pillarova, Paula
78	Pinto Ahmad, Sara	In Vivo Magnetorelaxometry of Iron Oxide Nanoparticles: Temporal Evolution of Relaxation Behaviour Following Injection	London, UK	Pinto Ahmad, Sara
79	Ployart, O	Magnetic hyperthermia at the nanoscale	Paris, France	Fresnais, Jerome
80	Porru, Margherita	Magnetic Nanoflowers as MRI Contrast Agents: Shape, Coating and Size Effect on ¹ H-NMR Properties	Pavia, Italy	Porru, Margherita
81	Radon, Patricia	Framework for Assessing the Distinguishability of Magnetic Nanoparticles used in Color Magnetic Particle Imaging	Berlin, Germany	Radon, Patricia
82	Reichl, Teresa	Magnetic Nanoparticles as Sensor for Brain Perfusion	Würzburg, Germany	Vogel, Patrick
83	Rodriguez Garcia, Miguel Ramon	Empirical evaluation of non-harmonic asymmetric waveforms magnetic hyperthermia with magnetic nanoparticles	Pozuelo de Alarcon, Spain	Rodriguez Garcia, Miguel Ramon
84	Rodriguez Garcia, Miguel Ramon	Magnetic hyperthermia treatment using pulsed-shaped waveforms in glioblastoma multiforme cell line using nanoflowers-shaped nanoparticles: migration and immunogenic tests	Pozuelo de Alarcon, Spain	Rodriguez Garcia, Miguel Ramon
85	Rossa, Lea	Urease-Powered Nanorobots Enhance Tumor Penetration and Hyperthermia Efficiency in 3D Cancer Cell Spheroids	Darmstadt, Germany	Rossa, Lea
86	Sagastuy, Marine	Fusion of Magnetic Liposomes with Model and Plasma Membranes: Towards Cytoplasmic Delivery	Paris, France	Menager, Christine
87	Schoenen, Max	A Theranostic Implant Concept for Advancing Magnetic Hyperthermia and Magnetic Particle Imaging Towards Clinical Use	Hamburg, Germany	Slabu, Ioana
88	Seino, Satoshi	Micro Powder Drying of Magnetic Nanoparticle Dispersions: Toward Re-dispersible Powder Formulations	Osaka, Japan	Seino, Satoshi
89	Simsek, Ece	ULF-Mag: A Compact Ultra-Low Frequency Electromagnetic Device for Magnetic Microsphere Applications in Cell Culture	Antalya, Turkey	Simsek, Ece
90	Siska, Zuzana	Microtron Electron-Beam Defect Engineering of Ultrasmall Ceria Nanoparticles for Tuning Optical and Magnetic Properties	Brno, Czech Republic	Sojkova, Tereza
91	Sojka, Martin	Transition-Metal-Doped Iron Oxide Nanoparticles: Synthesis, Phase Composition, and Structure Evolution	Brno, Czech Republic	Sojka, Martin
92	Strbak, Oliver	CODERAM: Coating-dependent Relaxation Model for Prediction of MRI Relaxivities of Iron Oxide Nanoparticles with Different Coatings	Martin, Slovakia	Strbak, Oliver
93	Suarez-Lopez, Yael del Carmen	Multi-Parameter MRI Mapping for Identifying SPION in Gastrointestinal Tissue Models	Uppsala, Sweden	Suarez-Lopez, Yael del Carmen
94	Toffanello, Francesca	Synthesis and Characterization of Co-doped Iron Oxide Nanoparticles for Torque-based Actuation	Zürich, Switzerland	Christiansen, Michael
95	Totter, Elena	BacBots: Engineering bacteria-based biohybrid microrobots for torque-driven actuation	Zürich, Switzerland	Schuerle, Simone
96	Tran, Nguyen Thuy Linh	Magnetic Phenotyping of Red Blood Cells and Monocytes to Assess the Pain Severity and Risk of Vaso-Occlusive Crises in Sickle Cell Disease	Lubbock, TX, USA	Gomez Pastora, Jenifer
97	Ullah, Faiz	Mussel-Inspired Janus Films Incorporating Polydopamine-Coated Magnetite Nanoparticles for Skin Cancer Therapy and Tissue Regeneration	Barcelona, Spain	Suarez Garcia, Salvio
98	Valdes, Daniela	Segmentation Strategies for Quantitative Biodistribution in Magnetic Particle Imaging	Gainesville, FL, USA	Valdes, Daniela
99	Venegas-Gomez, Alejandro	Probing protein and drug interactions by nanoparticle dynamical magnetization phenomena	Madrid, Spain	Teran, Francisco
100	Wang, Xuyiling	Characterising exogenous and endogenous magnetic nanomaterials in biological samples using a magneto-optical multifunctional microscope	Stoke-on-Trent, UK	Wang, Xuyiling
101	Washino, Masaomi	Harmonic Magnetic Response of Iron Oxide Nanoparticle Powders: Influence of Interparticle Dipolar Interactions	Hyogo, Japan	Washino, Masaomi
102	Weber, Paula	Synthesis by Physics: Development of Superparamagnetic Thin Films Containing Nanoparticles via Magnetron Sputtering	Darmstadt, Germany	Bakenecker, Anna
103	Weidner, Andreas	Preparation of a binder-free electrode to assess magnetic nanocatalysts in a study of novel Cu _x O _y -IONP-clusters for electrochemical nitrate reduction	Ilmenau, Germany	Weidner, Andreas
104	Weisspflog, Maria	Synthesis of Cobalt-Doped Ferrite Nanoparticles by Green Hydrothermal Synthesis: From Shape Anisotropic Particles to Chain-like Structures	Hamburg, Germany	Hankiewicz, Birgit
105	Wenck, Christina	Development of a continuous flow micromixer synthesis of hydrophobic MNPs for encapsulation in lipid nanoparticles for theranostic applications	Mainz, Germany	Wenck, Christina
106	Zara-Danceanu, Camelia-Mihaela	pH-Modulated Adsorption and Desorption of BSA onto Mn/Zn/Co-Fe ₃ O ₄ Magnetic Nanocarriers for Biomedical Applications	Iasi, Romania	Dragoi, Brindusa
107	Zuo, Can	Real-Time Prediction of Coupled Physical Parameters in Magnetic Particle Systems for Drug Delivery Monitoring	Shanghai, China	Wen, Yumei

Magnetic Hyperthermia and Mechanical Ablation Induce an Anti-Tumor Immune Response in Pancreatic Ductal Adenocarcinoma

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Pancreatic ductal adenocarcinoma (PDAC) is a cancer with a poor prognosis, resistant to conventional therapies. Moreover, PDAC progression is not only determined by the genotype of cancer cells, but also by their interactions with its tumor microenvironment. Within the PDAC microenvironment, CAFs (Cancer-Associated Fibroblast) play key roles, notably by secreting abundant proteins constituting the dense extracellular matrix (ECM) and a barrier limiting the penetration of chemotherapeutic agents into the tumor, but also the infiltration of immune cells restricting an effective anti-tumor immune response.

Magnetic iron oxide nanoparticles (IONPs) are innovative therapeutic nanoplatforms. Exposed to a high frequency alternating (AMF) or a low frequency rotating (RMF) magnetic field, they respectively release thermal energy, causing cell death by magnetic hyperthermia (HM), or generate mechanical forces causing cell death by magnetic-mechanical ablation (MMA). We developed IONPs, vectorized with gastrin, called NF@Gastrin, which specifically target pancreatic cancer cells and CAFs expressing the CCK2 receptor (MiaPaca2-CCK2 and CAF-CCK2). The aim of this study was to investigate whether local HM or MMA can stimulate immunogenic cell death and enhance an antitumor immune response in the PDAC.

We showed that NF@Gastrin internalize and accumulate in the lysosomes of MiaPaca2-CCK2 and CAF-CCK2 cells. We demonstrated that HM and MMA specifically killed these cells in 2D culture model and 3D MiaPaca2-CCK2/CAF-CCK2 spheroids (Figure 1). Finally, we demonstrated that HM and MMA increased the expression of the Damage-Associated Molecular Pattern: calreticulin and HSP70 at the surface of the targeted cells in 2D and 3D models. This effect was associated with an increase in phagocytosis of these cells by human THP-1 macrophages as well as with an increase in the cytotoxic activity of Natural Killers (NK-92) when they were in contact with these cells. Moreover, an enhanced infiltration of THP-1 macrophages and Natural Killers (NK-92) were observed within the MiaPaca2-CCK2/CAF-CCK2 spheroids treated by HM or MMA (Figure 2). Taken together, these results strongly highlight the potential of HM and MMA to induce immunogenic cell death and restore an anti-tumor immune response in cancer, paving the way for further evaluation in *in vivo* models to establish its translational validation.

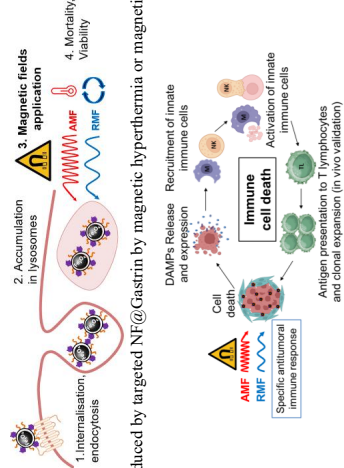


Figure 1. Cell death induced by targeted NF@Gastrin by magnetic hyperthermia or magnetic-mechanical ablation.

Magnetic Bead Redispersion: The Often Overlooked Control That Shapes Automated Chemiluminescent Assay Outcomes

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Superparamagnetic microparticles, or “magnetic beads”, are commonly used as separation supports for complex heterogeneous biological mixtures, including blood, urine, food, or tissues. Magnetic beads are often functionalized to make them selective for a specific analyte. The incorporation of magnetic beads as solid phases in Chemiluminescent Immunoassays (CLIA) can present many challenges to assay developers. Optimization of several parameters is often necessary to achieve assay reproducibility, maximum signal-to-noise ratio (S/N), and avoidance of false positives or negatives. Suboptimal assay data can be the result of complex protein interactions between the antibody pair selected for sandwich assays. However, magnetic beads can also significantly influence CLIA performance if poor bead-handling techniques are used. Homogeneous magnetic bead redispersion and solids content are two intrinsically linked parameters that are easily overlooked due to time constraints and elevated costs of the material. Bead losses during protein conjugation, incomplete ligand coupling due to heterogeneous bead dispersion, or inaccurate addition of bead solids will contribute to irreproducible, misleading data that could result in detrimental interpretation of the assay outcome.

Several redispersion procedures were applied to LodeStars magnetic beads. Gravimetric analysis was performed to determine redispersion efficacy where solids content variations of more than 3% were recorded. When these variations were incorporated into an automated CLIA assay (Figure 1), impactful results were observed favoring the obtention of false positives or negatives. With this study, we demonstrate how considering magnetic bead redispersion can improve assay data consistency, and highlight the impact of poor bead solids calculations in CLIA applications.

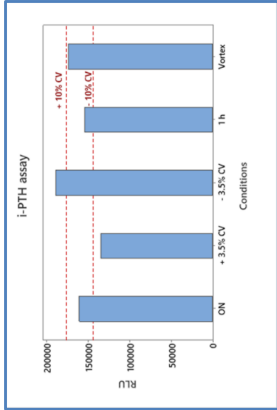


Figure (1). The redispersion impact of LodeStars beads on an i-PTH CLIA assay.

Figure 2. Immunogenic cell death mechanism triggered by magnetic hyperthermia or magnetic mechanical forces.

Amino Acid-Functionalized Magnetic Nanoparticles with Enhanced Colloidal and Relaxivity Properties for MRI Applications

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Magnetic nanoparticles (MNPs) are promising nanomaterials for biomedical applications, particularly as contrast agents in magnetic resonance imaging (MRI). However, their clinical use is often limited by poor colloidal stability and insufficient targeting ability.

In this study, MNPs were synthesized using a simple precipitation method and stabilized with a polyethylene glycol (PEG) coating to improve their stability in aqueous media. In addition, the nanoparticles were functionalized with amino acids (AAs), namely arginine (Arg) and glutamic acid (Glu). This innovative, simple one-pot synthesis approach enabled us to produce highly stable magnetic fluids and to create NPs with both positive (Arg-PEG-MNPs) and negative (Glu-PEG-MNPs) surface charges, which can serve as platforms for the further loading of various agents or drugs.

High-resolution transmission electron microscopy (HRTEM) revealed that the prepared MNPs were approximately spherical in shape, with a diameter between 8 and 12 nm. The average hydrodynamic diameters of the PEG-MNPs, Arg-PEG-MNPs, and Glu-PEG-MNPs, determined by dynamic light scattering (DLS), ranged from 80 to 150 nm. Modifying the nanoparticles with PEG caused only minor changes in their magnetic properties (from 74 emu/g for bare MNPs to 60 emu/g for PEG-MNPs), while still exhibiting superparamagnetic behaviour at room temperature. Fourier transform infrared (FTIR) spectroscopy and thermogravimetric analysis (TGA) confirmed the functionalization of the MNP surfaces with amino acids and the presence of the PEG layer on the MNPs.

The colloidal and thermal stability of the nanoparticles was evaluated by measuring the particle surface charge and hydrodynamic diameter at various pH values and ionic strength using DLS and zeta potential measurements. The zeta potential dropped from 35.0 mV to 12.3 mV with increasing NaCl concentration, indicating a decrease in the stability of the PEG-MNPs (Fig. 1). However, the magnetic fluids remained stable over the temperature range of 25–65°C (Fig. 2) and across a broad pH range.

The MRI relaxometric analysis demonstrates that PEG-functionalized MNPs exhibit enhanced transverse relaxivity r_2 and favorable r_2/r_1 ratios (Table 1), indicating strong potential as T_2 -weighted MRI contrast agents. Modification with amino acids, which is needed to bind potential drugs, however, revealed a slight decrease in relaxivity for Arg and a significant decrease for Glu. Despite this reduction, the relaxivity values remain sufficiently high for effective MRI contrast, while the added surface functionality significantly enhances further biofunctionalization for advanced theranostic applications.

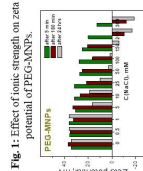
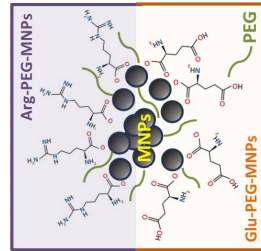


Fig. 1: Effect of ionic strength on the zeta potential of PEG-MNPs.

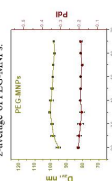


Fig. 2: Effect of temperature on the z-average of PEG-MNPs.

Table 1: Relaxivity values with 95% confidence interval.

SAMPLE	relaxivity r_1 [mM ⁻¹ s ⁻¹]	r_2 [mM ⁻¹ s ⁻¹]	r_2/r_1 [mM s]	r_2/ρ_{Fe} [mL/g s]	r_2/ρ_{Fe} [mL/g s]
PEG-MNPs	2.7 ± 0.6	40.0 ± 21.1	575.4 ± 35.9	164.4	215.0
Arg-PEG-MNPs	2.4 ± 0.5	36.4 ± 23.7	445.1 ± 14.9	151.3	184.8
Glu-PEG-MNPs	1.3 ± 0.5	129.8 ± 2.1	174.9 ± 32.3	102.0	137.5
Resonance [1]	2.8 ± 0.1	176 ± 9	-	62.9	-
Verdine [1]	2.3 ± 0.1	105 ± 5	-	45.7	-

[1] Estelrich, J.; Sanchez-Martín, M.J.; Busquets, M.A. Int. J. Nanomed. 2015, 10, 1727–1741.

Acknowledgement: This work was supported by the Science Grant Agency VEGA (grant number 2/0080/26 and 2/0049/23), the Slovak Research and Development Agency (Contract No. APVV-22-01448 and APVV-22-0122), the European Union, under the Slovakia Programme (project NFP401/01C479), the EU NextGenerationEU through the Recovery and Resilience Plan for Slovakia under Grant 09NXX-GB-V04-00231, and MYS B-2024-71.

Positively charged Gold-Iron oxide Nanoparticles for Immune Therapy

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Triple negative breast cancer (TNBC) is one of the most aggressive forms of breast cancer, characterized by a high tendency to metastasize and poor survival rate. Current therapeutic options remain limited, which highlights the urgent need for innovative strategies. Recent findings of increased tumor-infiltrating lymphocytes in TNBC suggest that immune-based approaches could be highly effective. However, the immune response is suppressed through the programmed cell death protein 1 (PD-1) receptor on T cells, which acts as a natural checkpoint to prevent autoimmunity but is exploited by tumors to evade immune attacks.

To overcome this limitation, PD-1 expression can be silenced using RNA interference (RNAi). In this study, a nanoparticle-based delivery system was developed that enables both PD-1 suppression and radiation dose enhancement. Gold-iron oxide (Au-Fe₃O₄) nanoparticles with patchy structures were synthesized by adding gold acid, Fe (II) salt and mercapto carboxylic acid into an ammonia solution and functionalized with positive charged ligands. The positively surface charge allows stable electrostatic binding of negatively charged siRNA molecules.

The siRNA-functionalized nanoparticles were taken up by T cells, resulting in effective downregulation of PD-1 expression. This will reactivate the cytotoxic activity of T cells against TNBC cells. Once activated, the T cells infiltrate tumor tissue and induced tumor cell killing. In a subsequent step, fractionated X-ray therapy will be applied, where the nanoparticles served as radiosensitizers to enhance the therapeutic effect by increasing local radiation dose deposition. The nanoparticles generated additional radicals, thereby overcoming the cellular defense system and DNA repair, while also promoting the formation of cytotoxic substances. [1]

The work demonstrates the synthesis and functionalization of Au-Fe₃O₄ nanoparticles as a multimodal therapeutic platform that combines siRNA mediated PD-1 silencing, adoptive T cell therapy and radiation dose amplification. This strategy holds promise for overcoming immune resistance in TNBC and improving treatment outcomes.

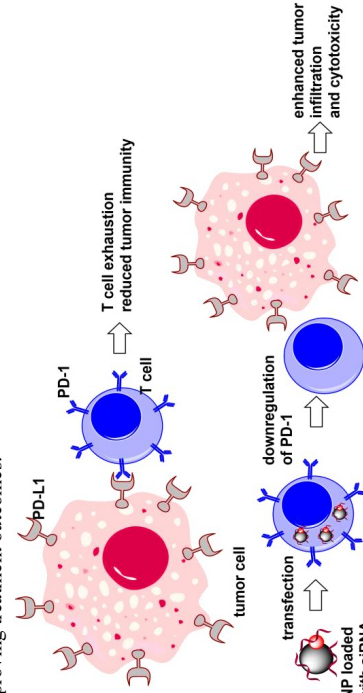


Figure. PD-1 can be downregulated with nanoparticle (NP) loaded with siRNA. The siRNA-functionalized nanoparticles were taken up by T cell and enhance the therapeutic effect and cytotoxicity

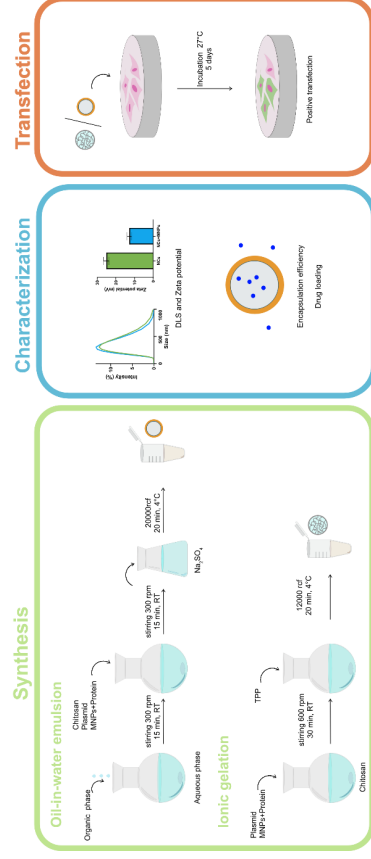
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Magnetic–Chitosan Nanocarriers for CRISPR/Cas9 Delivery in *Hermetia illucens*

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Polyethylene terephthalate (PET) is one of the most widely used synthetic polymers and a major contributor to global plastic pollution due to its high chemical stability and resistance to environmental degradation. Enzymes such as PETase can hydrolyse PET under mild conditions, providing a promising biological route for polymer depolymerization. Here, we explore a nanotechnology-based strategy for delivering CRISPR/Cas9 components aimed at enabling PETase expression in the larvae of *Hermetia illucens*, an insect species widely used for organic waste bioconversion, potentially allowing the use of PET-contaminated substrates for the production of high-value products. To this end, two different approaches were tested for the preparation of chitosan nanocarriers: ionic gelation and oil-in-water emulsion. Proteins and nucleic acids were co-encapsulated together with PMAO-coated magnetic nanoparticles (~13 nm core size), generating magnetically responsive hybrid systems. The resulting nanoparticles displayed an encapsulation efficiency of 95% and a cargo loading of 3.4 µg/mg, while maintaining hydrodynamic diameters in the range of ~250–350 nm and a positive surface charge, indicating stable colloidal systems suitable for nucleic acid delivery. The incorporation of magnetic nanoparticles provides the basis for magnetically assisted transfection (magnetofection), potentially enhancing cellular uptake and enabling spatial control of gene delivery. Future studies will evaluate transfection efficiency in insect cell cultures, detect CRISPR-mediated genome editing, and assess PETase enzymatic activity. Magnetic responsiveness may further enable targeted delivery into *H. illucens* eggs as a minimally invasive strategy for gene transfer. This work establishes a biocompatible magnetic nanocarrier platform for CRISPR delivery and explores the feasibility of engineering *H. illucens* as a biological system capable of contributing to PET degradation.



This project has received funding from the European Union's Horizon Europe research and innovation programme under the Marie Skłodowska-Curie grant agreement No 101204748.

UV-C Activated APTES Functionalization of Fe₃O₄ Magnetic Nanoparticles for RNA Separation

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Magnetic nanoparticles are widely used in bioseparation technologies due to their ability to be rapidly manipulated by an external magnetic field. In particular, surface-modified iron oxide nanoparticles provide a versatile platform for the isolation of nucleic acids in molecular biology and diagnostic workflows. In this work, Fe₃O₄ nanoparticles with two distinct morphologies, polyhedral and cubic, were synthesised using a thermal decomposition approach. The particles were subsequently subjected to ligand exchange with polyacrylic acid (PAA), creating a surface rich in carboxyl functional groups. Surface amination was achieved through modification with 3-(aminopropyl)triethoxysilane (APTES). In contrast to conventional coupling strategies, the attachment of APTES was facilitated by UV-C irradiation (254 nm), which promoted photochemical activation of the PAA layer and enabled effective surface functionalisation. The prepared nanoparticles were analysed using several structural and surface-sensitive techniques including X-ray diffraction, scanning electron microscopy, ATR-FTIR spectroscopy, X-ray photoelectron spectroscopy, and zeta potential measurements. Magnetic properties were evaluated by SQUID magnetometry. Differences in particle morphology were reflected in their magnetic behaviour, with polyhedral nanoparticles exhibiting higher saturation magnetisation compared with cubic particles. To assess their practical applicability, the functionalised nanoparticles were tested in an RNA isolation protocol and compared with silica-coated magnetic nanoparticles commonly used in commercial extraction systems. The results indicate that the developed particles can provide efficient nucleic acid binding while maintaining favourable magnetic responsiveness, suggesting their potential for simplified magnetic separation platforms in molecular biology applications.

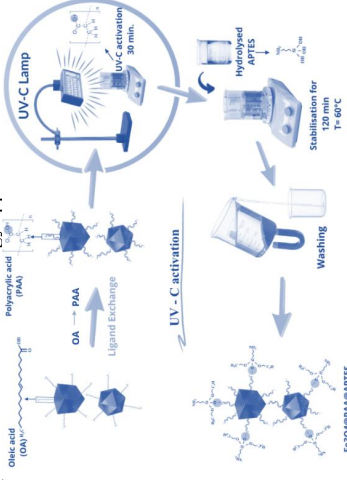


Figure. Scheme of surface modification of MNPs with the organic ligand APTES using UV-C radiation.

Acknowledgments

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Characterization of citric acid coated magnetic nanoparticles attachment to $Y_2O_3:Eu$ for recycling applications

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Citric acid-coated magnetic nanoparticles (MNPs) have recently demonstrated selective and reversible electrostatic attachment to $Y_2O_3:Eu$ (YOX) phosphor particles and their successful application in carrier magnetic separation for the recovery of rare-earth elements from fluorescent lamp waste. This approach represents a promising pathway to overcome the limitations of conventional physical separation processes when dealing with ultrafine (<10 μm) and compositionally complex secondary resources.

In this study, we focus on the detailed characterization of the interaction mechanisms between citric acid-coated MNPs and YOX particles. The main focus is on understanding how attachment occurs at the nanoscale and how the particles interact with each other. Atomic force microscopy (AFM) is employed to directly visualize the surface coverage and spatial distribution of MNPs on YOX particles (see Figure 1). Complementary to this, magnetic particle spectroscopy (MPS) is used to probe changes in the magnetic response upon attachment, enabling indirect quantification of attached nanoparticles and offering a sensitive tool to monitor heterocoagulation dynamics.

Together, these methods provide complementary insight into both the structure and dynamics of MNP attachment. The results contribute to a better understanding of the underlying interaction mechanisms and support the further development of carrier magnetic separation processes for recycling applications.

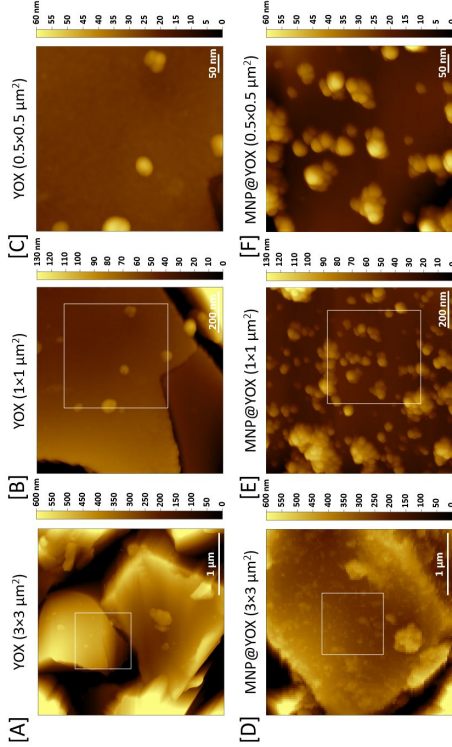


Figure 1. AFM topographic image of the surface of bare YOX [A-C] and MNP@YOX [D-F].

Fibrin matrices dissolution enhanced by self-assembling magnetic colloid's actuation

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An ischemic stroke, characterized by the interruption of blood flow in the brain, occurs when a blood clot forms within a vessel. To avoid serious and irreversible consequences on its health, the patient must be treated within a few hours. Current treatment consists in passive intravenous drug diffusion to the clot, which can take up to 60 minutes due to the absence of blood flow. In order to enhance this process, we introduce a vector to deliver the thrombolytic drug toward the thrombus' site. Indeed, rotating self-assembled magnetic nanoparticles can generate a recirculation flow that convectively diffuses the drug along the blocked vessel (Fig. 1.a).

In this work, we used a suspension of polymer-coated multicore iron oxide nanoparticles in pig plasma. The suspension is injected inside a closed microfluidic channel and placed at the center of a three coils system powered by alternating current, allowing us to produce a superposition of a rotating magnetic field and a magnetic field gradient. This configuration enables the nanoparticles to assemble into micro-sized elongated aggregates oriented along the field's direction and produces a gradient of their concentration across the channel (Fig. 1.b). The aggregates then rotate synchronously with the field, translate due to their interaction with the channel's wall and generate a macroscopic recirculation flow. Their geometry and volume fraction were then measured by image analysis.

This nanoparticles suspension was then used to conduct fibrin matrices dissolution experiments. Model clots were synthesized *in vitro* from pig plasma directly at one end of a microfluidic channel, to represent an occluded blood vessel. The dissolution agent used, tissue plasminogen activator (tPA), is added to the suspension, injected into the empty part of the channel and the microfluidic device was placed into the experimental setup. With this method, we were able to observe a clear dissolution front and study its displacement (Fig. 1.c). The aggregates' actuation allowed a lysis speed ~10 times higher than the tPA passive diffusion lysis speed. This study shows promising results for clot lysis treatment by enhanced thrombolytic drug convection along a blocked blood vessels.

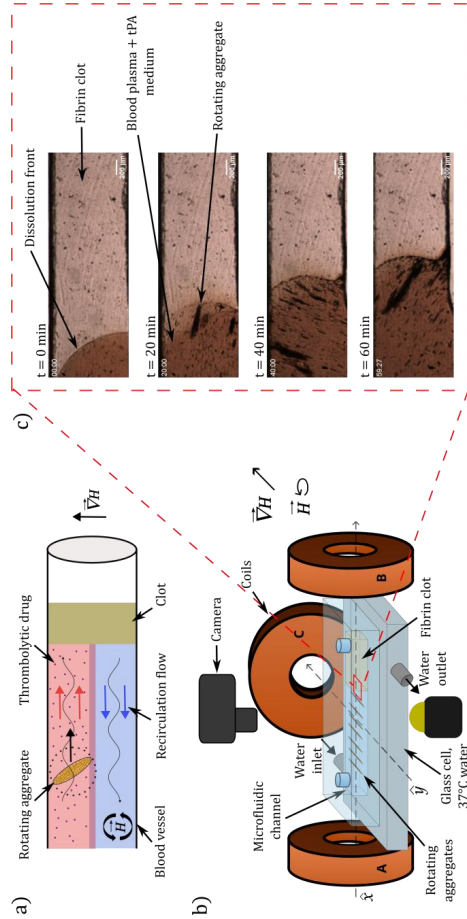


Figure 1: a) Sketch of the problem: drug convection along an occluded blood vessel. b) Experimental setup. c) Kinetics of dissolution of a fibrin matrix in a microfluidic channel, enhanced by rotating aggregates.

MPI guided soft magnetic fluid hyperthermia using antibody-conjugated MNPs allows Blood-Brain Barrier opening in the rat

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Magnetic particle imaging (MPI) combined with magnetic fluid hyperthermia (MFH) enables a unified approach for the detection and controlled heating of magnetic nanoparticles (MNPs), allowing imaging-guided and spatially resolved hyperthermia application within one platform. Following intravenous administration, MFH can be applied remotely and minimally invasively. However, a major limitation of this approach is that while MNPs can be locally heated, their continuous circulation in the bloodstream leads to rapid heat dissipation, preventing the achievement of therapeutically relevant temperatures.

Here, we present first results of an approach to improve MFH efficiency by antibody conjugation of the MNPs. PECAM(CD31)-antibodies conjugated to standard synomag-D70 (micromod Partikeltechnologie, Germany) magnetic nanoparticles (MNPs) were used to target vascular endothelial cells in the brain. Here, we exploit the resulting increase in local nanoparticle concentration to enable thermally induced blood-brain barrier (BBB) opening. For these experiments we used a theranostic platform consisting of a commercial magnetic particle scanner (Bruker BioSpin GmbH & Co. KG, MPI 25/20 FF) and a custom heating insert.

A controlled intravenous infusion protocol was used to administer either CD31-conjugated or non-functionalized synomag-D70 as a control. MFH application (721 kHz, 11.8 mT) was meanwhile started and continuously applied for 1 hour.

At the end of the experiment, Evans' Blue was injected into the tail vein and allowed to circulate for 1 h and subsequently the brains were extracted for further analysis. The clear discoloration of the PECAM-conjugated brain indicates successful BBB opening which is absent in the native synomagD70 brain (Figure 1a). Evan's Blue extravasation was verified with fluorescent microscopy (Figure 1b). Both brains were scanned ex-vivo with MRI. The T₁-FLASH acquisition sensitive to iron (signal cancellation) confirms the presence of MNPs in the PECAM-conjugated brain (Figure 1c).

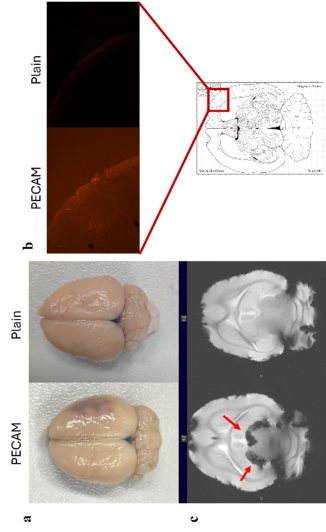


Figure 1: Magnetic fluid hyperthermia-induced blood-brain barrier opening using antibody-conjugated synomag-D70. The rat receiving CD31-conjugated nanoparticles exhibited Evan's Blue extravasation into brain tissue, indicating BBB opening (a). Fluorescence microscopy confirmed increased Evan's Blue signal in the antibody-treated brain (b). Post-mortem MRI revealed elevated iron accumulation in the antibody-conjugated brain, consistent with targeted nanoparticle binding (c).

Tuning field amplitude to minimise heat-loss variability in magnetic hyperthermia

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Magnetic fluid hyperthermia (MFH) relies on the generation of heat by magnetic nanoparticles (MNPs) under alternating magnetic fields, where both the average heating power and local uniformity play crucial roles [1]. In this study, we theoretically examine how particle shape-induced anisotropy dispersion and AC field amplitude jointly affect the magnitude and heterogeneity of local heating in magnetite nanoparticle assemblies [2].

We employ real-time Landau-Lifshitz-Gilbert simulations incorporating thermal fluctuations alongside a macrospin model that combines intrinsic cubic magnetocrystalline and uniaxial shape-induced anisotropies to analyze shape-polydisperse systems [3]. For relatively large particles (25–30 nm), a moderate field (4–12 mT) minimizes variation in single-particle heating while maintaining substantial power. The optimal field is primarily determined by particle size and excitation frequency, with only minor effects from shape dispersion [3]. These findings provide practical guidance for enhancing performance in MFH-based systems and underscore the importance of accounting for both shape and intrinsic anisotropies in realistic nanoparticle assemblies. An illustrative example is shown in Fig. 1, SLP over the ensemble-averaged SLP versus AC field amplitude is shown in Fig. 1, highlighting the influence of shape polydispersity on heating heterogeneity.

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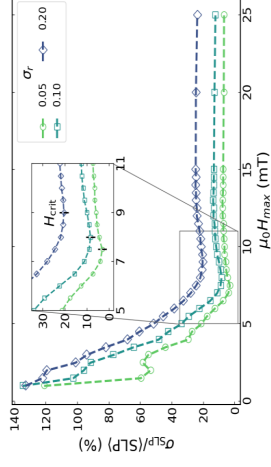


Fig. 1: $\sigma_{SLP}/(SLP)$ vs. $\mu_0 H_{max}$ for $f = 1000$ kHz and $D = 25$ nm. The inset highlights the corresponding critical fields H_{crit} .

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Innovative detection of biological targets
using a magnetic sensor-based biochip prototype for future early diagnosis

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The development of rapid, sensitive, portable and inexpensive early diagnosis techniques is a challenge in the healthcare field. In 2006, the World Health Organization established criteria (known by the acronym REASSURED) that point-of-care diagnostic tests must meet, thereby demonstrating the real need in terms of public health [1]. The expansion of micro- and nano-biotechnologies over the last few decades allowed the creation of all kinds of high-performance, increasingly competitive lab-on-chip devices. In this context, we established in a previous work the proof-of-concept of a patented Giant Magneto Resistance (GMR) sensor-based biochip to detect magnetically biological targets one by one [2]. It offers the advantage of being easy to use, inexpensive and suitable for use with biological targets of various sizes in complex matrices. As biological objects are not naturally magnetic, they are labeled using magnetic particles (MPs) functionalized with monoclonal antibodies specifically directed against the target of interest (figure 1a-b). The latter, flowing in a microfluidic channel, are dynamically detected simultaneously by GMR sensors placed face-to-face above and below this channel (figure 1c, principle of the device fully described in [2]). In order to assess the performance of this GMR-based biochip and its suitability as a diagnostic tool, we first carried out a comprehensive and detailed work on a preliminary case study involving the detection of cancer cells (NS1 murine myeloma cells), in a semi-complex matrix [3]. This easy-to-use eukaryotic model has been chosen because it is non-pathogenic, enabling the study to be performed outside a high-risk laboratory and it is also possible to visually control cell magnetic labeling and MP aggregation at different stages of the experiments using a standard optical microscope. Several criteria, such as specificity, sensitivity, reproducibility and robustness of the detection, have been evaluated in a semi-complex matrix without sample pretreatment. We were able to demonstrate the specificity of our measurements, with an average detection limit of 500 cells/mL. The results obtained in this study are promising and make our technique highly competitive with routine laboratory tests such as flow cytometry or ELISA (figure 1d). These very promising first results motivate us to use this biochip for the detection in blood of bacteria or yeasts responsible for sepsis. The challenge is the rapid and specific detection of causative pathogens (*E. coli*, *S. aureus*, *C. albicans* and *S. enterica*) in very low quantities (a few pathogens/mL) in complex clinical samples, without a prior enrichment step (like hemoculture used in routine clinical practice), in order to speed up patient management, sometimes in life-threatening emergencies. One of the main obstacles to be overcome, particularly in blood, is the self-aggregation of MPs and non-specific binding, which can cause false positives or false negatives and limit the sensitivity of our test. Functionalization of MPs with antibodies seems the main cause of these problems. Work is currently underway to optimize this process. This project is being carried out as part of the Sepsis IHU (University Hospital Institute of Paris-Saclay) which aims to halve the mortality and long-term complications associated with sepsis within the next ten years. It is being conducted in close collaboration with the APHP (Bacteriology and Hygiene Department of the Bédère Hospital).

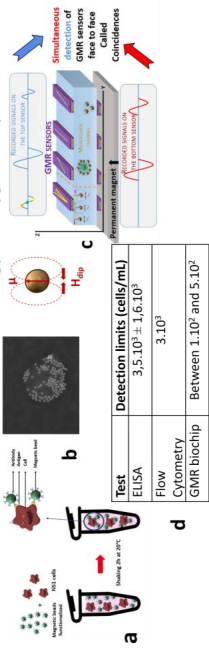


Figure 1 (a), Illustration of the NS1 cell labeling principle with magnetic particles (b) Environmental Scanning Electron Microscope (ESEM) photograph of magnetically labeled NS1 cell. The image was obtained with a ZEISS EVO 15 microscope equipped with a Pellet stage for the cooling at 0.5 °C of wet biological sample (c) Principle of the GMR based-biosensor, (d) Comparison of NS1 cell detection in culture medium by flow cytometry, ELISA and GMR biochip.

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Design of Anisotropic Magneto-Opto-Mechanical Nanocapsules for Cancer Treatment

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When trying to alter the magnetic and optical response or biological performance of magnetic nanoparticles (MNPs) shape tuning is often overlooked by other properties such as size and surface functionalization, even though anisotropic MNPs produce larger mechanical disruption on membranes or biofilms when subjected to an alternating magnetic field (AMF) and have better biodistribution and targeted cell interaction than spherical ones [1]. MNPs can be shaped during or after the synthesis (e. g., promoting material growth along a specific crystallographic plane or assembling the nanoparticles in a certain structure, respectively). However, MNPs achieved in the former are too small, and so, have low blood circulation [2], and, in the latter, uniform size and shape control can be challenging. Moreover, MNPs by themselves are not capable of drug loading, which limits the much-needed multifunctionality in nanomedicine [3]. In this work, a simple and cost-effective synthesis of anisotropic MNPs with drug loading ability is presented.

Cubic 18 nm MNPs were synthesized via thermal decomposition of iron (III) oleate and later incorporated in poly(lactide-co-glycolic acid) 150 nm nanocapsules by single emulsion evaporation. Finally, the nanocapsules were embedded in a film that was stretched and anisotropic magnetic nanocapsules (AMNCs) were easily recovered (Figure 1a). The AMNCs' possessed a superparamagnetic behaviour, presented a large photothermal response (Figure 1b), could rotate in the presence of an AMF and internalized inside THP-1 monocytes (Figure 1c). These anisotropic properties could be exploited for multitherapeutic magneto-mechanical, photothermal and chemical cancer treatments.

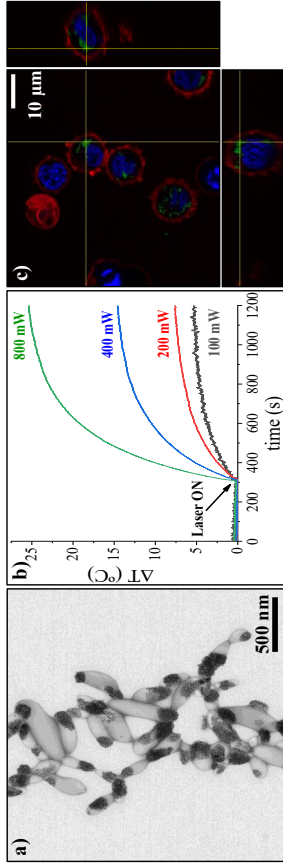


Figure 1. (a) Transmission electron microscopy image of the AMNCs. Average aspect ratio of 2.3. (b) Heating curves of AMNCs (0.1 mg/mL Fe) when irradiated with an 808 nm laser at different power values. (c) Confocal orthogonal views of AMNCs internalized in THP-1 cells. Red: cell membrane; Blue: nucleus; Green: AMNCs.

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Spectroscopic Study of Cellular Uptake, Metabolism and Systemic Effects of ^{57}Fe -labeled Iron Oxide Nanoparticles

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Although magnetic iron oxide nanoparticles (IONPs) and their potential biomedical applications have been extensively studied over the past decades, their clinical translation remains limited due to concerns regarding nanoparticles toxicity arising from their complex and insufficiently understood metabolic pathways. In particular, the fate of IONPs in living organisms, including their biotransformation and metabolic products, remains poorly characterized. A key challenge is the inability to distinguish exogenous nanoparticle-derived iron from endogenous iron pools. To overcome this limitation, an integrated spectroscopic approach based on ^{57}Fe -enriched SPIONs combined with atomic, molecular, and nuclear techniques is proposed.

Magnetite-core, PEG-coated iron oxide nanoparticles enriched in the ^{57}Fe isotope were synthesized and applied as a model system enabling selective tracking of nanoparticle-derived iron. The study was conducted at three complementary levels. At the cellular level, Sertoli cells and uterine smooth muscle cells were exposed to nanoparticles (5-100 $\mu\text{g Fe/mL}$, 24 h), and Raman microspectroscopy was applied to investigate nanoparticle internalization, intracellular distribution, and associated biochemical changes, supported by cytotoxicity, viability, and apoptosis assays. At the whole-organism level, Mössbauer spectroscopy was employed to analyze the metabolism and fate of ^{57}Fe -labeled nanoparticles in rats, taking advantage of its isotope selectivity. Finally, at the systemic level, total reflection X-ray fluorescence (TXRF) was used to evaluate changes in the elemental composition of rat serum following nanoparticle exposure.

Raman microspectroscopy confirmed cellular uptake of nanoparticles in both male and female reproductive cells, revealing differences in accumulation patterns and indicating nanoparticle-related biochemical changes. Toxicity assays demonstrated dose-dependent cytotoxic effects detectable even at low concentrations, with a more pronounced response in Sertoli cells. Mössbauer spectroscopy further demonstrated the feasibility of detecting nanoparticle-derived ^{57}Fe in biological samples, supporting the applicability of this approach for tracking nanoparticle-associated iron *in vivo*. TXRF analysis indicated that SPION exposure is associated with significant alterations in plasma elemental composition, suggesting a potential impact on systemic metal homeostasis.

Intelligent Multiparametric QCM Detection of Magnetically Labeled Molecules

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Detection of disease-related molecules in complex biological samples is shifting from single-concentration readout toward multiparametric characterization. In magnetically labeled molecular systems constructed with functionalized magnetic particles, target concentration, complex size, aggregation state, and medium viscoelasticity jointly contribute to signal formation, often resulting in feature mixing and non-unique parameter mapping, which limits the accurate resolution of multidimensional information by conventional end-point assays. Quartz crystal microbalance (QCM) offers high sensitivity at liquid interfaces, real-time dynamic readout, and simultaneous responsiveness to interfacial mass loading and viscoelastic coupling, making it well suited for characterizing the interfacial motion of magnetically labeled molecules under external-field stimulation.

To address these challenges, this study proposes an intelligent multiparametric QCM detection method for magnetically labeled molecules and establishes an integrated analytical framework consisting of multimodal magnetic excitation, QCM dynamic readout, multifeature extraction, and joint inversion. Programmable multimodal magnetic fields are employed to drive magnetically labeled complexes to undergo approach, departure, oscillation, and aggregation-related motions in the vicinity of the QCM-sensitive interface, while dynamic response features, including frequency shift (Δf), dissipation factor (ΔD), harmonic response (H_n), and transient variation (τ), are synchronously acquired. Component analysis and feature dimensionality reduction are further introduced to achieve structured representation of complex signals. On this basis, a joint inversion strategy coupling a forward physical model with a deep neural network is developed, integrating physical constraints, feature learning, and parameter mapping to establish nonlinear relationships between multifeature responses and concentration, particle size, aggregation state, and viscoelasticity, thereby enabling automatic interpretation of complex dynamic signals and synchronous estimation of multiple parameters. The methodological innovation of this approach lies in actively encoding complex-state information into QCM dynamic responses through multimodal magnetic excitation, replacing single end-point readout with multifeature cooperative sensing, and improving parameter identifiability and interpretability through physics-guided, data-driven joint inversion. This study is expected to extend QCM detection from single mass readout to intelligent multiparametric inversion and to provide a methodological basis for *in vitro* multiproperty detection of magnetically labeled molecules.

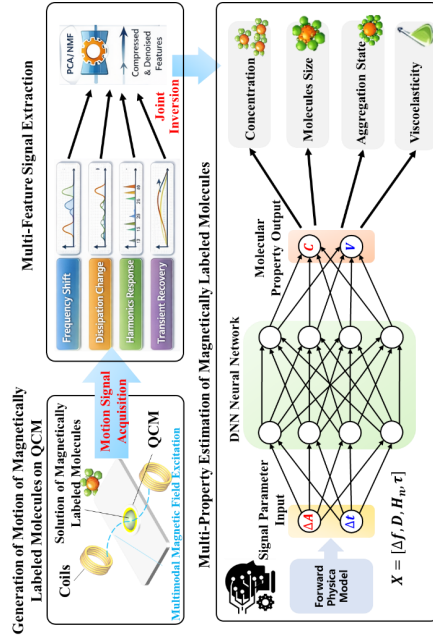


Figure 1. Schematic illustration of the intelligent multiparametric QCM detection method for magnetically labeled molecules.

Starch Makes The Difference: Surface-Engineered Magnetite Nanoparticles For Improved Magnetite Hyperthermia Effect

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Polysaccharide-modified magnetite nanoparticles have attracted increasing attention due to their potential in targeted and controlled drug delivery, as well as their applicability in magnetic hyperthermia-based therapies. Surface functionalization plays a crucial role in determining their performance, with organic modifiers such as polysaccharides (e.g., dextran, starch) significantly enhancing biocompatibility, colloidal stability, and the ability to conjugate therapeutic agents. These biopolymeric coatings create a protective and biocompatible interface, reducing toxicity and immune recognition while enabling prolonged circulation and selective accumulation in target tissues. Importantly, surface modification is also a key factor in optimizing the magnetic hyperthermia effect. The presence of a polysaccharide layer can prevent nanoparticle aggregation, ensuring better dispersion and more efficient heat generation under an alternating magnetic field. Additionally, controlled surface chemistry influences magnetic interactions, relaxation mechanisms, and heat dissipation efficiency, all of which are critical parameters for achieving effective hyperthermia performance.

In this study, we synthesized magnetite-based materials modified with wheat starch via a high-temperature decomposition method. Furthermore, the particle surfaces were functionalized with selected organic acids. The research investigates the influence of both synthesis conditions and surface functionalization on the physicochemical properties and magnetic hyperthermia effect of the obtained materials. Structural characterization was performed using X-ray diffraction (XRD) to determine phase composition and crystallite size. Morphological features were examined in detail using transmission electron microscopy (TEM). The proportion of the polysaccharide coating was quantified by thermogravimetric analysis (TGA). Additionally, the magnetic hyperthermia efficiency of the polysaccharide-modified magnetite nanoparticles was evaluated and compared with that of unfunctionalized magnetite.

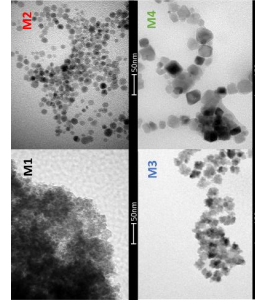


Figure 1. Examples of TEM micrographs illustrating significant differences in nanoparticle size and morphology depending on synthesis conditions. Samples M1 and M2 correspond to nanoparticles synthesized in triethylene glycol, whereas M3 and M4 were obtained using benzyl ether as the reaction medium. In addition, starch functionalization was introduced at different stages of synthesis: for M1 and M3, starch was added at the onset of the reaction, while for M2 and M4 it was introduced after the stage of nanoparticle crystallization.

Acknowledgements: Research was carried out as a part of the "Implementation Doctorate" program of the Ministry of Education and Science in Poland project No. DWD/7/0232/2023.

Cytotoxicity and MRI Relaxometry of Iron Oxide Nanoflowers in Neuronal Cells

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Magnetic nanomaterials, especially iron oxide nanoparticles (IONPs), have attracted considerable interest for biomedical applications, especially as contrast agents in magnetic resonance imaging (MRI). Their superparamagnetic properties allow them to strongly influence the relaxation of surrounding hydrogen nuclei, enhancing MRI contrast (1). Surface modifications further improve nanoparticle stability, biocompatibility, and interactions with cells (2).

Among the various morphological forms of iron oxide nanostructures, iron oxide nanoflowers (IONFs) have recently attracted particular interest. These multi-core nanoparticles are composed of clustered nanocrystals, enabling enhanced magnetic coupling. This results in higher magnetic moments and improved relaxometric properties compared to single-core IONPs, supporting their use in advanced MRI and theranostic applications.

In our study, we evaluated the cytotoxicity and MRI relaxometric properties of two types of IONFs (bare and poly-L-lysine-functionalized, PLL-IONFs), with a focus on neuronal cells *in vitro*. Cytotoxicity was assessed in SH-SY5Y human neuroblastoma cells using flow cytometry after exposure to various iron oxide concentrations present in IONFs, allowing the identification of safe ranges for biological applications. Relaxometric properties were measured as longitudinal (T₁) and transverse (T₂) relaxation times at a 7 T magnetic field for both aqueous nanoparticle dispersions and cells incubated with nanoparticles.

The results showed that IONFs significantly affected hydrogen relaxation, particularly by shortening T₂ relaxation times, indicating their potential as negative contrast agents. Measurable differences were observed between aqueous suspensions and nanoparticle-treated cells, suggesting that cellular internalization and microenvironment influence relaxometric behavior. Cytotoxicity remained low across the tested concentrations, with no pronounced decrease in cell viability (Figure a,b), supporting their biocompatibility.

Overall, our findings demonstrate that IONFs combine enhanced relaxometric performance with acceptable cytotoxicity, highlighting their potential for future biomedical theranostic applications. Surface functionalization (e.g., poly-L-lysine) may offer additional advantages for cellular interactions, particularly in MRI contrast enhancement and for cell tracking.

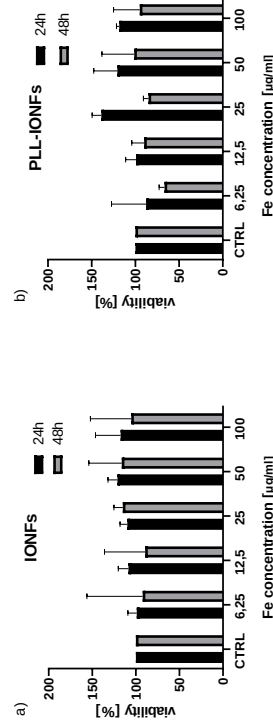


Figure (a,b): The graphs show the relative viability of SH-SY5Y cells after 24 and 48 hours of exposure to IONFs and PLL-IONFs.

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SPIO nanoparticles as promising drug carriers for neurodegenerative disease treatment

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Millions of people worldwide are living with dementia, with Alzheimer disease (AD) being the prevalent cause. Current medications only being able to slow down progression of disease and suppress its effects. Memantine, as one of certified medicaments for (AD) treatment, blocks human body glutamate receptors, reducing their activity. However, systemic administration of such drugs can lead to unwanted side effects. Employing nanoparticles as drug targeting delivery vehicles can significantly reduce such effects, enabling the controlled release of their cargo, in this case through blood brain barrier (BBB) to the human brain, without being spread through the whole body, or it can be continuously released into the blood stream in smaller doses for long term effect. Superparamagnetic iron oxide nanoparticles (SPIONs) are great candidates for this purpose due to their appropriate size for BBB crossing, high MRI contrast properties and high biocompatibility. In this study, SPIONs were prepared through soft biomineralization process in the presence of alginate acid (a natural polysaccharide from brown algae). Produced NPs were used in preparation of 2 types of complexes with memantine and an experimental N-methyl-D-aspartate receptor (NMDAR) K1395, where drugs were covalently conjugated to nanoparticles. The loaded drug content was quantified by HPLC. Memantine drug loading reached 28.6%, while K1395 was 12%. Drug release studies performed in water and blood plasma showed that complexes' drug release is adequate for practical use with release in plasma medium being multiple times higher, as its components help to break the NPs-drug covalent bonds. In vitro toxicity of complexes was measured, demonstrating that there is no decrease in viability of human cells after 24h incubation with nanoparticles and conjugating drugs to the nanoparticles decreases their overall cytotoxicity. In conclusion, 2 types of drugs were covalently conjugated to prepared SPION nanoparticles and their loading/release capabilities evaluated. These SPION/drug complexes appear as promising candidates for specific targeting of neuronal cells which will be further studied by using in vitro neurochemical methods and on BBB cellular models.

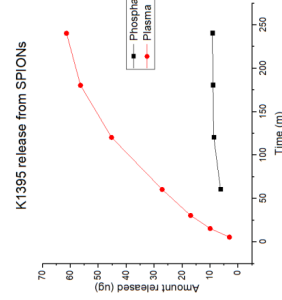


Figure: Representation of K1395 release in different environments. For both media release 1 mg of drug loaded SPIONs, was placed in dialysis membrane with 12.6 kDa MW cut-off. Release temperature was kept at 37°C. After each time point samples were immediately measured via HPLC.

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Investigation of dynamic hysteresis in Hard-Soft binary ferrofluids: dimers and short chains

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Magnetic Fluid Hyperthermia (MFH), i.e., the release of heat by magnetic nanoparticles (10–30 nm) dispersed in a solvent (typically water) when subjected to AC magnetic fields (moderate amplitude: 10–20 mT, frequency range: 100–1000 kHz), is strongly dependent on the Magnetic Anisotropy Energy (MAE) of the particles (governed by their size D and the material's anisotropy constant K), as well as on the intensity of their Dipolar Interactions (DI). For sufficiently large particle sizes, even at low concentrations, these nanoparticles can form linear clusters (dimers and short chains), leading to an enhancement of the heat released through the dynamical hysteresis process [1].

In this work, we report on numerical investigations of the stochastic Landau-Lifshitz-Gilbert (sLLG) equation applied to dipolarly coupled magnetically hard and soft nanoparticles (dimers and short chains). We consider uniaxial anisotropy, dipolar interactions, and an AC magnetic field in the frequency range of 100 kHz–500 kHz. Our simulations focus on the hysteresis loops of these clusters, composed of mixed hard and soft particles (using $K_S = 10 \text{ kJ/m}^3$ and $K_H = 100 \text{ kJ/m}^3$) resolving both the average and internal (per particle) hysteresis loops of the chain/dimer at 3K and 300K and for aligned or randomly orientated easy axes. Our results reveal deformed hysteresis loops, consistent with recent experimental and numerical findings on binary ferrofluids reported [2].

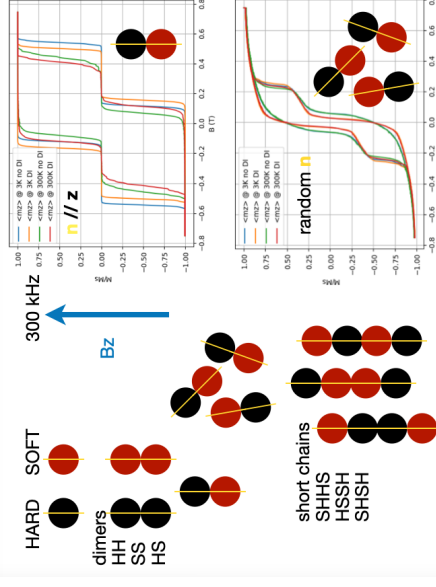


Figure: hard/soft dimers and short chains - example of simulated dynamic hysteresis cycles at 300 kHz of hard/soft dimers for aligned (along z) and randomly oriented anisotropy axes at 3 K and 300K (diameter D = 20 nm).

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Stiffness-Dependent Magnetic Responses in MNP-Loaded 3D-Printed Hydrogels

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Magnetic nanoparticle (MNP)-loaded hydrogels have emerged as promising materials for remotely actuated biomedical scaffolds, enabling a range of functionalities such as actuation, hyperthermia, and imaging/sensing under external magnetic fields [1–3]. However, the role of hydrogel stiffness in governing these magnetically induced responses has not yet been systematically investigated.

Here, we demonstrate that the magnetic behavior of 3D-printed hydrogels, including field-driven actuation and Magnetic Particle Spectrometry (MPS) signal generation, is strongly dependent on the stiffness of the hydrogel network (as schematically illustrated in Figure 1). To investigate this relationship, scaffolds with tunable stiffness in the range of 10–70 kPa were fabricated from Gelatin methacryloyl (GelMA)-based hydrogel inks loaded with superparamagnetic iron oxide nanoparticles (SPIONs) and classified into low-, medium-, and high-stiffness groups. The effect of stiffness was then systematically evaluated across these groups [4].

These findings highlight the decisive role of hydrogel stiffness in modulating the magnetic behavior of MNP-loaded hydrogel systems. This study provides a framework for understanding the interplay between mechanical properties and magnetic performance, supporting the design of magnetically actuated hydrogel scaffolds for future biomedical applications.

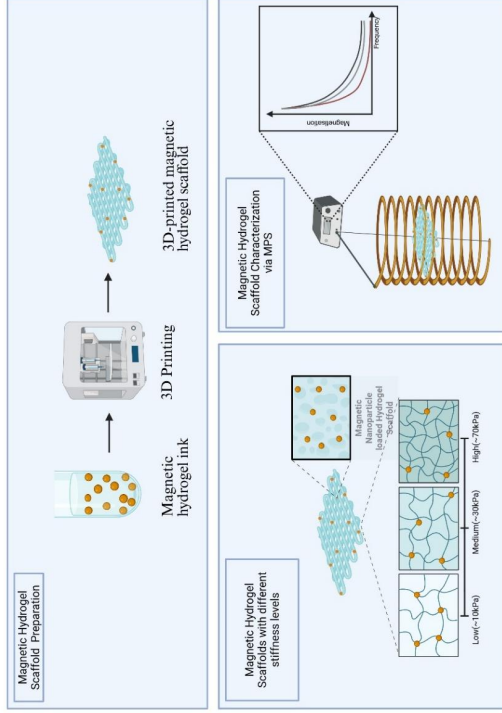


Figure 1: Experimental workflow illustrating preparation of MNP-loaded hydrogel inks, extrusion-based 3D printing of scaffolds with varying stiffness, and evaluation of stiffness-dependent magnetic responses using Magnetic Particle Spectrometry (MPS) and actuation measurements.

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In-silico Investigation of Interacting Magnetic Nanoparticle Response in Physiological Environments Using Single- and Dual Frequency MPS

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Magnetic nanoparticles (MNPs) are pivotal in biomedical applications such as imaging, hyperthermia, and biosensing due to their relaxation dynamics under alternating magnetic fields (AMF). In vivo, MNPs are injected into the bloodstream and gradually internalized inside cells and tissue, where confinement increases effective viscosity due to immobilization and simultaneously decreases interparticle distances due to agglomeration, both effects altering the magnetic relaxation response of MNP. Magnetic particle spectroscopy (MPS) characterizes MNP relaxation changes in such environments via harmonic spectra. Frequency-mixing MPS (FM-MPS) adds a second AMF frequency, extending harmonic spectra via mixing-frequency terms.

Using stochastic Neel-Brownian coupled relaxation dynamics simulations we predicted the magnetic response of magnetic MNP ($M_s = 476 \text{ kAm}^{-1}$, $K_D = 11 \text{ kJ} \cdot \text{m}^{-3}$, $T = 310 \text{ K}$) to a single-frequency AMF excitation ($H_{ac} = 20 \text{ mT}\mu_0^{-1}$, $f = 25 \text{ kHz}$), and dual-frequency AMF excitation with a low-frequency driving field ($H_L = 1 \dots 20 \text{ mT}\mu_0^{-1}$, $f_L = 63 \text{ Hz}$) and a high-frequency excitation field ($H_H = 1.25 \text{ mT}\mu_0^{-1}$, $f_H = 40.5 \text{ kHz}$). We simulated dynamic M(H) curves for core sizes $d_c = (16, 20, 24, 28) \text{ nm}$ with log-normal distribution width $\sigma = 0.05$, and hydrodynamic size $d_H = d_c + 100 \text{ nm}$. To assess confinement effects on (FM-)MPS signal generation, we modelled gradual immobilization by varying the effective viscosity $\eta = (0.89, 5, 20, 500, 5000) \text{ mPa} \cdot \text{s}$, and average interparticle distances $r_{avg} = (d_c, d_H, 2d_H, 3d_H, 4d_H) \text{ nm}$ to control magnetic particle-particle interaction (pp/AA) upon gradual agglomeration from spaced MNP to touching cores ($r_{avg} = d_c$)

Figure 1 shows for MPS and FM-MPS signal intensity normalized to the iron concentration, revealing strongest signal for mid-sized MNP (16–20 nm). A strong signal-suppressing effect from pp/AA at smaller interparticle distance ($r_{avg} \leq d_H \leq 100 \text{ nm}$) is seen. The onset of this effect begins at larger interparticle distances ($r_{avg} < 2d_H = 200 \text{ nm}$) for larger core sizes ($d_c \geq 24 \text{ nm}$) which is captured specifically by FM-MPS. In contrast, viscosity has only marginal effects. These preliminary results could provide guidance for AMF-instrumentation as well as tailored MNP design aiming to maximize signal generation in complex biological environments.

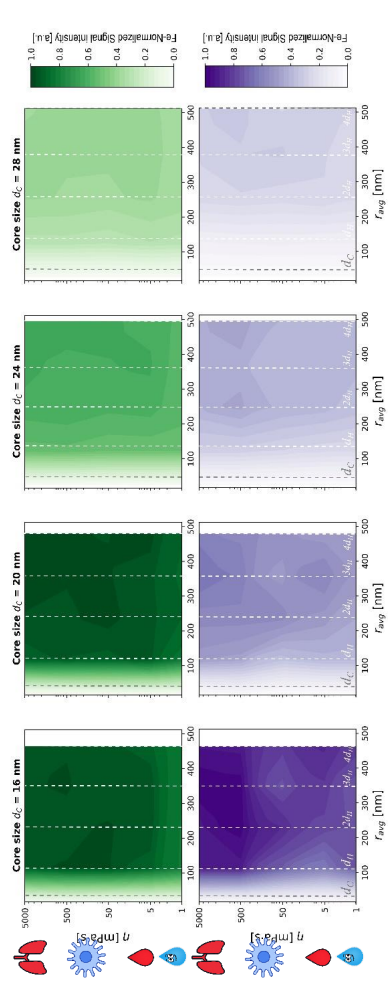


Figure 1: Contour plots showing viscosity, and average interparticle distance effects on Fe-normalized 3rd harmonic signal intensity (MPS, green) and Fe-normalized $f_L + 2f_H$ signal intensity (FM-MPS, purple). The dashed lines mark the simulated interparticle distances r_{avg} .

Encapsulation of a poorly water-soluble anti-cancer drug in ultra-magnetic liposomes for its controlled and locoregional release

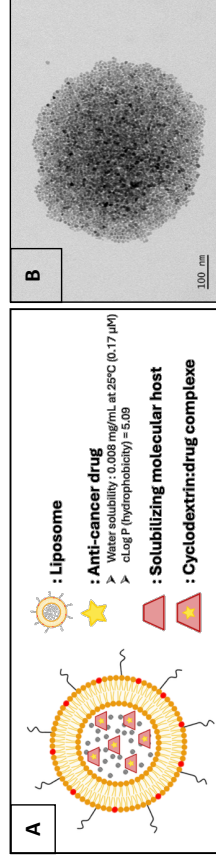
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Colorectal cancer remains the second deadliest cancer worldwide due to treatment resistance and metastatic progression.¹ While new drug delivery strategies are crucial for poorly water-soluble molecules, the encapsulation of hydrophobic drugs within the aqueous core of liposomes remains a challenge. In this work, we propose a novel approach combining cyclodextrin (CD) complexation and remote loading to enable locoregional accumulation and ultrasound-triggered delivery, thanks to the production of ultra-magnetic liposomes (UML). In preliminary studies, the locoregional accumulation of magnetic liposomes in colon² and in tumors was validated by magnetic targeting.^{3,4}

To increase the solubility of the drug and to allow its encapsulation in the aqueous core of the magnetic liposomes, CD:Drug complexes were prepared by a co-evaporation method⁵, and two encapsulation strategies were tested: direct and remote loading. SBE- β -CD significantly improves drug solubility by 47-fold at a 1:5 ratio, compared to the drug alone. While standard direct loading methods result in poor encapsulation yields ($\leq 3\%$), our optimized remote loading strategy using SBE- β -CD multiplies the encapsulation yield by 3 ($9.0 \pm 0.5\%$). Regarding drug delivery, High focused ultrasound (HIFU)-triggered heating of thermosensitive magnetic liposomes was evaluated and compared to a passive release. A 5-minute sequence at 42°C doubles drug release compared to passive diffusion exposure. These results highlight the potential of this strategy for future *in vivo* applications.



(A) Schematic of thermosensitive magnetic liposomes encapsulating CD:Drug complexes; (B) TEM picture of a magnetic liposome after encapsulation of CD:Drug

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Shape-Dependent Magnetic Properties of CoFe₂O₄ Nanoparticles for MRI Applications

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Magnetic resonance imaging (MRI) is one of the most powerful non-invasive diagnostic techniques used in modern medicine. In recent years, magnetic nanoparticles have attracted significant attention as potential contrast agents due to their unique magnetic properties, biocompatibility, and the possibility to tailor their structural parameters. Among them, spinel ferrite nanoparticles, such as cobalt ferrite (CoFe₂O₄), represent a promising class of nanosystems for MRI applications, as their magnetic behaviour can strongly influence the relaxation processes of surrounding water protons.

In this work, CoFe₂O₄ nanosystems with three different morphological modifications (spherical, cubic, and octopod-like shapes) were prepared in order to investigate the effect of particle shape on their structural and magnetic properties. The nanoparticles were synthesized using a thermal decomposition approach, allowing precise control over their size and morphology. Structural characterization confirmed the formation of crystalline cobalt ferrite nanoparticles with well-defined shapes and narrow size distributions.

The magnetic properties of the prepared nanosystems were studied using magnetometry techniques, revealing typical superparamagnetic or near-superparamagnetic behaviour at room temperature and pronounced shape-dependent magnetic responses. Differences in magnetic parameters were observed among the individual morphological modifications, indicating that particle shape, surface effects, and shape-induced anisotropy significantly influence the overall magnetic behaviour.

Furthermore, the influence of nanoparticle morphology on MRI performance was investigated. Using MRI parametric mapping, performed by a 7 T BioSpec Bruker system at three different protocols (T1, T2 and T2*), the effect of particle shape on relaxivity was studied. The results indicate that nanoparticle shape and the associated shape anisotropy play an important role in determining their MRI contrast efficiency.

These findings highlight the importance of controlling nanoparticle morphology when designing magnetic nanosystems for biomedical imaging applications.

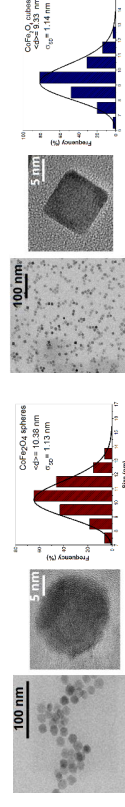


Figure 1. TEM micrograph of CoFe₂O₄ nanoparticles with spherical (A) and cubic (B)

Acknowledgements

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Optimizing Magnetic Hyperthermia Performance under Safety Limits

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Magnetic hyperthermia uses magnetic nanoparticles (NPs) to convert energy from an alternating magnetic field into heat for cancer therapy. Despite early clinical success, its broader adoption has been limited by biocompatibility issues [1], delivery challenges, and incomplete physical models. Heating efficiency is quantified by the specific loss power (SLP), which depends critically on magnetic anisotropy [2]. Anisotropy governs both the maximum dissipated energy and the field threshold for significant losses. In much of the MH literature, experimental data are interpreted using an effective uniaxial anisotropy, often linked to particle aspect ratio and assumed to be dominated by shape anisotropy. This simplification typically neglects the intrinsic magnetocrystalline contribution, which for magnetite is cubic and negative. Most interpretations assume an effective uniaxial anisotropy dominated by particle shape, neglecting the intrinsic magnetocrystalline term. While this simplification works at large fields, it fails under physiological conditions where the Brezovich criterion restricts $H_{\max}$ to a few mT. Using controlled computational modelling of magnetite macroparticles, we assess how intrinsic cubic anisotropy, small departures from spherical shape (incorporated as an additional uniaxial shape term, see Fig.1), and dipolar interactions jointly determine SLP under these physiologically relevant field conditions. Our results show that even slight deviations from spherical shape can significantly influence the heating efficiency of NPs. We identify specific NP size ranges and aspect ratios that optimize heat delivery, constrained by the field amplitude and different frequency safety limits required for clinical application [3,4] (see Fig. 1). Dipolar interactions significantly reduce heating in disordered clusters, underscoring the need for strategies that minimize aggregation. Work supported by Spanish MINECO (PID2024-157172NB-I00, RYC2020-029822-I and CNS2024-154574. We thank CESGA for computing support.

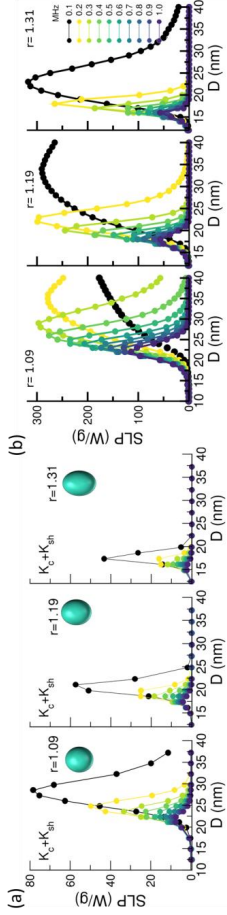


Fig. 1: Size-dependence of the SLP of ellipsoidal particles of aspect ratios $r = 1.09, 1.19, 1.31$ with uniaxial shape anisotropy added to the cubic one for different frequencies and maximum AC fields accomplishing: (a) the Brezovich criterion $H_{\max} f = 4.85 \times 10^8 \text{ A/m.s}$, (b) the Thiesen criterion $H_{\max} f = 1.8 \times 10^9 \text{ A/m.s}$

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Insights into internal magnetic structure of iron oxide nanoparticles: a combined small-angle neutron scattering and magnetometry study

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This work continues our previous studies on spherical iron oxide nanoparticles [1] to systematically investigate the magnetic structure of the nanoparticles in a broad range of particle sizes (nominal iron oxide core diameter 5, 10, 12, 15 and 20 nm). The parameters of the core-shell structure (iron oxide core, oleic acid shell) were determined using small-angle neutron and X-ray scattering. A non-magnetic layer at the nanoparticle surface was determined using small-angle scattering with polarized neutrons at saturating fields. Room temperature hysteresis data was obtained using vibrating sample magnetometry and the $M(H)$ curves were inverted to obtain the magnetic moment distribution within the nanoparticle systems.

The detailed magnetic structure of the nanoparticles is obtained by analyzing the results of the non-magnetic layer and the distribution of the size and magnetic moment. The results suggest that a particle size of 15 nm is optimal.

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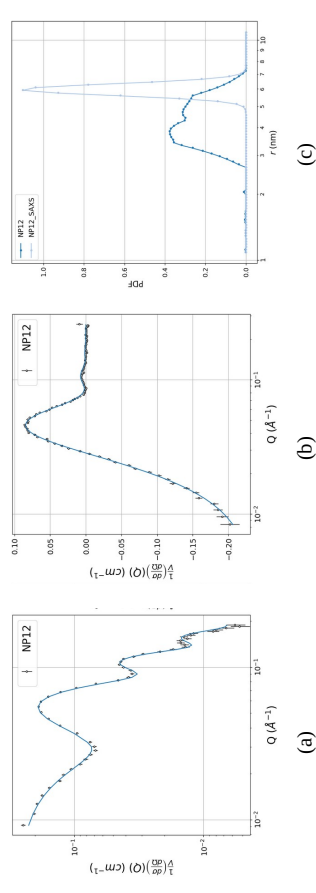


Figure. Exemplary results for 12 nm particles: (a) core-shell fit to determine oleic acid shell thickness, (b) fit of the nuclear-magnetic interference to determine non-magnetic shell thickness and (c) comparison of the size distribution obtained from small-angle X-ray scattering and from the inversion of $M(H)$ hysteresis curve inferring about a reduction of the overall particle magnetic moment.

Magnetic hyperthermia in focus: emerging non-cancer applications of magnetic nanoparticles

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We have recently prepared a review work highlighting emerging applications of magnetic hyperthermia (MH) beyond its traditional use for cancer therapy (Fig. 1) [1]. In this context, MH is rapidly emerging as a versatile tool at the interface of nanotechnology, biomedicine and sustainable chemistry.

The work is divided in two parts. The first one, encompasses biomedical applications in which magnetically induced local heating can enable functionalities such as on-demand drug release, pathogen eradication, tissue cryopreservation, manipulation of cellular membranes and signaling pathways, nanorobotics or sensing technologies among others. The second part focuses on non-biomedical applications such as magnetically assisted catalysis (e.g. hydrogen production), environmental remediation (including water treatments, soil remediation and air pollution control), or material transformations such as self-healing polymers, cementation and oil mobilization.

These diverse applications rely on tailoring both the magnetic nanomaterials and the operating field conditions. Biomedical approaches typically employ biocompatible iron oxide nanoparticles under clinically safe alternating magnetic field regimes, whereas non-biological applications open the door to a broader materials palette and more extreme excitation conditions.

Taken together, these developments reveal MH as a powerful platform technology for remote, localized energy delivery at the nanoscale, opening great opportunities for the research community working on magnetic nanoparticles.

Ref. [1] H. Gavilán and A. Gallo-Cordova, et. al. Magnetic hyperthermia in focus: emerging non-cancer applications of magnetic nanoparticles *Nanoscale*, 2025,17, 27734-27761

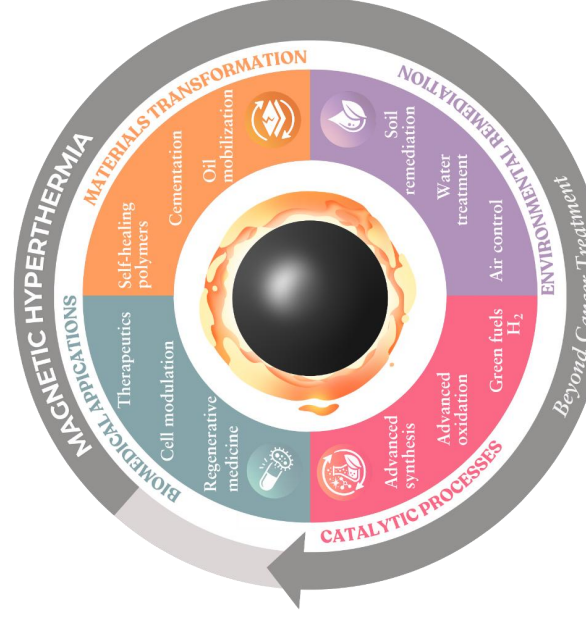


Fig. 1 Emerging non-cancer applications of magnetic nanoparticles. The second part focuses on non-biomedical applications (e.g. hydrogen production), environmental remediation (including water treatments, soil remediation and air pollution control), or material transformations such as self-healing polymers, cementation and oil mobilization.

Engineering HER2-targeted magnetosomes displaying immunotherapeutic proteins to enhance radiotherapy efficacy in solid tumors

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The development of more selective and less toxic therapeutic strategies remains a major challenge in the treatment of solid tumors. In this context, nanoparticle-based approaches are gaining increasing attention due to their potential for targeted delivery and multifunctionality. Among these, magnetosomes—magnetic nanoparticles biosynthesized by magnetotactic bacteria—represent a promising and versatile platform for cancer therapy [1].

In this study, we engineered magnetosomes through genetic modification of magnetotactic bacteria to display DARPin proteins on their membrane. These proteins were designed to confer a dual functionality: (i) specific binding to HER2, a receptor overexpressed in several cancer types, and (ii) immunotherapeutic activity. We demonstrate that these engineered magnetosomes exhibit enhanced specificity toward HER2-positive cancer cells compared to HER2-negative counterparts. Quantitative cellular uptake analyses revealed significantly increased internalization of functionalized magnetosomes relative to wild-type controls, confirming the contribution of DARPin-mediated targeting.

Ongoing *in vitro* studies are investigating the potential of these HER2-targeted magnetosomes to enhance radiotherapy efficacy. We hypothesize that the combination of selective cellular internalization and intrinsic immunotherapeutic properties will potentiate radiation-induced cytotoxicity specifically in HER2-overexpressing tumor cells, while minimizing off-target effects [2].

Overall, our findings highlight the potential of genetically engineered magnetosomes as a novel theranostic platform, combining targeted delivery, immunomodulation, and radiosensitization for improved treatment of HER2-positive solid tumors.

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Photothermal and phototherapeutic effects induced by gold/iron oxide nanoparticles to facilitate the penetration of anticancer agents

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One of the primary limitations to chemotherapy efficacy in cancer treatment is the extremely dense tumor microenvironment, which significantly limits drug penetration and activity (1). In this study, we aim to enhance the therapeutic effectiveness of an anti-cancer agent, Gemcitabine, by combining chemotherapy with phototherapy. This technique uses hybrid nanoparticles activated by near-infrared (NIR) irradiation to locally induce mild hyperthermia (temperature increase lower than 10°C). Hybrid nanoparticles were created by combining gold nanoparticles with superparamagnetic iron oxide nanoparticles (SPION). This design enables a dual phototherapeutic strategy: photothermal therapy (PTT) and photodynamic therapy (PDT) (Figure 1). Particularly, under NIR irradiation, gold nanoparticles convert light into heat, increasing the local temperature within the tumor microenvironment and thereby disrupting the tumor tissue and selectively destroying cancer cells (2). Besides, both nanoparticles have the ability to generate reactive oxygen species (ROS), creating a cytotoxic microenvironment that induces cancer cell death and contributes to photodynamic therapy (3). (4). Initial photothermal evaluation showed that hybrid nanoparticles composed of gold nanostars (GNS) and SPION (GNS@SPION) increased the temperature by approximately 2.0–9.3°C after 30 minutes of NIR laser irradiation. Besides, treatment of HT29 colorectal cancer spheroids with GNS@SPION showed slightly higher levels of superoxide anion, which is a type of ROS, compared with GNS alone. Nevertheless, this conclusion still needs to be confirmed by evaluating the generation of different types of ROS in the pancreatic cancer model currently under study.

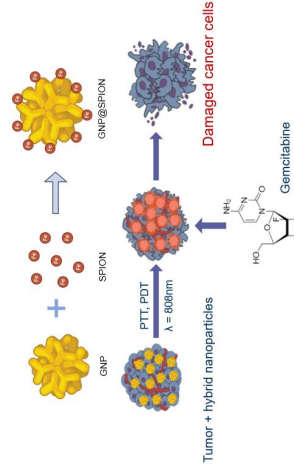


Figure 1. Principle of the PTT/PDT strategy using gold/SPION hybrid nanoparticles.

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Magnetic field-responsive bioMOF drug delivery nanocomposite based on Bi(III)-ellagate SU-101

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Bio-derived metal–organic frameworks (bioMOFs) have attracted interest as functional materials for medical-related applications due to their biocompatibility and structural tunability. However, the integration of external stimulus responsiveness into bioMOF architectures while preserving framework integrity remains a significant challenge.

Herein, we designed and characterized magneto-responsive nanocomposites based on the microporous Bi(III)-ellagate bioMOF SU-101 incorporating ultrasmall magnetic nanoparticles. We demonstrate the successful integration of magnetic nanoparticles and the loading of a fluorescent cargo within the MOF matrix without compromising its structural integrity. The resulting magnetic nanocomposites exhibit excellent structural stability under ambient storage conditions for at least 18 months. The nanocomposites internalized in cells and accumulated within the lysosomal compartments. Moreover, the magnetic nanocomposites exhibit a well-defined magnetic response under high frequency alternating (AMF) and low frequency rotating (RMF) magnetic fields that enable remote modulation of thermal and mechanical effects, leading to significant cargo release and a marked reduction in cancer cell viability. Moreover, magnetic resonance imaging (MRI) relaxivity measurements confirm the potential of these nanocomposites as magnetic resonance contrast agents.

Overall, these results highlight the strong potential of magnetically responsive bioMOF SU-101-based nanocomposites as multifunctional platforms for biomedical applications.

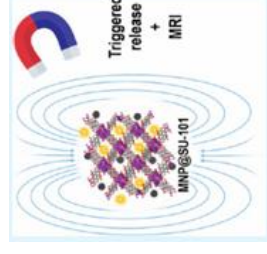


Figure 1. Schematic representation of MNP@SU-101 bioMOF nanocomposite for drug delivery and MRI applications.

Low Frequency Inductive Sensing of Magnetic Microrobots

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A primary challenge in deploying magnetic microrobots for biomedical applications is obtaining real-time feedback on their position, distribution, and state. For real-time feedback in deep physiological environments, existing approaches typically combine magnetic manipulation with distinct imaging modalities such as x-ray fluoroscopy or ultrasound. Others instead make use of magnetic fields for both sensing and actuation, usually by leveraging existing instrumentation designed for magnetic particle imaging or magnetic resonance imaging and toggling between an imaging mode and a control mode. While these approaches are promising, an ideal solution would provide uninterrupted, simultaneous feedback using compact hardware that could be added to instrumentation optimized for magnetic manipulation.

In this work, we present progress toward simultaneous actuation and inductive sensing of magnetic microrobots with rotating magnetic fields (RMFs) in the frequency range of Hz to 10s of Hz. Through careful design of low frequency gradiometer coils, we can sense micro- and milli- robots via voltages induced by their magnetic moments, while canceling out the inductive contribution of the driving field.¹ The resulting signals can reveal their position and assess torque transfer from an applied RMF without interrupting actuation. The technique shows promise for detecting both magnetically responsive diffuse agents and individual micromagnets.¹⁻² Here, we highlight recent experiments demonstrating: 1) Inductive sensing of spatially selective torque delivery by combining a magnetostatic field free point with an RMF (Fig A); 2) The use of inductive signals for closed loop control of a swimming microrobot along a 1D path, and 3) A gradiometer design incorporated as post-market addition to a commercial 8-axis electromagnet (Fig B).

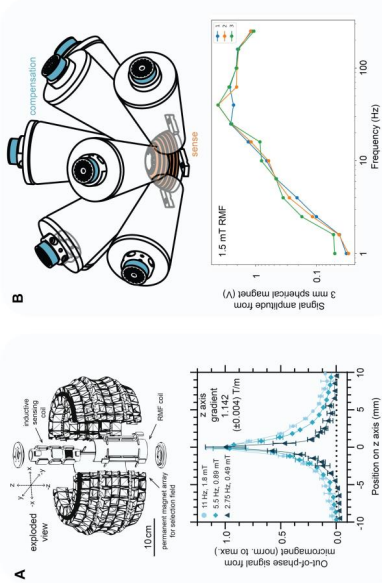


Figure. (A). Inductive sensing in an RMF is combined with a selection field generated by a partial magic sphere. Below, inductive signals are shown for a cylindrical micromagnet of diameter 300 μm and length 500 μm . The spatial resolution of torque transfer within of the field-free point depends on the ratio of the magnitudes of the RMF and the selection field. Adapted from Ref. [2]. (B) Sketch of gradiometer design for isolating signal from the workspace of a commercial 8-axis electromagnet (Magnetoix MFG-100). The hemispherical sense coil surrounds the workspace and the 8 compensation coils produce signals balanced to cancel signals from the driving field for each independent current. Plot shows signal magnitude isolated from the workspace for a frequency sweep revealing stepout behavior for a 3 mm spherical magnet in glycerol with a 1.5 mT RMF.

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Magnetic Nanoflower-Mediated Hyperthermia Activates Concurrent Apoptosis and Ferroptosis on Prostate PC3 and Melanoma DX3 cells

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Magnetic hyperthermia therapy (MHT) has many potentials in cancer therapy due to its controllable heating, precise position, and biocompatibility, however, its underlying mechanisms of damaging cancer cells are still not fully understood. Herein, we employed magnetic nanoflowers (NFs) as a high-performance heating agent under an alternating magnetic field (AMF) to investigate the cytotoxic mechanisms of MHT on prostate cancer PC3 and melanoma DX3 cells. Cytotoxicity assays (CCK-8, trypan blue, and clonogenic assay) were conducted to confirm viability loss in both cell lines. Flow cytometry for reactive oxygen species (ROS), Fe²⁺, and apoptosis detection, combined with glutathione (GSH) and lipid peroxidation assays, suggested that MHT can concurrently induce hallmarks of apoptosis and ferroptosis. Confocal microscopy visualized apoptotic progression, mitochondrial depolarization, and lysosomal involvement. Western blotting (WB) further identified altered expression of key apoptotic markers (Caspase-3/7, Bax/Bcl-2) and ferroptosis regulators (FSP1, GPX4), confirming a mixed apoptotic-ferroptotic signal triggered by MHT. These mechanistic findings were also validated in 3D spheroid tumor models. Moreover, heat generation studies in cells, test tubes, and chicken breast demonstrated NF's efficient and tunable thermal output. Additionally, heat mapping at the cellular level provided spatial-temporal profiles of intracellular temperature gradients, offering a novel framework for evaluating nanoscale thermal dissipation in MHT. Collectively, this work advances understanding of the MHT mechanism and elucidates the therapeutic potential of NFs in inducing coordinated tumor cell death.

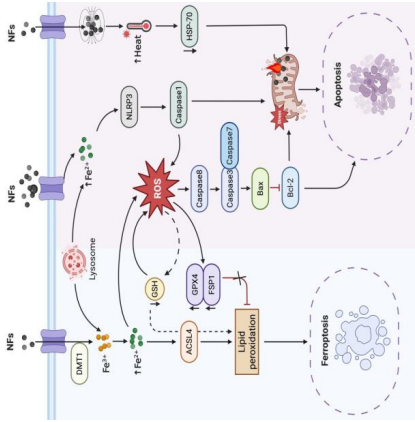


Figure 1. Schematic illustration of proposed molecular events in both apoptosis and ferroptosis pathways triggered by NFs-mediated MHT.

Hydrogel-Based MPS-Sensor for the Visualization of Microenvironmental Changes and Identification of Pathological Conditions

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Magnetic particle spectroscopy (MPS) is a powerful technique to probe the dynamic magnetic response of superparamagnetic tracers such as small iron oxide nanoparticles. As their mobility, confinement, and local interactions govern the magnetic response, MPS provides a sensitive platform for investigating and monitoring microenvironmental changes in biological media non-invasively. When embedded in responsive hydrogels, sensing elements can be designed that bridge specific pathological changes towards magnetic readouts. Specifically, tuning the polymer matrices, e.g. pore size, molecular composition, and network architecture enables precise control over the tracer's mobility changes and allows the tailoring of these sensors towards clinically relevant conditions.

In this work, we demonstrate the utilization of hydrogel-based MPS sensors for the detection of atypical enzyme and pH levels as proxies for pathological conditions such as inflammation or pancreatitis. Iron oxide nanoparticles were incorporated into responsive hydrogel matrices, which undergo network degradation through cleavage of specific molecular sites, or alter their degree of protonation, leading to shifted osmotic conditions. Through this, the MPS signals encode physicochemical changes and prove the feasibility of such sensors in a preclinical setting. Further, one-dimensional assemblies of superparamagnetic iron oxide nanoparticles were prepared to serve as a next-generation magnetic tracer material. Rooted in their collective magnetic behavior, these structures demonstrated improved magnetic properties compared with those of individual nanoparticles in both vibrating sample magnetometry (VSM) and MPS. Their increased magnetic susceptibility in VSM was reflected by enhanced signal characteristics in MPS, allowing for higher signal output and sensing performance when employed as tracers in hydrogel matrices. Together, these findings highlight the potential of hydrogel-based magnetic sensor platforms and advanced nanoparticle assemblies for sensitive detection of microenvironmental changes and pathological conditions.

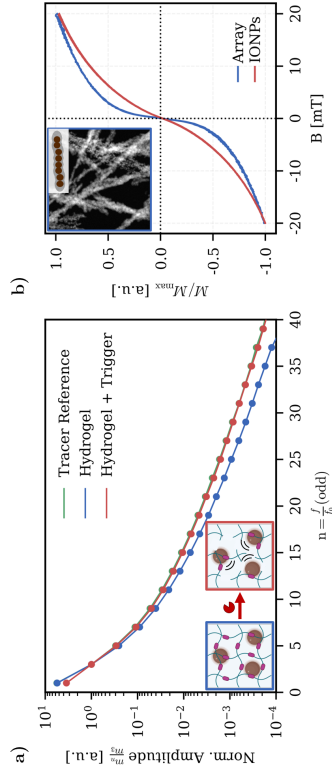


Figure 1: a) MPS signals obtained from three different sample systems: nanoparticles immobilized in a hydrogel, nanoparticles in a hydrogel after addition of an external trigger component, and free nanoparticles in solution. b) VSM response of individual nanoparticles in aqueous solution and one-dimensional nanoparticle arrays. The nanoparticle arrays exhibit higher magnetic susceptibility than the individual nanoparticles. Their morphology is shown in the inset as a scanning transmission electron microscopy image.

UV-Vis spectroscopy of turbid dispersions containing magnetic nanoparticles and drugs

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Ultraviolet-visible (UV-Vis) spectroscopy is a widely used tool in biomedical research for identifying biomolecules, monitoring drug loading and release, and determining analyte concentrations. In optically clear solutions, simple background correction is typically sufficient for quantitative readout. However, in multicomponent systems that exhibit turbidity, this approach becomes questionable. Particularly, for strongly scattering and turbid colloidal nanoparticle dispersions straightforward background subtraction to remove the nanoparticle contribution often fails. Although this limitation is generally recognized, its practical impact on detection limits in realistic systems remains poorly quantified.

Here, we investigated the effects of magnetic nanoparticle (MNP) hydrodynamic size and concentration on UV-Vis spectral saturation and the detectability of co-dissolved analytes. We used two commercial and one in-house synthesized iron oxide MNPs with different hydrodynamic diameters (24, 30, and 70 nm) in the presence of the drugs metronidazole and riboflavin. Two experimental series were conducted: (i) at fixed drug concentration, the iron concentration was varied from 10 to 250 $\mu\text{g mL}^{-1}$ to determine up to which turbidity level the drug remained detectable; and (ii) at fixed iron concentration, the drug amount was varied from 200 pmol to 4 mmol in 130 μL sample volumes ($\sim 1.5\text{--}30\ \mu\text{M}$) to determine the limit of detection in the presence of the MNP.

At high MNP concentrations ($\geq 150\ \mu\text{g mL}^{-1}$), the UV-Vis spectra exhibit a pronounced saturation regime with apparent absorbance $A \approx 4$ at low wavelengths, indicative of optically thick, strongly scattering samples. The upper wavelength limit of this saturation window is size-dependent (Figure a): for the 24 nm MNPs, saturation is confined to approximately 190–265 nm, whereas for the 30 and 70 nm MNPs it extends to about 190–340 nm and 190–370 nm, respectively. As the MNP concentration is decreased, the saturation window narrows for all three systems, and at $10\ \mu\text{g mL}^{-1}$ the low-wavelength region approaches the spectrum of pure water. After subtracting the spectra of MNP-only dispersions, distinct drug absorbance peaks are recovered (Figure b). Nevertheless, at the highest MNP concentrations, recovery of the drug signal, particularly for the 70 nm MNPs, becomes difficult or impossible. In the series with fixed MNP concentration, drug calibration curves were obtained by subtracting MNP backgrounds (Figure c). Under these conditions, both drugs remain detectable down to approximately 200 pmol.

In conclusion, we determined a practical operating window for UV-Vis spectroscopy in MNP dispersions: a size- and concentration-dependent saturation regime in which the spectra are dominated by MNP extinction, and a lower-turbidity regime in which conventional background correction yields reliable drug detection.

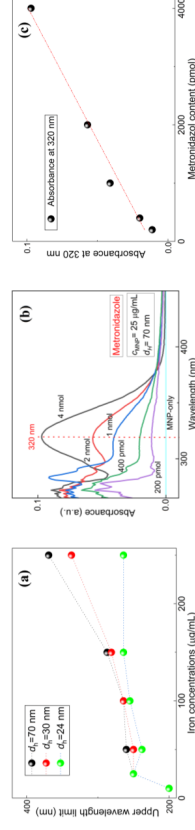


Figure (a) the upper wavelength limit of saturation window for different MNP diameter and iron concentrations, (b) background corrected spectra for detecting different metronidazole amounts, and (c) the calibration curve obtained using A_{320}

Revealing the temperature inside induction-heated magnetic nanoparticles and their surroundings – hotspots defined

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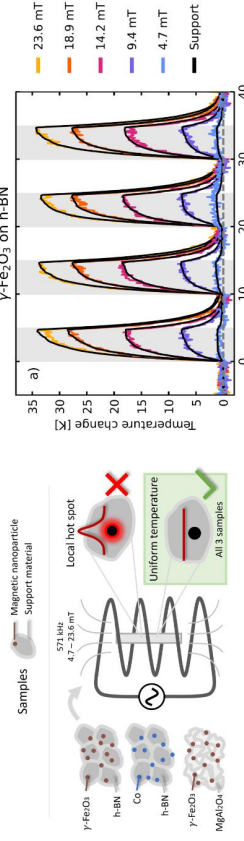
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Localised heating of magnetic nanoparticles in an AC field due to hysteresis can be utilised, e.g., for magnetic hyperthermia in cancer treatment and electrified heating of catalytic reactions [1,2]. To this end, understanding how and on which time scales the heat is deposited in nanoparticles and their near surroundings is important for optimising applications. Nevertheless, measuring temperature at the nanoscale is difficult, and the local temperature distribution inside and around the magnetic nanoparticles is a topic of controversy. As of now, the scientific literature is divided on the extent to which temperature differences between the magnetic nanoparticles and their surroundings, i.e., hotspots, can build up [3–7]. By use of thermosensitive molecules, the temperature has been determined a few nm away from the magnetic nanoparticle surface, reporting significant temperature differences (tens of °C [7]) between magnetically heated nanoparticles and their surrounding fluids. On the contrary, Faure et al. [8] determined the internal temperature of induction-heated magnetic iron oxide nanoparticles on solid support via X-ray diffraction. Within a sensitivity of ±5°C and 200 s, they found that there was no temperature difference between the magnetic nanoparticles and the solid matrix, in agreement with theoretical temperature predictions [3,4].

To shed more light on this debate, we present here a new time-resolved in-situ powder X-ray diffraction study, with unprecedented time and temperature resolutions of 0.05 s and 1°C. By this, we have been able to determine the internal and external temperatures during magnetic induction-heating of magnetic nanoparticles on different powder supports through the thermal expansion of the materials [10]. Across all three samples investigated and all field settings used, we find that no hotspots exist, in agreement with theory [3,4]. Based on this, we conclude that hotspots do not exist beyond the sub-kelvin regime. Additionally, we find that the X-ray diffraction method is versatile to different nanoparticle-support systems since no modification of the design, morphology, or chemistry of the nanoparticles is required to probe the internal temperature. Also, our preliminary results show that the X-ray diffraction thermometry method can be expanded to magnetic nanoparticles in liquid phases such as water or cell media.



A) No hotspots found across all three samples. B) Temperature change of the induction heated magnetic nanoparticles (coloured lines) and support powder (black). The temperatures are determined by X-ray diffraction. The grey areas indicate when the induction field is on.

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Monte Carlo-Based Cone Angle Approach for Torque Analysis in Hybrid BD-KMC Simulations of Magnetic Nanoparticles

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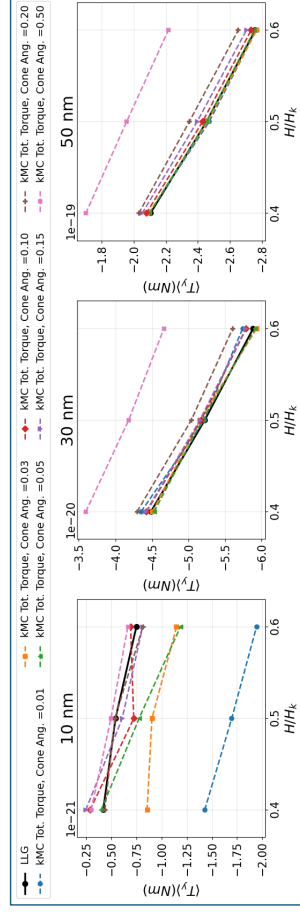
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Magnetic nanoparticles (MNPs) display special dynamic features when exposed to the external alternating magnetic field, which makes them relevant for a variety of applications such as magnetic hyperthermia, drug delivery and high-density storage devices. A factor which controls the response of this system is the orientation and distribution of their easy axis. To understand and predict this phenomenon accurately requires efficient simulation models. The Landau-Lifshitz-Gilbert equation (LLG), which represents the precessional motion of spins, can be used to capture the dynamics of magnetic moments. However, when analysing big systems or long-time scales, LLG simulation become computationally expensive as they need very small timestep increments. For this reason, the alternative Kinetic Monte Carlo (KMC) approach is used, because it can simulate thermally activated changes of the magnetic moment over longer time scales with reduced computational cost. In this work, the hybrid Brownian Dynamics-Kinetic Monte Carlo (BD-KMC) simulation is used to investigate the anisotropy torque and average of easy axis orientation of magnetic nanoparticles under different alternating-current (AC) magnetic fields.

The model considers nanoparticles with uniaxial anisotropy under different initial configurations, where the easy axis is fixed random or at 30° angle from the applied magnetic field. The equilibrium orientation of the magnetic moment is determined by the torque balance between the magnetic field torque and the anisotropy restoring torque. Using this framework, we compute the averaged anisotropy torque and easy axis evolution as a function of Monte Carlo (MC) steps. Simulations are performed for particle sizes ranging from 10 nm to 50 nm and for applied magnetic fields corresponding to fractions of the anisotropy field (0.4H_k, 0.5H_k, and 0.6H_k). For instance, in the figure we plot only the (Ty) components for all sizes. The result in the figure shows that the anisotropy torque increases with particle size, since larger particles have higher anisotropy energy. As a result, larger nanoparticles exhibit stronger torque amplitudes, while smaller particles show lower torque due to their weaker anisotropy. The amplitude of the torque also increases with the strength of the applied magnetic field. These simulations allow us to analyse the dependence of torque amplitude and easy-axis evolution on both particle size and applied field strength. Furthermore, comparison with simulations based on the LLG shows that the BD-KMC approach can reproduce similar trends in torque behaviour while adjusting the proper cone angles and MC steps.



Comparison of the average y-component of torque, (Ty), as a function of the applied field H normalized by the anisotropy field H_k, for magnetic nanoparticles of sizes 10 nm, 30 nm, and 50 nm. Solid (black) and dashed lines represent LLG and KMC simulation results, respectively, for different trial cone angles (Δθ = 0.01–0.50 rad). The figure illustrates how torque magnitude increases with particle size and applied field and shows the effect of varying the KMC cone angle on the calculated torque.

Sustainable Valorization of PET Nanoplastics: Integrated Magnetic Harvesting and Upcycling via Mesocrystalline Iron Oxide Nanoflowers

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The transition of functional nanomaterials into viable technological applications requires synthetic routes that balance scalability with rigorous structural control. In this work, we present a microwave-assisted polyol synthesis for iron oxide nanoflowers (NFs), achieving a drastic reduction in reaction times from the standard 24 hours in an autoclave to just 120 minutes with a reproducibility exceeding 90 % (Fig. 1A). By refining the thermal profile (0.2 °C/s ramp and microwave sintering at 250 °C), we optimized mesocrystalline order and magnetic anisotropy, which are critical for both catalytic and thermal performance. These multicore architectures were deployed as high-efficiency magnetic collectors for polyethylene terephthalate (PET) nanoplastics in aqueous media. The NFs demonstrated an exceptional capture capacity of up to 10,000 mg of nanoPET per gram of collector (Fig. 1B), facilitating rapid extraction via external magnetic gradients. Addressing the ubiquitous coexistence of nanoplastics and organic pollutants in aquatic environments, moving beyond simple removal is essential. Here we propose a paradigm shift: the functional valorization of waste PET through the creation of nanoPET/NF hybrids. In this system, the nanoplastic ceases to be a pollutant and becomes a structural and functional component of the material for the degradation of other organic pollutants like methylene blue (MB). Spectroscopic analysis (EPR and synchrotron XAS) confirms that the local organization and specific redox-active sites drive massive generation of reactive oxygen species (ROS), predominantly hydroperoxyl radicals (OOH). Under alternating magnetic field activation, considering that pristine NFs exhibited the highest SAR values (710 W/g) at 200 kHz and 24 kA/m, the hybrid nanoPET/NF achieved greater degradation efficiencies of MB via localized magnetic heating compared to RT experiments without the need to bulk heat the media (Fig. 1C). This approach transforms plastic “nanowaste” into a functional platform for advanced water treatment under a circular economy model.

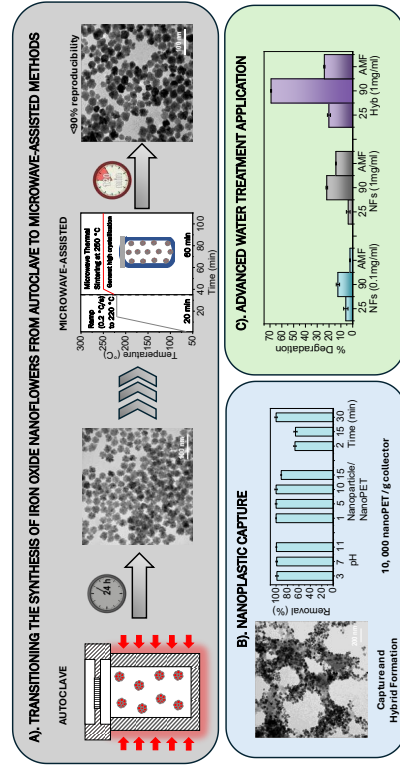


Figure 1: Comprehensive approach for nanomaterial-based water purification, detailing the synthesis optimization, high-capacity nanoplastic capture, and advanced catalytic degradation A). Adapting iron oxide nanoflower synthesis from autoclave to microwave-assisted heating. B). Targeted nanoplastic removal with high efficiency. C). The catalytic performance of the resulting hybrid system in a water treatment application.

Interactions of silica-coated magnetic nanocarriers with cell membranes

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Magnetic nanoparticles (MNPs) represent highly promising systems for diverse biomedical applications. Currently, they are utilized as contrast agents in magnetic resonance imaging (MRI), as well as in targeted drug delivery and hyperthermia therapy. Nevertheless, several limitations obstruct their direct clinical implementation. Extensive research has documented the adverse effects of MNPs on living organisms, including nanoparticle disintegration, the generation of reactive oxygen species, the formation of a protein corona, and the unintended modulation of cellular signaling pathways. A primary source of MNP toxicity is linked to mechanical alterations within cellular membranes. It is established that cell membranes interact with MNPs via multiple mechanisms; specifically, NPs can adsorb onto the surface, integrate into the membrane, translocate through, or even compromise the structural integrity of the lipid matrix.

The specific interaction scenario is dictated by a multitude of factors related to the physicochemical properties of both the nanoparticles and the membrane. Due to the inherent complexity of biological membranes, investigations into these phenomena are typically conducted using simplified models, such as lipid bilayers. The use of lipid bilayers facilitates the elimination of extraneous interaction effects, allowing for a focused elucidation of the fundamental processes that occur upon close contact between the MNP and the bilayer.

We investigated the interactions of core@shell MNPs with a lipid bilayer using neutron reflectometry and quartz crystal microbalance (QCM-D). Nanoparticles featuring magnetic Fe₃O₄ cores and a porous silica (SiO₂) shell were exposed to a planar DMPC (1,2-dimyristoyl-sn-glycero-3-phosphocholine) bilayer. The system was characterized both in the absence and presence of an external magnetic field. The findings obtained via neutron reflectometry were corroborated by both QCM-D experiments and *in vitro* studies with living cells. Our results indicate that this NP system does not interact with DMPC lipid bilayer even upon application of external magnetic field. On the other hand, the *in vitro* experiments show that a fraction of

our MNPs penetrates the cell membrane and can be found located in the vicinity of the cell nucleus. The data suggest that the mechanism of nanoparticle internalization by the living cell is rather biological process than just pure physical or chemical one. Nevertheless, the *in vitro* experiments confirmed high biocompatibility of the prepared MNPs, suggesting significant potential for its application as a targeted drug delivery agent in biomedicine.

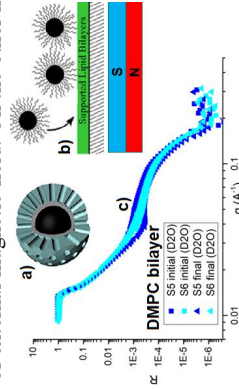


Figure. a) Nanoparticles with a magnetic core and a porous silica shell are exposed to b) supported lipid bilayers. c) The neutron reflectometry data show that the lipid bilayer has not been affected by the MNPs.

Magnetic Hyperthermia for Chemo-Thermal Therapy via Intracellular GSH-Responsive Prodrug Release

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Magnetic hyperthermia offers precise spatiotemporal control, yet therapeutic impact is often limited by inefficient coupling between heating and intracellular drug activation.^[1] Here, we develop a magnetically actuated chemo-thermal platform in which alternating magnetic field (AMF)-induced hyperthermia amplifies glutathione (GSH)-responsive activation of a lipophilic Pt(IV) cisplatin prodrug. Multicore iron oxide nanoflowers were encapsulated into magnetoliposomes (MLPs) together with the Pt(IV) prodrug to co-localize heat generation and redox-triggered platinum release. Under AMF, the formulation generated rapid heating (Fe conc. = 0.5 mg/mL; $\Delta T = 11.8^\circ\text{C}$ in 1 h; ILP = $11.3 \pm 0.9 \text{ nH}\cdot\text{m}^2/\text{kg}\cdot\text{s}$). In head and neck cancer (HNC) cells, hyperthermia transiently modulated intracellular GSH and accelerated prodrug release and activation relative to non-heated controls. The combined treatment produced enhanced cytotoxicity, reducing viability from $76.47 \pm 1.46\%$ (CisPt-C6@MLP) to $38.92 \pm 1.00\%$ (CisPt-C6@MLP + AMF), and increased DNA damage signalling in HNC cells, with $\gamma\text{-H2AX}$ foci per cell rising to ~ 130 at 24 h under AMF (vs ~ 10 in control), alongside reduced late-stage 53BP1 foci. These results establish a design principle for magnetic carriers: leveraging hyperthermia-induced redox dynamics can amplify GSH-gated prodrug activation for on-demand chemotherapy.

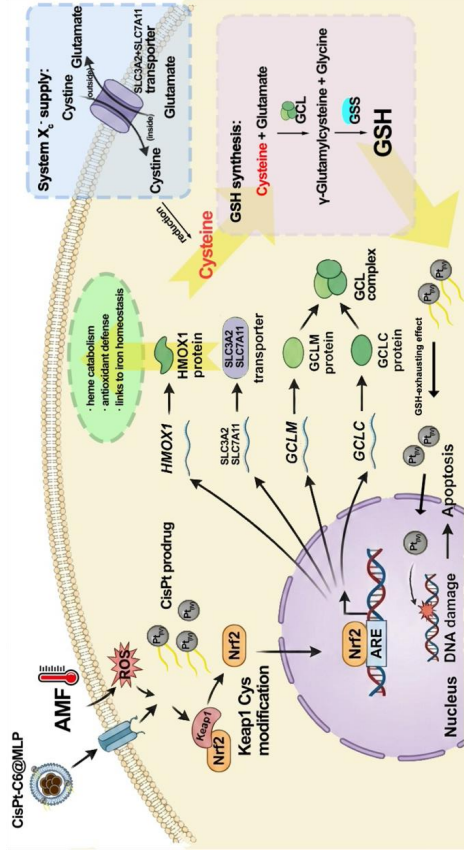


Fig 1. Schematic of magneto-thermal responsive CisPt-C6@MLPs internalised into cancer cells for chemo-thermal therapy.

Acknowledgement: China Scholarship Council-UCL

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A High-Throughput Thermal Decomposition Synthesis Platform for Optimizing Magnetic Nanoparticles

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Magnetic nanoparticles are a promising class of nanomaterials for various biomedical applications, including magnetic particle imaging and magnetic fluid hyperthermia. A key advantage is the ability to tailor particle properties through controlled synthesis, allowing them to be optimized for particular use cases. Thermal decomposition is a common synthesis method for producing iron oxide particles because it enables the production of monodisperse, highly crystalline, and highly magnetic particles, but it is not without its challenges. In general, the mechanisms of thermal decomposition are not well understood due to the high temperatures involved, promoting various side reactions and limiting the ability to use in situ measurement techniques. While many studies have demonstrated the ability to influence particle properties through various reaction parameters, they often use limited sample sizes due to the complexity and relatively long reaction times necessary. This obscures the statistically evaluated effects of these changes and the reproducibility of such methods.

Here, we report a synthesis platform capable of carrying out up to 16 thermal decomposition synthesis reactions in parallel at a reduced scale. Efforts to maximize reproducibility include the ability to independently track the temperature of the internal reaction solution and external temperature of the reactor wall as well as controllably mix each reactor. This shifts the major bottleneck of the process away from synthesis and toward characterization and data analysis, allowing for much more rapid systematic exploration of the very large reaction parameter space. As proof of concept, we have explored the effects of iron concentration, surfactant to precursor ratio, solvent, and precursor iron source on the physical properties of produced iron oxide nanoparticles. Some factors matched well with established expectations from literature, such as the correlation between solvent boiling point and particle size. Others disagreed with expectations or had more complex relationships that depended on multiple factors. We further examined the effects of a post-synthesis oxidation procedure on particles of various sizes and morphology while evaluating their magnetic properties and performance for magnetic particle imaging and hyperthermia. From this, we have established the high-throughput reactor as a useful tool for rapid optimization of thermal decomposition syntheses, with the potential to be expanded to explore other reaction parameters and material systems such as mixed ferrites.

BSA-Coated Magnetic Nanoparticles for Betulinic Acid Delivery and Hyperthermia

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Hyperthermia is a promising cancer treatment because, as a localized therapy, it causes fewer side effects than chemotherapy or radiotherapy and can be combined with conventional treatments. Biocompatible iron oxide nanoparticles (Fe_3O_4 or $\gamma\text{-Fe}_2\text{O}_3$) are used for *in vivo* magnetic hyperthermia due to their low toxicity and established metabolic pathways, generating heat under an alternating magnetic field via Brownian and Néel relaxation. To prevent agglomeration and enable functionalization, these nanoparticles are coated with protective shells, such as bovine serum albumin (BSA), which ensures excellent biocompatibility and provides essential functional groups for drug attachment.

In this study, magnetic nanoparticles were prepared by co-precipitation and stabilized with perchloric acid (HClO_4). The resulting ionically stabilized maghemite nanoparticles (MF) were then coated with BSA to enhance their stability and provide functional groups suitable for drug attachment. Betulinic acid (BA), employed in this work as a therapeutic agent, is a naturally occurring pentacyclic triterpenoid found in the bark of white birch trees and other plants, known for its anticancer and antiviral activities. Due to these characteristics, BA was chosen for conjugation to the BSA-coated nanoparticles (MFBSA). Physicochemical analysis showed that the hydrodynamic diameter increased from 34.0 nm (MF) to 52.1 nm (MFBSA) and after BA binding, it further increased to 89.9 nm (MFBSA-BA). Furthermore, the initial decrease in zeta potential from +31.0 mV (MF) to +19.8 mV (MFBSA) confirms the successful coating of the positively charged maghemite core with amphiphilic BSA molecules. The fact that the zeta potential remained relatively unchanged after BA attachment (+15.9 mV) suggests that the BA molecules are likely embedded within the protein matrix or stabilized through hydrophobic interactions, rather than significantly altering the surface charge density. The increase in size was associated with a steady decline in heating efficiency, with SAR dropping from 30.05 to 26.87 and 25.51 W/g (at $H = 7.4$ mT, $f = 1.05$ MHz), and ILP from 0.83 to 0.74 and 0.70 nH·m²/kg, respectively, in the order MF, MFBSA, and MFBSA-BA. The observed decrease in heating efficiency can be attributed to the increased local viscosity and the formation of BSA and BA shells, which restrict the rotational freedom of the nanoparticles. This damping effect primarily hinders the Brownian relaxation mechanism, leading to the decline in SAR and ILP values. In conclusion, these BSA-functionalized magnetic nanoparticles carrying BA represent a promising platform for combined magnetic hyperthermia and targeted drug delivery.

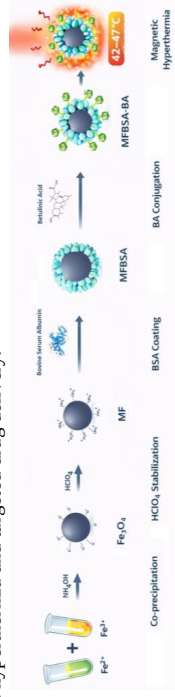


Figure. Schematic illustration of magnetic nanoparticle synthesis, BSA-coating, and BA loading for magnetic hyperthermia.

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Engineering intra-particle spin disorder to tailor heat generation

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Magnetic nanoparticles (MNPs) play a central role in nanomedicine, engaged in promising applications such as drug delivery or magnetic hyperthermia [1]. Iron oxide nanoparticles, approved by the FDA for their medical use in humans, have already reached pre-clinical trials in pancreatic cancer tumors [2], yet improving their heating efficiency remains a key challenge to enhance their therapeutic performance.

In recent years, engineering magnetic defects has been proposed as a promising pathway to enhance the heat release of MNPs, supported by numerical predictions [3, 4]. However, such a design strategy requires a more detailed theoretical framework than the macrospin approximation which is ubiquitously used nowadays. Within this conception, the intraparticle magnetization is assimilated to a single “super-spin” with no internal degrees of freedom [5], restricting the role of disorder as a detrimental accident.

In this work, we use a micromagnetic description to break this paradigm and redefine magnetic disorder as a design asset to tailor the heat release in iron oxide nanoparticles [6]. In this work, we elucidate the influence of intra-particle disorder on the magnetization reversal and associated heat release of maghemite nanoflowers, excellent nanotransducers in magnetic hyperthermia [7]. We identify the spatial location and temporal extent of intra-particle hot spots, providing guidance for optimal nanoparticle design.

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High Magnetisation Magnetite Particles for Biomedical Applications

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We have produced magnetite nanoparticles with increased crystallinity and bulk magnetisation closer to the theoretical maximum value of 92emu/g, by modification of the standard co-precipitated technique [1]. This is achieved through the addition of Fe²⁺ salt to seed magnetite nanoparticles in an aqueous alkaline solution with heating. The procedure is a Controlled Growth Process (CGP) and produces particles with size distributions close to that produced using the carbonyl process for producing cobalt nanoparticles. The CGP particles show higher bulk saturation magnetisation (80–85 emu/g) compared to standard co-precipitated particles (65–75 emu/g). This represents an over 10% increase on the bulk saturation magnetisation. Conventional co-precipitation does not produce particles of narrow size distribution (figure 1a). The CGP nanoparticles are of higher crystallinity as is evident from TEM studies (figures 1b and 1c). In addition conventional co-precipitation produces particles with standard deviations of typically 0.4, whereas the CGP particles are typically 0.2 and comparable to the distribution seen for metal nanoparticles such as cobalt. The CGP particles exhibit reduced aggregation due to the ease of binding of carboxylic acids to the Fe²⁺ rich surface. The CGP method has been patented [2].

The magnetite nanoparticles produced by the CGP can be tailored to make magnetite between 10nm to 15nm in diameter. This is achieved by controlling the level of Fe²⁺ added to the seed particles. The CGP particles can be incorporated into micron scale polymer beads, by coating with a surfactant, dispersing in a monomer and encapsulated through a suspension or dispersion polymerisation processes.

There is a potential application of polymer beads (SphereMAG®) incorporating the CGP particles for magnetic hyperthermia to treat tumours. The CGP particles, commercially known as HyperMAG®, typically have three particle sizes, 10nm (A), 11nm (B) and 15nm (C). Recent work by O'Grady et al [3], shows that significant hysteresis heating produced by incorporating HyperMAG-C nanoparticles into micron sized polymer beads, produces heating due to hysteresis losses alone. Due to the predictable hysteresis heating of magnetic polymer beads, these materials will allow greater control of hyperthermic heating, by eliminating unpredictable heating caused by dynamic effects such as stirring, aggregation of nanoparticles, which is the case for magnetite nanoparticles not encapsulated and therefore not locked physically. This then allows the possibility of a dosimetric approach to magnetic hyperthermia.

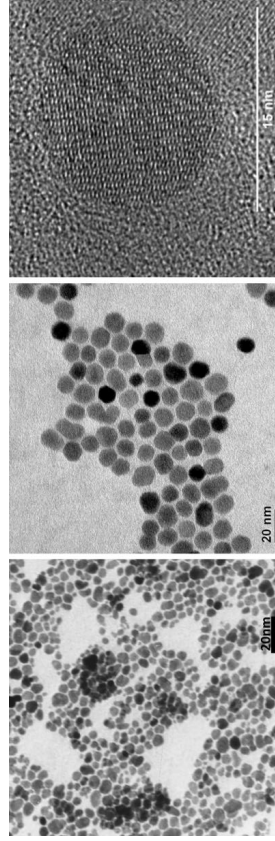


Figure 1a: Magnetite particles produced using standard co-precipitation. Figure 1b: Magnetite particles produced using the CGP. Figure 1c: Magnetite particles produced using the CGP showing crystalline structure to the perimeter of the particle.

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Poly-L-Lysine Functionalized Iron Oxide Nanoparticles: Single-Core vs Nanoflower Structures for potential MRI, Hyperthermia, and theranostic applications

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Iron oxide nanoparticles (IONPs) are widely studied as multifunctional platforms for theranostic applications that combine magnetic resonance imaging (MRI), magnetic hyperthermia (MH), and radionuclide therapy. In this work, we performed a comparative study of conventional single-core iron oxide nanoparticles (IONPs) and multicore iron oxide nanoflowers (IONFs), both in their native form and when functionalized with poly-L-lysine (PLL). The aim was to evaluate how nanoparticle architecture and surface modification influence physicochemical, magnetic, and functional properties important for combined diagnostic and therapeutic applications.

PLL functionalization was used to improve colloidal stability and introduce surface amino groups suitable for the coordination of radiometals. Dynamic light scattering revealed hydrodynamic diameters of approximately 91.2 nm and 89 nm for bare IONPs and IONFs, respectively. After PLL coating, the hydrodynamic diameter increased to 112.6 nm for PLL-IONPs but decreased to 67 nm for PLL-IONFs. Surface modification also significantly raised the positive surface charge, with ζ -potential values increasing from +18 mV to +34.4 mV for IONPs and from +29.3 mV to +43.4 mV for IONFs, confirming successful functionalization and improved colloidal stability. Transmission electron microscopy showed core sizes of approximately 10–11 nm for single-core IONPs and about 23–24 nm for multicore nanoflower structures. All samples maintained high saturation magnetization at 300 K, ranging from 57.2 to 75.6 emu/g.

Magnetic hyperthermia performance was evaluated under an alternating magnetic field ($f = 252$ kHz, $H_0 \approx 15.9$ kA/m). Multicore nanoflowers exhibited significantly higher heating efficiency, achieving a specific absorption rate (SAR) of 250 W/g for IONFs and 150 W/g for PLL-IONFs, compared with 99.7 W/g for PLL-IONPs. The enhanced hyperthermia performance of nanoflowers can be attributed to strong dipolar interactions and collective magnetic behavior within their clustered nanocrystalline architecture.

Relaxometry measurements further highlighted the benefits of nanoflower structures for MRI applications. The longitudinal relaxivity increased from 1.66 mM⁻¹s⁻¹ for PLL-IONPs to 3.23 and 3.44 mM⁻¹s⁻¹ for IONFs and PLL-IONFs, respectively. A significant increase in transverse relaxivity was also observed, with r_2 values up to 651.8 mM⁻¹s⁻¹ and r_2^* values up to 742.6 mM⁻¹s⁻¹, resulting in high r_2/r_1 ratios (up to 245), indicating excellent performance as T₂-weighted MRI contrast agents.

Radial labeling of PLL-IONPs and PLL-IONFs with no-carrier-added ¹⁷⁷LuCl₃ was successfully achieved, where PLL surface amino groups acted as coordination sites for radionuclide binding. This resulted in high radiochemical purity and good *in vitro* stability. Therefore, these characteristics make them promising candidates for further investigation into their potential theranostic applications.

Overall, the results show that multicore iron oxide nanoflowers, particularly after PLL functionalization, exhibit a very advantageous combination of magnetic, hyperthermia, relaxometric, and radiolabeling properties. These findings highlight their strong potential as multifunctional platforms for integrated MRI diagnostics, magnetic hyperthermia, and radionuclide-based theranostic applications.

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Drug-Coated Magnetic Microrobots as a Targeted Drug Delivery Platform for Cancer Drug Studies

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Systemic chemotherapy lacks spatial selectivity, resulting in high off-target toxicity and limited therapeutic efficiency. Magnetically actuated microrobots offer a promising engineering solution for targeted drug delivery, enabling remotely controlled motion, localised payload release, and minimally invasive intervention. In this study, we present an integrated electromagnetic actuation and imaging platform capable of high-precision manipulation of drug-functionalised microrobots for in-vitro cancer-cell studies.

Magnetic microrobots (Fig. 1 (B)) were fabricated using SU-8 photoresist via laser-based 3D lithography (Nanoscribe). The polymer structures were then sputter-coated with approximately 150 nm Nickel-Iron alloy (NiFe) which provides the required magnetic functionality. The fabricated microrobots (approximately 150µm length 75µm diameter) navigate in fluid environments using externally applied magnetic fields (field limited 10 mT, experimental setup is shown in Fig. 1 (A) and (B)). Biocompatibility tests demonstrated that Cancer cell confluence increased from ~10% at seeding to ~20-21% after 32 h, comparable to control wells, indicating that the microrobots did not inhibit cell proliferation (Fig. 1 (C) and (D)). The microrobots will subsequently be coated with polydopamine, enabling efficient drug loading and facilitating the transport of therapeutic agents to targeted cancer cells and will be used as precise, automated, and effective drug study platform.

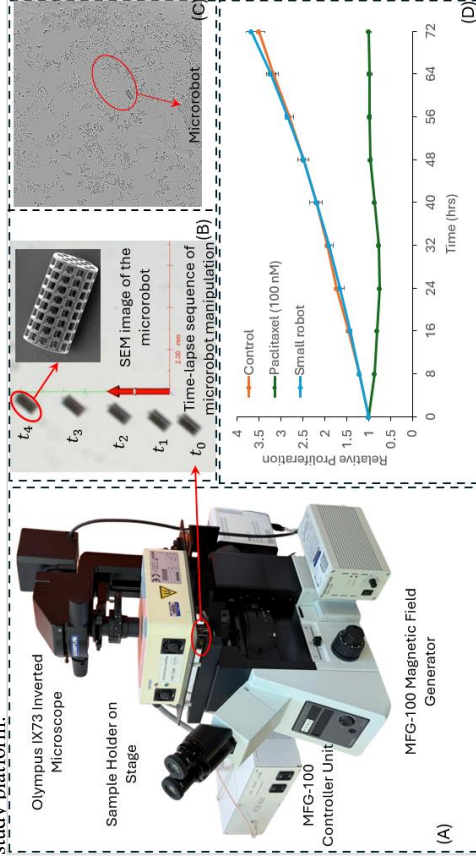


Fig. 1. (A) Integrated electromagnetic set-up, (B) Microrobot locomotion under magnetic field. (C) The microrobot and cells are placed in the sample holder for biocompatibility study. (D) Shows the biocompatibility test results.

Magneto-Plasmonic Nanoparticles for X-ray triggered cancer therapy

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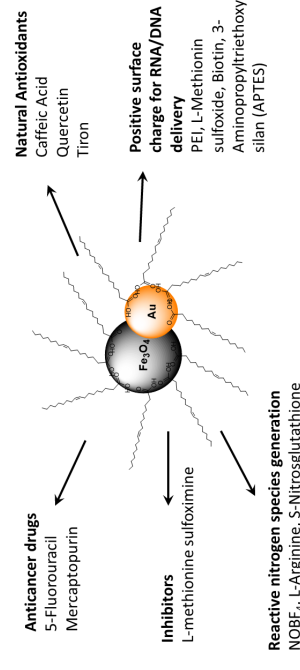
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Currently, surgery, chemotherapy and radiation therapy are widely used in clinics for cancer treatment. However, some cancers and more often metastases may not be discovered in time for surgical intervention and non-surgical methods are often limited by severe side effects. In addition, heterogeneity of tumor tissues as well as resistance of cancer cells towards monotherapies indicates the necessity to combine two or more modalities of cancer treatments

Inorganic, magneto-plasmonic Au-Fe₃O₄ nanoheterodimers (NHDs) were designed for X-ray triggered cancer therapy combining radiation therapy, drug delivery or immune therapy. X-ray radiation activates the catalytic functionality of the Fe₃O₄ surfaces. Surface standing Fe²⁺ and Fe³⁺ ions effectively catalyze the Fenton and Haber-Weiss reaction generating oxygen radicals. Due to alterations in the reactive oxygen detoxifying enzyme levels, cancer cells often have elevated H₂O₂ levels. H₂O₂ is converted to the highly toxic OH[•] radical, so that the Fe²⁺ driven Fenton reaction is favored. However, under ambient conditions surface Fe²⁺ ions gradually oxidize to Fe³⁺ ions. Fe₃O₄ nanoparticles epitaxially grown on gold nanoparticles (AuNPs) retain Fenton catalytic activity. In addition, X-rays release photo or Auger electrons and secondary X-rays from the gold component, leading to the synergistic formation of reactive oxygen species. In cells, the interactions of X-rays with drug-loaded NHDs causes the release of drugs into the cytosol.

Since the as-synthesized NHDs are surface stabilized with oleic acid/oleylamine, ligand exchange is required for water solubility. For example, the ligand exchange with nitrosyl tetrafluoroborate yields NO⁺-functionalized NHDs, which provide synergistic generation of reactive oxygen and nitrogen species under X-ray exposure [1]. To obtain NHDs with a radioprotective function in healthy cells, the NHDs are functionalized with the natural antioxidant and anti-cancer drug caffeic acid. Caffeic acid-functionalized NHDs are shown to act as radioprotectors in healthy breast epithelial cells, but as X-ray dose enhancers in breast cancer cells in (2D) monolayer cell cultures [2] as well as in (3D) multicellular spheroids [2-4]. The functionalization with positively charged ligands allows the electrostatic binding of negatively charged molecules like siRNA. This enables the transfection of T cells downregulating the expression of e.g. PD-1 expression and reactivates the cytotoxicity of T-cells.



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Setup for dynamic control of magnetic particle concentration enabling versatile measurement applications

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In magnetic measurement methods, analyzing the behavior of magnetic particles over a range of concentrations, such as in a serial dilution, is a routine task. Here, we introduce a novel platform that enables dynamic adjustment of magnetic nanoparticle (MNP) dispersion concentration through a microfluidic control system. By supplying defined flow rates of MNP suspension and diluent to a microfluidic mixing chip, both the concentration and flow rate of MNPs can be precisely set and continuously tuned during operation. This approach allows various measurement applications to be implemented using well-defined, time-dependent dilution protocols with controlled MNP concentration.

The setup was validated using time-resolved magnetic particle spectroscopy (MPS) (MPS-3, Bruker Biospin, Germany) in a flow cell insert that enables direct measurement of the resulting dilution in flow. We demonstrated the reproducible setting of dilutions in a range from $c(\text{Fe})=7.6 \text{ mmol/L}$ (1:10) to $c(\text{Fe})=0.076 \text{ mmol/L}$ (1:1000) at a flow rate of 1 ml/min using Perimag COOH (130 nm, $c(\text{Fe})=76 \text{ mmol/L}$, micromod, Germany) prediluted to 1:10 with distilled water (Fig. 1a). Figure 1b shows the mixing setup with a two channel Flow EZ microfluidic flow controller (Fluigent, France) and a Baffle mixing chip (microfluidic ChipShop, Germany).

Next, the setup was tested by examining dynamic variations in MNP concentration with commercial magnetic particle imaging (Bruker MPI 25/20 FF, Bruker Biospin, Germany), mimicking concentration changes in the circulatory system. For this purpose, a spiral flow phantom has been 3D-printed that can be directly integrated into the setup performing spatial resolution studies (Fig. 1c). Additional phantom configurations include V-shaped resolution patterns, anatomical vessel geometries, and structures for spill-over investigation using statically embedded MNP, illustrating the broad range of measurement applications enabled by 3D-printed phantom geometries. Reproducibility has been demonstrated using MPS, and the first MPI measurements have confirmed feasibility of imaging experiments using the setup.

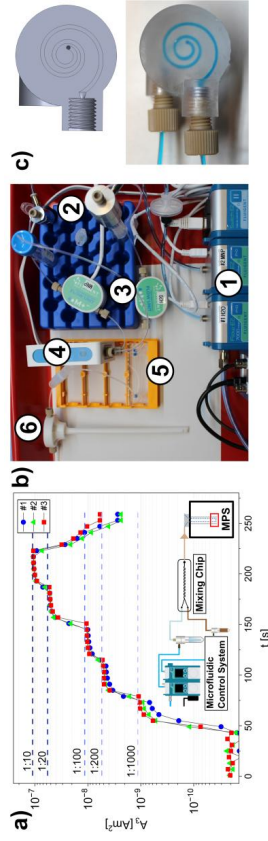


Figure 1. MNP flow setup for dynamic control of MNP concentration. a): Third harmonic amplitude values from time-dependent MPS measurements, b): The MNP mixing setup: 1: microfluidic flow controller, 2: MNP and distilled water reservoirs, 3: flow rate sensors, 4: valve for controlling MNP addition, 5: mixing chip, 6: MPS flow cell, c): Spiral MNP phantom design for 3D-printing and flow test with colored water.

Determination of unique pure system functions for Color- Magnetic Particle Imaging of cellular states

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Magnetic particle imaging (MPI) enables sensitive, quantitative detection of magnetically labeled cells. To date, MPI has mainly been focusing on spatial cell tracking neglecting the physiological state of the cell. Here, we expand MPI toward functional cell tracking by exploiting cell-physiology-dependent magnetic signatures using color-MPI. Therefore, it is mandatory to establish a distinctive reference system that mirrors the cellular states for adequate calibration by recording system functions (SF) used in color-MPI. The procedure of linear decomposition of two SFs of mixed samples into pure system functions is first demonstrated using defined mixtures of Perimag[®] and Synomag[®] magnetic nanoparticles. Then, the separation of cellular states was assessed by THP-1 cells labelled with citrate-coated Synomag COOH[®]. The cell samples were prepared in two different states, an untreated viable type (V) and a damaged type (D) after H₂O₂ treatment for 24 h to induce cellular stress. For MPI a preclinical scanner (Bruker MPI 25/20 FF, GER) equipped with a separate receive coil was used. Two SFs of differently mixed cellular states (22.9% V, 77.1% D and 78.7% V, 21.3% D as analyzed by Cyan ADP flow cytometer, Beckman Coulter) were recorded and then decomposed into two system functions describing pure cellular states. As imaging phantom, an untreated cell sample was placed beneath a treated cell sample containing the same V/D ratios (see Fig.1, left side). The reconstructed distributions using the measured mixed system functions identify the corresponding major cellular type fractions with poor quantification accuracy.

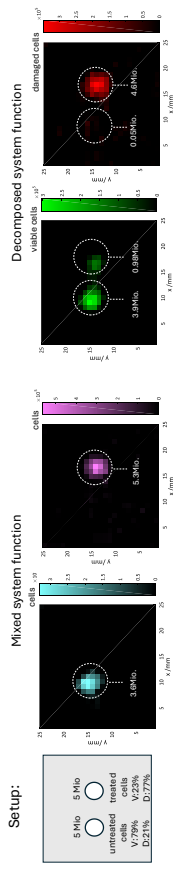


Figure 1: Left side: Setup of the measured phantom, **Middle panel:** Imaged distribution and quantification using system functions of the mixed cellular states, **Right side:** Imaged distribution and resulting quantification using the decomposed system functions.

The decomposition of the system function is incorporated as a linear complex operation prior to image reconstruction and is applied to mathematically separate the magnetic signatures of the reference samples used for the SFs into their individual components, i.e., pure healthy cells, and pure damaged cells. As a result, by employing decomposed system functions (right side panel) an improved identification of the two individual cellular states with better quantification results is obtained.

Since biological systems are often a combination of different cellular states, e.g. viable and damaged cells are always present concurrently for a given cell sample, improved functional MPI including differentiation of cellular states are enabled by system function decomposition.

The quantitative imaging is demonstrated using untreated and H₂O₂-treated samples concurrently. In conjunction with our prerequisites, we have expanded color-MPI to determine cell location and the state of cell physiology at the same time providing a robust approach to monitor immune cell fate and therapeutic efficacy during cell-based immunotherapy.

Magneto-Mechanical Remodelling of Bacterial Biofilms Using Bimodal Chemo-Mechanical Nano- Microrobots

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Bacterial biofilms are structured microbial communities embedded within an extracellular polymeric substance (EPS) matrix that acts as a protective barrier, limiting antibiotic penetration and promoting antimicrobial resistance. Consequently, new strategies capable of mechanically disrupting biofilm architecture are of increasing interest [1]. In this work, we explore magneto-mechanical biofilm loosening using anisotropic magnetic particles (AMPs) actuated by low-frequency rotating magnetic fields (RMF).

First, we investigate the influence of particle size, shape, and magnetic properties on torque-driven biofilm removal. AMPs, such as magnetic microrods, nanochains, and nanorods with distinct dimensions were actuated under identical RMF conditions on implant-relevant titanium substrates colonized by *Enterococcus faecalis*. Micron-scale magnetic microrods generated sufficient magnetic torque to mechanically disrupt the EPS matrix and detach biofilm structures, significantly increasing the number of suspended bacterial cells without pronounced bactericidal effects. In contrast, nanoscale particles did not induce significant biofilm detachment but caused membrane changes/damage and increased the proportion of injured bacterial cells, indicating a size-dependent transition between macroscale biofilm detachment and nanoscale membrane interactions.

In another study, we introduced dynamically assembling magnetic nanochains as bioinspired swarm-type nanorobots capable of penetrating planktonic biofilms [2]. Under low-intensity RMF (<20 mT, <10 Hz), the nanochains exhibit propelling and rotational motion, enabling their attachment to bacterial aggregates and multidirectional penetration throughout *Staphylococcus epidermidis* biofilms. The resulting torque-driven mechanical interactions destabilize and loosen the EPS matrix and significantly enhance antibiotic penetration, leading to near-complete (99.99%) bacterial eradication when combined with methicillin.

Finally, in a separate study we investigated how AMP properties, specifically surface roughness and particle size, influence biofilm removal under magnetic actuation, using both classical colony-forming unit quantification (viability assessment) and fluorescence-based detection of bacteria via reporter protein. Although individual AMP characteristics contributed only modestly to biofilm disruption, a synergistic effect was observed when AMPs were grafted with silver nanoparticles. Pronounced species-dependent variability of silver-based treatments was also observed for *Enterococcus faecalis* and *Candida albicans*. These results demonstrate that anisotropic magnetic micro- and nanoscale structures represent promising magnetically actuated tools for targeted biofilm disruption and improved antimicrobial therapies.

Acknowledgement: This research was also funded by the Slovenian Research and Innovation Agency (ARIS) through the core funding No. P2-0089, P4-0432 and ARIS projects: No. J2-60047, J1-70022, J2-3043, J3-3079, J7-4420, L2-60141.

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Development of Amino-Functionalized Magnetic Nanoparticles for Theranostic Applications

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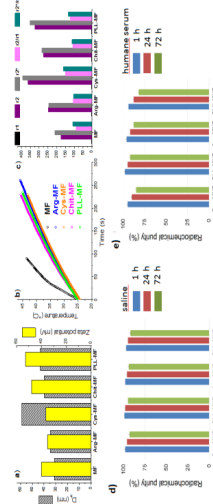
Iron oxide based magnetic nanoparticles (IONPs) continue to be a topic of interest across various research fields. Among these, biomedical applications are particularly attractive due to the potential to exploit their unique properties. In this study, IONPs were prepared by co-precipitation method, stabilized with perchloric acid to form a stable magnetic fluid (MF), and subsequently amino-functionalized using amino acids, namely cysteine (Cys) and arginine (Arg), as well as complex substances containing amino groups, such as poly-L-lysine (PLL) and chitosan (Chit). These fluids were characterized in terms of their basic properties (size, zeta potential, magnetization). In the next stage, a calorimetric study of heating efficiency, magnetic resonance imaging (MRI) and radiolabeling were performed with the aim of developing a multifunctional nanoplatform for imaging and therapy.

The hydrodynamic diameters of the NPs measured by dynamic light scattering were 31.0 ± 0.3 nm for the MF and showed a gradual increase after modification with Arg (34.6 ± 0.2 nm), Chit (39.7 ± 0.1 nm), PLL (43.1 ± 0.2 nm), and Cys (58.8 ± 0.5 nm). The zeta potential increased upon modification with Chit and PLL, whereas a slight decrease was observed after Arg and Cys addition (Fig. 1a). Magnetization measurements confirmed the superparamagnetic behaviour of both, unmodified and amino-modified NPs.

The heating efficiency study was conducted in an alternating magnetic field ($H = 15.9$ kA/m, $f = 252$ kHz), and the specific and intrinsic loss power (SLP and ILP) values were calculated for all studied samples. The obtained values are similar for all NPs with partial overlap of heating curves (Fig. 1b). While the SLP values did not exceed 50 W/g, and the ILP values were less than 1 nHm²/kg, they can be considered as sufficient. MRI relaxometry measurements showed that the prepared magnetic nanoparticles and all their modifications exhibited strong contrast properties in T_2 (T_2)-weighted imaging. The highest values of transverse relaxivity (r_2 and r_2') and the best r_2/r_1 (r_2'/r_1) ratios, indicating excellent contrast potential, were observed for Cys-NPs (Fig. 1c).

The binding of the radionuclide ¹⁷⁷Lu to NPs was investigated under different conditions, varying in time and temperature. Applying the most effective conditions (1 h, 60 °C) resulted in stable radiolabeled NP suspensions, with the radiochemical purity (RCP) exceeding 95% for all studied Cys-NPs, Chit-NPs, Arg-NPs, and PLL-NPs. Further, the *in vitro* stability of ¹⁷⁷Lu-labeled NPs was evaluated in saline and human serum for up to 72 h. In saline, all functionalized samples showed high stability, maintaining RCP values above 90% after 72 h, with PLL-NPs exhibiting the highest radiolabel retention (95–96%) (Fig. 1d). In human serum, a greater decrease in RCP was observed for all samples due to competition from serum proteins; however, PLL-NPs still retained high stability (92% at 72 h). Cys-NPs, Arg-NPs, and Chit-NPs showed moderate but acceptable stability (Fig. 1e).

Based on the obtained results, we conclude that the studied samples demonstrate significant potential for theranostic applications. However, further optimization of their properties and additional investigation are required to develop the most effective nanoplatform for the studied applications.



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Synthesis of cobalt ferrite magnetic seed nanoparticles for magnetoelectric system

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Spinel ferrite nanoparticles (NPs) have the general molecular formula MFe_2O_4 (where M represents various metal cations) and have gained attention owing to their superparamagnetic properties and tailorable surface chemistries.¹ Among these NPs, compared to iron ferrite, cobalt ferrite offers distinct advantages such as stronger coercivity, superior magneto-crystalline anisotropy and higher chemical and thermal stability.

In this work, cobalt ferrite nanoparticles were synthesized through modified solvothermal protocol² which use homogeneous alcoholic solution, metal precursor and aldehyde in an autoclave. The whole process is simpler compared to the normal thermal decomposition protocol. XRD was used to confirm the structure of cobalt ferrite and TEM observation revealed excellent monodispersity. In addition, the effects of heating time on the morphology of the product were specifically investigated. When the heating time changes (from 7 h to 6 h), the size of the particles reduces from about 50 nm to 25 nm (Figure 1). Furthermore, the effects of different aldehydes and amines as a reagent on particle shape, size distribution, and crystal structure were also studied.

The potential for gram-scale production of these high-quality cobalt ferrite nanoparticles is not only attractive in the medical field but also plays a critical role in other applications such as manufacturer of magnetic recording materials, high-coercivity permanent magnets, and sensors.

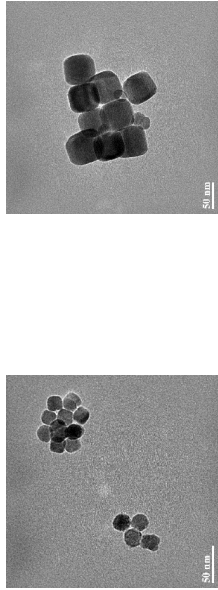


Figure 1. TEM image of CoFe_2O_4 core-shell nanoparticles from different heating time: 7 h (left) and 6 h (right) respectively.

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Blood Coagulation Testing using Magnetic Nanoparticles Measured by HTS-SQUID System

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Blood coagulation tests are widely used to diagnose disorders such as hemophilia. Conventional coagulation tests typically rely on optical measurements; however, fluctuations in turbidity can degrade measurement accuracy. To overcome this limitation, we have proposed a method for evaluating the viscosity of solutions by measuring the AC magnetic susceptibility of magnetic nanoparticles (MNPs) dispersed in the sample solution. Our previous studies have shown that the aggregation dynamics of MNPs are suppressed when the viscosity increases due to blood coagulation. This behavior suggests that the AC magnetic susceptibility of MNPs decreases in coagulated blood or in samples exhibiting coagulation abnormalities.

In this study, third-harmonic signals from MNPs were measured using an AC magnetic susceptibility measurement system equipped with a high-temperature superconducting quantum interference device (HTS-SQUID). An AC magnetic field with a frequency of 1.06 kHz and an amplitude of 8 mTpp was applied to the samples. To suppress environmental magnetic noise, the detection coil was configured as a gradiometer consisting of two oppositely wound coils.

The samples consisted of pure water, CaCl_2 solution, normal plasma, and factor VIII-deficient plasma, each containing dextran-coated MNPs (BNF dextran, particle diameter: 100 nm, iron concentration: 15 mg/mL). CaCl_2 solution was added to the plasma samples to induce coagulation. For each condition, 40 μL of sample solution was measured with three replicates.

Figure 1 shows the third-harmonic signals of the BNF dextran nanoparticles for each sample. The signal intensities were 1370 ± 38.4 , 597 ± 9.77 , 249 ± 6.57 , and 196 ± 5.05 μV for pure water, CaCl_2 solution, normal plasma, and factor VIII-deficient plasma, respectively. The signal obtained from normal plasma was 53 μV higher than that from factor VIII-deficient plasma. These results indicate that the proposed HTS-SQUID-based system can detect viscosity changes associated with blood coagulation through the nonlinear magnetic response of magnetic nanoparticles.

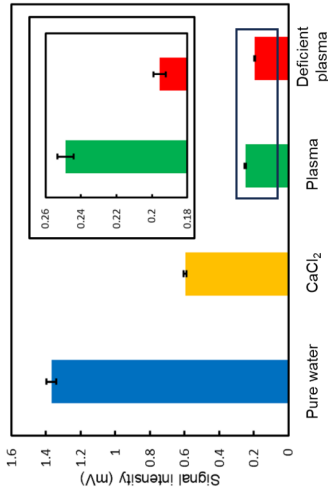


Figure. 1 Third-harmonic signal of BNF dextran measured with a sample volume of 40 μL .

3D-printed anatomic and geometric phantoms for platform-independent Magnetic Particle Imaging

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Magnetic particle imaging (MPI) is an imaging modality using magnetic nanoparticles as tracer with promising potential in many medical fields like cell tracking, inflammation detection, or hyperthermia. Since its first demonstration in 2005, a broad variety of hardware architectures, reconstruction methods, and medical use cases have been developed and explored. For this, a plenty of different phantoms have been used, but phantoms and working procedures facilitating inter-scanner comparisons are still lacking.

To close this gap, we developed a stackable phantom, fillable with long-term stable magnetic structures, and advanced the development of anatomically realistic phantoms. The stackable phantom consists of plates constructed in Blender and plotted with 3D printers from Anycubic (photon mono m7 pro) and Formlabs (Form 4). Anatomical phantoms are based on vessel structures segmented from a T2-weighted MRI human dataset. Anatomical structure was 3D-printed as a hollow model and connected to a micromixing control system which enables dynamic control of magnetic nanoparticle (MNP) concentration to simulate magnetic tracer material flow.

To explore and quantify the MPI image using the developed phantoms, the phantoms were filled with 3D-printed structures containing MNP as well as MNP loaded silicon structures. The magnetic behavior of the structures was determined by Magnetic Particle Spectroscopy (pureDevices) and their geometry was analyzed and verified (Revopoint 3D scanner) using structured-light 3D surface scanning. The resulting point cloud ($4 \cdot 10^5$ points) was then compared with a point cloud generated from the STL files by resampling the surface using Poisson-disc sampling. We present these phantoms with their structural and MPS/MPI characterization. The figure below shows representative results. Designed for compatibility with multiple MPI scanners, they enable round-robin studies across laboratories worldwide and support the development of standardized operating procedures.

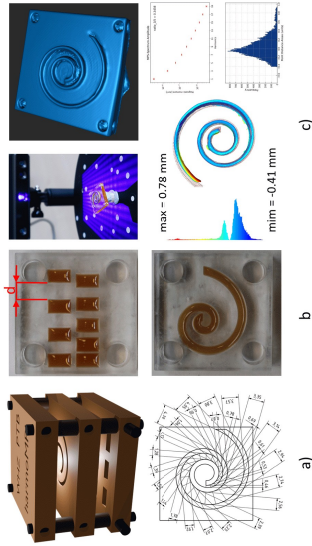


Figure: (a) The stackable phantom with the geometry of a helix plate schematic. In (b), two plates filled with polymer containing MNPs. The upper plate shows a resolution phantom consisting of molds with a volume of 18 mm³. The spacing between the molds ranges from $d = 0.5$ mm to $d = 3.5$ mm in steps of 0.5 mm. The lower plate shows a helix structure. In (c), the scanning setup and the scanning result are shown at the top. At the bottom, the difference in scan and reconstruction from the STL file is displayed, together with the MPS data and distribution of the differences.

Acknowledgements

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Towards a scaled-up, integrated system for Magnetic Particle Imaging and localized Hyperthermia for theranostic applications

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Magnetic Particle Imaging (MPI) is a fast and sensitive imaging modality that uses magnetic nanoparticles (MNPs) as tracers. It exploits their nonlinear magnetization response to a sinusoidal excitation, with signal arising exclusively from particles at the field-free point (FFP) of the gradient field, making the FFP central to spatial encoding. At the same time, this spatial selectivity enables localized heat generation at the FFP for magnetic hyperthermia (MFH), supporting targeted drug release and underscoring MPI's potential as a theranostic platform.

In our previous work we presented a new integrated system (see Fig. 1 left) that reuses the drive field for magnetic heating and spatial imaging. This frequency-mixing MPI system uses a high-frequency excitation of 285 kHz for both imaging and magnetic heating while low-frequency components below 1 kHz allow scan modulation and field-free point movement [1]. Furthermore, we were able to perform localized heating on an MNP conjugate triggering organ-specific xRNA drug release via a thermo-sensitive linker [2].

To prevent excessive tissue heating, precise temperature monitoring is required in addition to diagnostic imaging and localized hyperthermia. Here, we present initial results on MPI-based thermometry, in which temperature is estimated directly from multi-contrast image reconstruction (see Fig. 1 center). Furthermore, we are currently rebuilding the system to achieve full 3D coverage at a slightly larger scale, enabling the integration of vital sign monitoring for drug release studies in mice. In parallel, we are developing a scaled-up version designed to accommodate the size of human extremities (see Fig. 1 right), thereby expanding the potential clinical applications of the hybrid MPI approach.

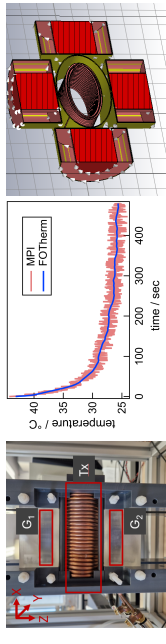


Figure 1: Left: MPI prototype with transmit coil (Tx) and gradient magnets (G_x). Center: Temperature estimation from image reconstruction compared to a fiber-optic thermometer. Right: CAD model of a next-generation MPI system accommodating a human hand.

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Flame-made Superparamagnetic Iron Oxide Nanoparticles for Non-invasive Diagnosis of Inflammatory Bowel Disease

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Inflammatory bowel disease is a chronic inflammatory disorder of the small and large intestines. Current diagnostic methods, endoscopy and mucosal biopsy, are invasive and costly and often require anesthesia when performed on children ⁽¹⁾. Magnetic Resonance Imaging (MRI) is emerging as a promising non-invasive alternative, but it still faces challenges in detecting mucosal changes and subtle inflammation. Therefore, effectively assessing intestinal inflammation remains a complex issue. Orally administered superparamagnetic iron oxide nanoparticles (SPIONs) can function as a contrast agent for MRI of the gastrointestinal tract. Moreover, the surface functionalization of SPIONs allows targeting of specific biomarkers in the gastrointestinal tract ⁽²⁾. This project aims to use targeted SPIONs to improve MR imaging of the gastrointestinal tract.

Our lab synthesizes silica-coated γ -Fe₂O₃ nanoparticles using a flame spray pyrolysis method, enabling cost-efficient, large-scale (several grams per hour) production of nanomaterials. The flame-made SPIONs are subsequently functionalized with PEGylated linear or cyclic RGD peptide. PEGylation facilitates nanoparticle transport through mucus, while the RGD motif targets cell-surface-bound integrins, which are upregulated in intestinal inflammation and are often utilized for targeted drug delivery ⁽³⁾.

Surface functionalization of SPIONs was confirmed by observing a shift in zeta potential of modified SPIONs, as well as detecting extra peaks with Fourier Transform infrared spectroscopy. Increased weight loss was observed with thermogravimetric analysis. SPION-PEG-RGD/cRGD stability was estimated using a microfluidic system mimicking the gastrointestinal tract in healthy and inflamed conditions. This experiment demonstrated that the hydrodynamic diameter of particles remained stable in both inflamed and healthy simulated fluids. Cell viability assay performed on Caco-2 cells indicated that the functionalized SPIONs are non-cytotoxic up to the concentration of 400 μ g/mL. In conclusion, SPION-PEG-RGD/cRGD particles showed successful functionalization, high stability in biologically relevant media, as well as negligible cytotoxicity. Further studies will investigate the particle uptake by Caco-2 cells, their diffusion patterns in mucus, and their biodistribution in the dextran sulfate-induced colitis mouse model.

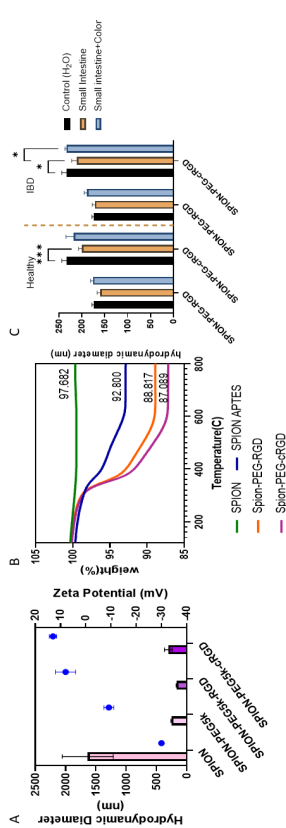


Figure 1. A) Hydrodynamic diameter and zeta potential of functionalized particles. B) thermogravimetric analysis of functionalized particles. C) Hydrodynamic diameters after exposing SPION-PEG-RGD and SPION-PEG-cRGD to simulated intestinal fluids.

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AI/ML-driven in vitro Platform for Quantification of Nanoparticle Transport Efficiency Across Biological Barriers

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The ability of engineered nanoparticles to traverse biological barriers remains a central challenge in nanomedicine, drug delivery, and nanotoxicology. Existing in vitro and analytical techniques - including Transwell assays, fluorescence microscopy, and inductively coupled plasma spectroscopy - are constrained by low reproducibility, limited throughput, or the requirement for particle labelling, which can alter physicochemical properties and compromise translational relevance. Here, we present a fully integrated analytical platform (*patent-pending EP25167065.9*) that combines microfluidic organ-on-chip technology with label-free brightfield microscopy and a multi-stage artificial intelligence/machine learning (AI/ML) pipeline to enable quantitative, reproducible assessment of nanoparticle transport efficiency (NTE), specifically validated for Fe₃O₄ magnetic nanoparticles (MNPs).

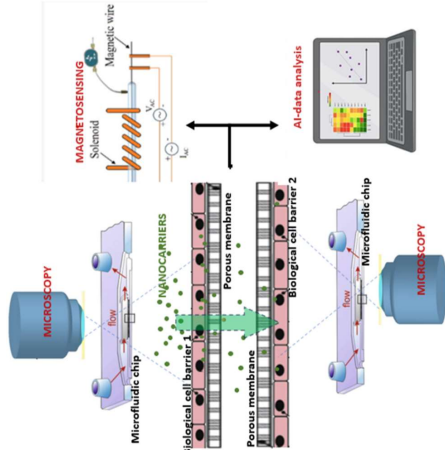
The platform is based on a cross-flow microfluidic chamber incorporating sequential porous-membrane cell barriers that mimic physiological interfaces such as endothelial, stromal, and glial layers. Transport of MNPs is monitored using standard brightfield microscopy, leveraging the intrinsic optical contrast generated by lysosomal accumulation of light-dense particles, which produces characteristic intracellular darkening without the need for labelling. These features are segmented using a pre-trained ResNet-UNet convolutional neural network (IoU = 0.85; precision = 93.2%, recall = 86.9%), followed by AI/ML-driven feature extraction, clustering, and regression-based quantification of transport efficiency and cell viability.

The system was validated across various MNPs including three surface chemistries (PLGA-coated, PEGylated, and uncoated Fe₃O₄ MNPs), five particle sizes (15–150 nm), multiple concentrations, and three human cell types. A key focus of this study is the effect of external magnetic field guidance on nanoparticle transport. Application of a 1 T static magnetic field resulted in a consistent and statistically significant enhancement of transport efficiency across all tested conditions. For example, 30 nm PLGA-coated MNPs exhibited transport efficiency increases from $23.0 \pm 1.2\%$ to $35.7 \pm 2.6\%$ in endothelial barriers (~30% relative improvement), representing the highest performance observed.

Orthogonal validation using magnetometry confirmed strong agreement with AI-derived measurements (Pearson $r \approx 0.9$), establishing that label-free optical readouts reliably reflect nanoparticle mass transport. In addition to endpoint transport efficiency, the platform enables extraction of kinetic descriptors, including transport rate, intracellular residence time, and transport heterogeneity.

Overall, this work establishes a scalable, cost-effective, and label-free methodology for quantitative characterization of magnetic nanoparticle transport. By integrating microfluidics with AI-driven image analysis, the platform provides a reproducible tool for early-stage nanocarrier screening, enabling mechanistic insight into magnetically assisted transport processes.

Figure. Schematic of MNPs translocation across multi-layer cellular barriers in a cross-flow microfluidic chip. MNPs enter the source channel and traverse sequential porous-membrane barriers under controlled flow, with optional magnetic guidance applied beneath the chip. Real-time, label-free brightfield imaging captures intracellular accumulation and barrier crossing, while integrated magnetic sensors quantify local MNP flux and mass transport. Image streams and sensor readouts are analyzed by a neural network pipeline (segmentation, feature extraction, and regression), yielding transport efficiency, kinetic descriptors (rate and residence time), and cell viability metrics.



Improved Thermal Management for Stable Continuous Measurement in Magnetic Particle Spectroscopy

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Magnetic Particle Spectroscopy (MPS) has attracted significant attention in immunoassays and cell dynamics monitoring for its potential in rapid, high-sensitivity liquid-phase measurements without washing steps and real-time tracking of particle binding and internalization [1,2]. For monitoring applications, continuous long-term acquisition of marker responses is desirable. However, Joule heating in excitation coils often makes many MPS systems unsuitable for such operations. While intermittent measurement is commonly used to prevent overheating, it cannot capture transient changes on the scale of seconds to minutes, such as rapid reactions or initial particle binding and internalization.

In this study, for establishing a reliable evaluation environment for magnetic nanoparticle (MNP) samples, we investigated the effects of a heat removal structure applied to an MPS device on improving thermal stability and suppressing fluctuations in MNP response characteristics during continuous measurement. We fabricated an MPS device with additional cooling structures shown in Fig. 1(a), based on the configuration of the open-source MPS (OS-MPS) [3]. The original design of OS-MPS utilized air cooling through the narrow gaps in the bias coils, which might result in poor heat exchange efficiency. Therefore, we introduced an indirect water-cooling structure within these gaps. Steady-state thermal analysis shown in Fig. 1(b) revealed that water cooling alone was insufficient, as the receiving coil area reached significantly elevated temperatures. It was attributed to the poor heat transfer efficiency caused by insulating air layers between the excitation/receiving coils and the surrounding components. Consequently, we applied thermal grease to the exterior of the excitation and receiving coils to enhance heat transfer. The temperature differences from the initial to the steady state in Fig. 1(c) shows that the combined structure of water cooling and thermal grease significantly suppressed temperature rise compared to the either structure. Additionally, thermal noise calculations showed a 40% reduction in noise levels. These results indicate that improved thermal management in the MPS system enhances thermal stability and reduces thermal noise, contributing to more stable MNP signal measurements during continuous operation.

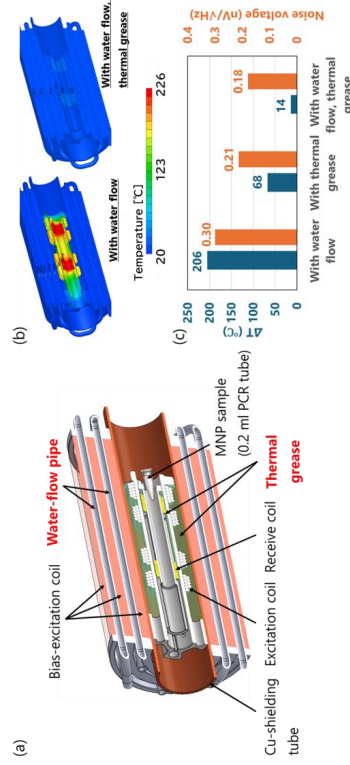


Figure 1 (a) Radial cross-sectional view of the MPS system: multi-cylindrical structure with a receiving coil unit, followed by an excitation coil unit, a copper shield, and a bias excitation coil unit. Water-flow pipes and thermal grease are additionally applied for improving thermal stability. (b) Analytical result of the steady-state temperature distribution of the entire system with water-cooling alone (left) and with water-cooling and thermal grease (right). (c) The temperature differences from the initial to the steady state (blue), the estimated thermal-noise voltage arises from receiving coil (orange).

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Disruption of Amyloid Fibrils by Nanoparticles: Effect of Pulsed and Rotating Magnetic Fields

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Accumulation of amyloid fibrils is a typical sign of various diseases, from Alzheimer's to Type II diabetes. These protein aggregates are highly stable and resist natural enzymatic degradation, making the development of effective disruption methods essential. This work investigates the effect of nanomaterials on the disruption of pre-formed insulin amyloid fibrils. Various magnetic nanoparticles, including nanodiamonds (NDs), magnetic nanodiamonds (magNDs), ferrofluids (FF), and biogenic magnetosomes (MTS) were employed to evaluate their direct anti-amyloid activity. We further explored whether this activity could be enhanced by external physical stimuli, namely rotating (RMF) and pulsed magnetic fields (PMF), inducing localized effects that further destabilize β -sheet-rich fibrillar structures.

The ability of the nanoparticles to affect protein amyloid fibrils was evaluated using Thioflavin T (ThT) fluorescence assays and visualized by Atomic Force Microscopy (AFM). Our results demonstrate that the nanoparticles were able to destabilize fibrils on their own, and this effect was further enhanced by the application of external magnetic fields, as documented for MTS (Fig. (a)), which showed a high response to magnetic stimulation even at very low concentrations due to their unique membrane-enveloped structure. Particles responded more strongly to PMF than to RMF, as the rapid, intense pulses induce mechanical stress sufficient to disrupt β -sheet structures stabilized by hydrogen bonds within amyloid fibrils. RMF also provided enhancement through continuous torque, although its impact was lower than that of the pulsed field.

The destruction of the typical amyloid fibril morphology was clearly demonstrated using AFM (Fig. (b), (c)). When fibrils were incubated with MTS and exposed to PMF or RMF, a lower number of shorter fibrils was observed (Fig. (c)). The results demonstrated that the precise selection of nanoparticles and controllable and tunable application of the magnetic fields may help enhance the therapeutic potential of the nanoparticles.

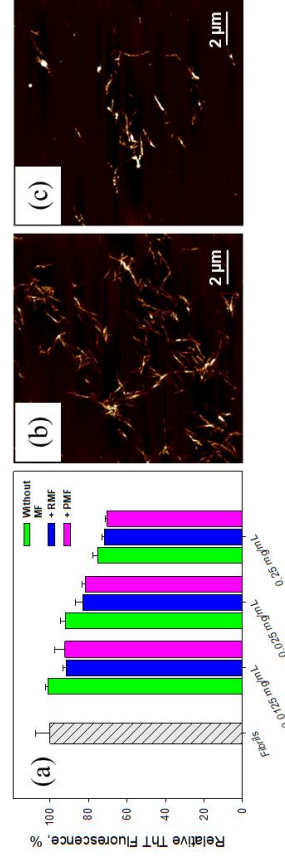


Figure. Anti-amyloid destructive activity of MTS on protein amyloid fibrils monitored by ThT fluorescence assay (a) and confirmed by atomic force microscopy (b), control amyloid fibrils; (c), amyloid fibrils incubated with MTS and the applied PMF).

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Biomolecule-functionalized CoFe₂O₄ nanoparticles: Balancing high heating efficiency with improved cellular safety

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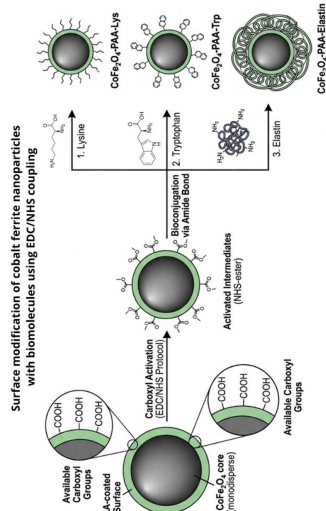
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Keywords: magnetic nanoparticles, EDC-coupling, magnetic hyperthermia

Magnetic nanoparticles based on iron oxides, especially magnetite (Fe₃O₄), have been extensively studied and are considered highly promising for various bioapplications due to their excellent biocompatibility and the presence of magnetic properties. However, for applications requiring high heating efficiency, such as magnetic hyperthermia, cobalt ferrite represents a better alternative due to its significantly higher magnetocrystalline anisotropy and the presence of hysteresis. Despite these advantages, the potential toxicity of cobalt-based cores remains a concern, requiring various surface functionalization strategies to ensure biosafety.

In this work, we present the synthesis and multi-step functionalization of monodisperse CoFe₂O₄ nanoparticles with an average core size of approximately 10 nm, prepared by thermal decomposition method. To ensure water dispersibility, the synthesized nanoparticles were modified with polyacrylic acid (PAA). Subsequently, three different biomolecules – lysine, tryptophan and elastin – were covalently conjugated to the PAA-coated surface using an EDC/NHS coupling protocol. The success of the surface modification and the efficiency of protein were verified by a combination of FTIR, UV-VIS spectra and Dynamic light scattering (DLS). FTIR and UV-VIS spectra confirmed the formation of amide bonds and the successful surface modification. DLS was used to monitor the evolution of hydrodynamic size and zeta potential, reflecting colloidal stability and surface charge changes at each functionalization step. Morphological properties were investigated by SEM and TEM, structural properties by XRD and EDS, and magnetic behavior by SQUID magnetometry.

The heating efficiency was quantified using magnetothermal response measurements (SAR and ILP coefficients). Finally, in vitro cytotoxicity assays were performed, demonstrating that the protein shell mitigates the inherent toxicity of the ferrite core. This study highlights the potential of protein-modified CoFe₂O₄ nanoparticles as effective and biocompatible mediators for targeted magnetic hyperthermia.



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Development of magnetic force biotechnology for neural regeneration.

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Restoration of long-range axonal connectivity remains a critical bottleneck in peripheral and central nervous system repair. Here, we report a magnetically driven strategy to induce directional axonal outgrowth using polymer-coated, zinc-doped magnetite nanoclusters (MNCs) in combination with a custom-engineered permanent magnet force vector system. Polyvinylpyrrolidone (PVP) and polyacrylic acid (PAA) coated Fe₃O₄-based MNCs were synthesised and characterised by TEM, dynamic light scattering, zeta potential analysis, confirming controlled cluster assembly (33–288 nm) and superparamagnetic behaviour.

A four-cylinder permanent magnet array arranged in an alternating S–N–S–N configuration was designed to generate a unidirectional magnetic field gradient. Field distribution and force vectors were mapped using a SENIS 3-axis Hall probe and MATLAB-based modelling, demonstrating a single dominant force direction across the neuronal growth region. Primary E17 cortical neurons were labelled with MNCs and cultured either on planar substrates or within microfluidic devices to assess both somatic uptake and free-axon internalisation.

Fluorescence microscopy and immunostaining (βIII-tubulin, DAPI) confirmed efficient MNC uptake by neurons and partial uptake within extending axons. Under applied magnetic force, neurons exhibited pronounced directional axonal alignment along the magnetic field gradient over millimetre-scale distances, in contrast to isotropic growth in control conditions. Stitched large-area imaging revealed coherent, long-range axonal orientation corresponding to the engineered force vector direction.

These findings demonstrate that highly magnetised nanoclusters combined with precisely configured magnetic force fields can actively guide axonal growth over long distances. This platform establishes a scalable, contact-free approach for directional neural regeneration and provides a foundation for future translation into spinal cord injury and neuro-repair applications.

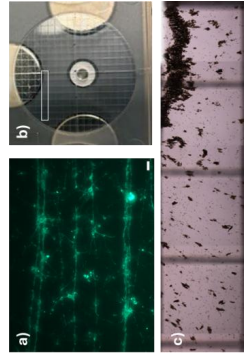


Figure (a) Fixed neurons stained with B3 tubulin showing neurons aligning across magnet field. Scale bar = 100um. **(b)** 2x2mm grid placed on top of magnet area demonstrating stitched image. **(c)** Stitched grid image of neurons aligning across magnetic field over larger areas.

Development of Theranostic Magneto-Microemulsion Platforms Based on Mn-Doped Magnetite Nanoparticles for Doxorubicin Delivery

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Despite the constant improvements in diagnosis and treatment, cancer still has a high incidence and remains a leading cause of mortality. Nanomedicine, which results from the integration of nanotechnology into medicine, holds great potential to enhance the efficacy of oncological treatments. In this regard, nanotheranostics bring additional advantages due to the combination of the therapeutic agent with a contrast agent allowing for real-time monitoring of the treatment. Due to their distinct physico-chemical characteristics and potential uses in magnetic hyperthermia, magnetic resonance imaging (MRI), and drug delivery, magnetic nanoparticles (MNPs), especially iron oxide-based systems, have attracted growing attention. To ameliorate their colloidal stability and drug-delivery performance, microemulsion systems have been explored as versatile nanostructured carriers due to their thermodynamic stability, ability to solubilize both hydrophilic and hydrophobic compounds, and capacity to modulate drug release profiles^{1,2}.

Herein, a magnetically responsive microemulsion system incorporating manganese-doped magnetite nanoparticles was investigated as a multifunctional platform for theranostic applications. Mn-doped Fe₃O₄ MNPs were synthesized via the coprecipitation method and subsequently incorporated into a thermodynamically stable oil-in-water microemulsion system. Since the functional performance of such systems is closely related to their physico-chemical properties, the resulting magneto-microemulsion was characterized using complementary techniques to assess the impact of nanoparticle incorporation on the microemulsion structure. Electrical conductivity measurements and dynamic light scattering analysis were employed to evaluate the characteristics of the continuous phase, the size distribution and structural organization of the dispersed domains within the microemulsion matrix.

Relaxometric investigations revealed a significant enhancement in transverse relaxivity following incorporation of the magnetic nanoparticles into the microemulsion matrix, with r_2 values reaching approximately 844 mM⁻¹·s⁻¹. The magneto-microemulsion system was further loaded with doxorubicin, and *in vitro* release studies showed a biphasic release profile, characterized by an initial burst phase followed by sustained diffusion from the microemulsion matrix. This behaviour indicates that the microemulsion environment modulates drug transport by introducing an additional diffusional barrier around the nanoparticle-associated drug.

Overall, these findings demonstrate that magneto-microemulsion systems based on Mn-doped Fe₃O₄ MNPs constitute effective nanostructured platforms capable of integrating MRI contrast enhancement, magnetic hyperthermia functionality, and controlled chemotherapeutic delivery within a single multifunctional nanosystem.

Acknowledgments: This work was supported by an H2020-ERA-Chair project, GA number 952390/2020.

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Effects of Mixing Hard and Soft Magnetic Nanoflowers: Theory and Simulations

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The development of magnetically controllable colloids with tunable magnetic properties has attracted significant experimental and theoretical interest [1]. While polydispersity in magnetic nanoparticles is often disadvantageous—since magnetic response scales with particle volume—well-defined binary mixtures offer new opportunities for tailoring magnetic behaviour [2,3,4]. Notably, such systems exhibit effects like the “poisoning effect,” where smaller particles suppress or modify the aggregation and magnetic response of larger ones, highlighting the importance of understanding interactions in binary ferrofluids [2].

In our previous work, we investigated experimentally and via simulations binary magnetic fluids composed of CoFe₂O₄ (hard) and MnFe₂O₄ (soft) nanoparticles [5]. These findings motivated us to extend our study toward a more general understanding of magnetisation dynamics in such mixtures.

Here, we combine coarse-grained molecular dynamics simulations with complementary approaches—the egg-model [5,6] and the hot Stoner–Wohlfarth paradigm [7]—and introduce a simple analytical model based on stochastic magnetodynamics equations to describe magnetic relaxation under step-like varying magnetic fields. We focus on generic binary systems exposed to AC magnetic fields and examine whether the effective softening of magnetically hard particles and hardening of magnetically soft ones is a universal effect.

By exploring the relevant parameter space, we identify the conditions under which this behaviour emerges. Our results provide insight into the interplay of magnetic anisotropy, dipolar interactions, and dynamic fields, contributing to the design of magnetic fluids with tunable properties for applications such as magnetic hyperthermia.

Acknowledgements: This research has been partially supported by the RSF Grant No 25-22-00762.

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Development and validation of magnetic particle imaging-guided modeling and comparison with magnetic fluid hyperthermia in 3D printed mouse phantoms

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Local hyperthermia has been studied as a cancer treatment as it minimizes off target effects while killing cancer cells. Different methods of inducing local hyperthermia include laser interstitial thermal therapy, radiofrequency ablative therapy, and nanoparticle-mediated hyperthermia. Magnetic fluid hyperthermia (MFH) is a nanoparticle-mediated therapy where biocompatible iron oxide nanoparticles can be injected into the tumor and under applied alternating magnetic fields, generate heat. This approach is valuable due to the non-invasive nature, the local heat generation, and the ability to treat deep-seated tumors. The current lack of effective methods to predict thermal dose within a target treatment volume, in a manner compatible with treatment planning, hinders further development and adoption of MFH into clinical practice. Problems including tissue heterogeneity and uneven particle distribution throughout the tumor volume preclude uniform temperature distribution during MFH and are at odds with achieving the prescribed thermal dose throughout the tumor. Drawing inspiration from the field of image guided radiation therapy, this work seeks to address challenges in MFH thermal dosimetry estimation by combining non-invasive quantitative imaging of IONPs and Multiphysics heat transfer models. Magnetic particle imaging (MPI) is an emerging biomedical imaging modality that enables quantitative imaging of the distribution of IONPs in living subjects. While the potential of MPI for image-guided spatially controlled MFH has been suggested, using MPI to predict thermal dose needs to be validated [1,2]. This work demonstrates how MPI and COMSOL can be used in conjunction to develop an accurate model of thermal gradients and compare them to hyperthermia conducted in a 3D printed mouse phantom containing an anatomically located tumor cavity. First, iron oxide nanoparticles dispersed evenly in water were loaded into the tumor cavity. The phantoms then underwent magnetic particle imaging and CT scans, as would live mice, to get information on particle distribution and concentrations. The mice phantoms were treated with magnetic fluid hyperthermia by applying an alternating magnetic field, and the tumor temperature was recorded non-invasively using thermal videography. COMSOL Multiphysics heat transfer models were developed and compared with experimental data to validate the model. Utilizing 3D printed mouse phantoms eliminates the need to sacrifice mice to develop and validate this workflow and allows for direct comparison as values obtained in the model and through imaging can be compared to ground truth values as the geometries, iron concentration, and thermal properties of the materials used in this system are well defined. Future work will use this model to guide treatment and perform thermal dosimetry in vivo.

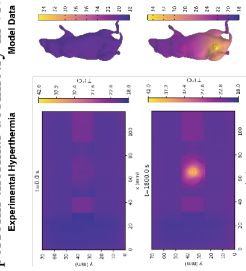


Figure. Hyperthermia experiment performed on 3D printed mouse phantom compared to model data generated for the same experimental conditions shows agreement.

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Repurposing mild magnetic hyperthermia for rapid intracellular labelling of immune cells for tracking applications

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Immunotherapy has revolutionized cancer treatment by leveraging the body's immune system through vaccines, allogeneic cell therapies, and immune-stimulating agents. Natural killer (NK) cells, key players in innate immunity, can eliminate abnormal cells without prior antigen exposure, making them pivotal for cancer therapy.¹ While NK-cell therapies have shown success in hematologic malignancies, their efficacy against solid tumors remains limited by biological barriers and immune evasion.^{2,3} Magnetic nanoparticles (MNPs) offer a versatile platform for targeted delivery, real-time imaging, and immune modulation via magnetic hyperthermia treatment (MHT).⁴⁻⁶ However, the inherent resistance of NK cells to MNP uptake, lower than macrophages and dendritic cells, remains a critical bottleneck for both diagnostic tracking and therapeutic strategies. Here, we present a novel protocol which makes use of mild heat generated by MNP under a safe radiofrequency to significantly enhance internalization in immune cells while preserving viability.⁷ We validated this approach using NK-92MI cells, primary NK cells, and other immune cell types, such as T cells. Short-term radiofrequency exposure resulted in a substantial increase in MNP uptake compared to passive incubation, as quantified by elemental iron analysis and confirmed by transmission electron microscopy. Importantly, MNP-loaded NK cells fully maintained their migratory properties alongside their degranulation ability and cytotoxicity against glioblastoma (U87) and neuroblastoma (SH-SY5Y) targets. The high MNP loading achieved also enabled the visualization and quantification of labeled cells using Magnetic Particle Imaging (MPI), providing a high-contrast, tracer-specific tool for non-invasive tracking.⁸ This simple test tube-based approach is robust, adaptable to various immune cell types and MNPs, and provides a clinically translatable platform to integrate nanomedicine with adoptive cancer immunotherapy.

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pH-Responsive Magnetic Iron Oxide Nanogels of Seed-Nanoflower-Chitosan for Cancer treatment

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This study aimed to develop pH-responsive magnetic nanocarriers for doxorubicin (DOX) delivery to improve therapeutic efficacy while minimizing the limitations and side effects associated with conventional chemotherapy. Iron oxide nanoflowers (IONFs) with an average size of approximately 50 nm were synthesized via a well-established one-pot polyol method [1]. The obtained nanogels were subsequently coated with chitosan (CS) using different crosslinking approaches involving NaOH, triphosphate (TPP), and glutaraldehyde (GLU), resulting in sIONFs@CS-NaOH, sIONFs@CS-TPP, and sIONFs@CS-GLU nanogels [2]. The successful fabrication of the nanogels and their DOX-loaded counterparts was confirmed by Fourier transform infrared spectroscopy (FTIR) and X-ray diffraction (XRD). Hydrodynamic size distribution, surface charge, and morphology were characterized by dynamic light scattering (DLS) and transmission electron microscopy (TEM). The drug loading capacity was quantified, and the *in vitro* release behavior of DOX was evaluated at different pH media to mimic tumour and physiological environments. Confocal laser scanning microscopy demonstrated enhanced cellular uptake of the nanocarriers in prostate and melanoma cancer cell lines. In addition, cytotoxicity was assessed using MTT assay, revealing that DOX-loaded nanoplatforms exhibited significant anticancer activity. Overall, the results suggest that sIONFs@CS-TPP-DOX nanogels constitute a promising, targetable, and biocompatible nanoscale drug delivery system for potential applications in cancer therapy.

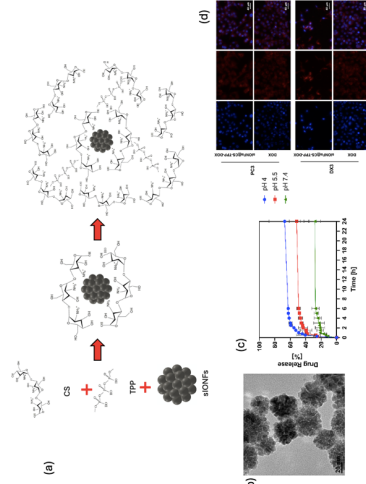


Figure 1. (a) Schematic illustration of the preparation of chitosan-based magnetic nanogels formed by coating sIONFs with chitosan using TPP crosslinking. (b) TEM image showing the morphology of the synthesized sIONFs nanostructures. (c) In vitro DOX release profiles of the nanocarriers under different pH conditions (pH 4, 5.5, and 7.4), demonstrating pH-responsive drug release behavior. (d) Confocal fluorescence microscopy images showing cellular uptake of FITC-labeled DOX-loaded nanocarriers in cancer cells.

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Predictive Magneto-Hydrodynamic Simulations of Ferrofluids for Biomedical Applications

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Magnetic nanoparticles (MNP) are widely employed in applications where they are dispersed in a fluid medium, including magnetic hyperthermia, biosensing, or drug delivery. Despite this, many theoretical and computational models neglect the particle motion within the fluid and the role of hydrodynamic interactions on particle dynamics. This simplification can lead to significant discrepancies when predicting experimentally relevant observables.

In this work, we present UAMMD-Magnetic, an extension of the UAMMD framework[1], originally developed for the hydrodynamic simulation of colloidal suspensions, which has been generalized to incorporate magnetic phenomena. The framework enables the coupled simulation of spatial and magnetic degrees of freedom as well as magnetic and hydrodynamic interactions within a unified GPU-accelerated environment.

We demonstrate the capabilities of the method through representative applications, including the prediction of AC magnetization cycles, dynamic susceptibility, and spectral response. In particular, we show that the framework is able to provide quantitative predictions of experimental signals (see Figure). Furthermore, we analyze how both magnetic and hydrodynamic interactions influence these observables, highlighting the importance of consistently accounting for their coupling in realistic modelling of MNP suspensions.

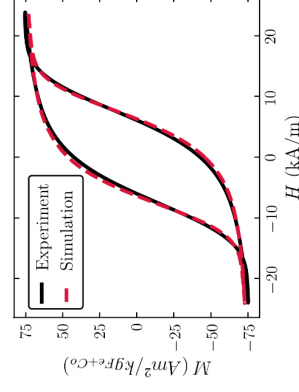


Figure. Example comparison between an experimentally measured AC magnetization cycle at 10 kHz and 24 kA/m and the corresponding numerical prediction

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Towards Magnetorelaxometry-Based Real-Time Remote Magnetic Nanoparticle Thermometry for Thermotherapy Applications

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A promising medical application of magnetic nanoparticles (MNP) is magnetic thermotherapy. To facilitate the success of the treatment and patient safety, this application requires monitoring of the MNP temperature. Magnetorelaxometry (MRX) shows potential for remote temperature monitoring. In MRX, the MNP moments are first aligned using an external DC magnetic field pulse and then the relaxation of the net magnetization is recorded after sudden deactivation of the field. A temperature dependence has already been demonstrated for the typical relaxation signal parameters relaxation amplitude and relaxation time (Arsalani et al., *Phys. Med. Biol.*, 2023). However, this temperature effect has not yet been investigated for the MNP-mediated magnetic thermotherapy. For this reason, we investigated changes in MNP temperature during a magnetic heating regime with the long-term goal to estimate the temperature based on the MRX parameters.

A sample consisting of 100 μL RCL-01 (Resonant Circuits Limited, UK) immobilized in gypsum was placed inside a magnetic heating unit (Resonant Circuits Limited, UK) and directly in front of an optical magnetic gradiometer (OMG, Twinleaf, USA) and an excitation coil (see Fig. 1, left). A background magnetic field of $B \approx 16 \mu\text{T}$ was applied for operating the OMG. The sample temperature was measured directly within the sample using a fiber-optic thermometer (OSENSA Innovations Corp., Canada). All components were placed inside a magnetically shielded room. A measurement procedure consisting of two heating phases (each approx. 230 s long) and two passive cooling phases (each approx. 460 s long) with continuous MRX was performed. The repetitive excitation regime consisted of an RF pulse (duration 400 ms, $f \approx 790 \text{ kHz}$, $H \approx 2.3 \text{ kA m}^{-1}$) followed by MRX with 100 ms excitation phase ($B \approx 16 \text{ mT}$) and 3000 ms measurement phase. For each MRX shot, both relaxation parameters were calculated.

Figure 1 (right) shows the preliminary results for the change in relaxation amplitude during the first heating phase as a function of MNP temperature. As the temperature increases, the absolute value of the relaxation amplitude decreases slightly. It is assumed that a more pronounced temperature effect can be observed both through an optimized selection of parameters for simultaneous heating and MRX and by considering the full hyperthermia temperature range up to approximately 45°C .

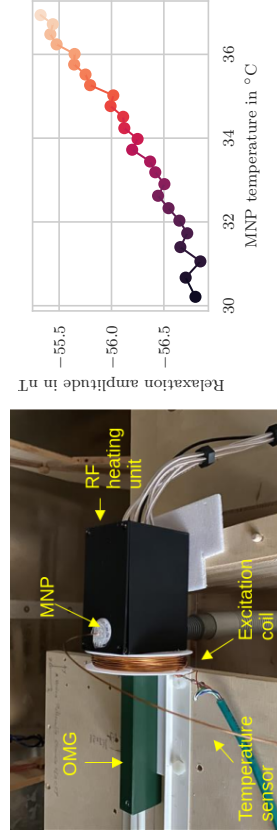


Figure 1. Left: Combined setup for RF heating and MRX measurement. **Right:** Relaxation amplitudes of the RCL-01 sample as a function of MNP temperature measured directly inside the sample during magnetic heating.

Dual-Session Magnetic Fluid Hyperthermia Induces Complete Regression of Hetero-Multicellular Stroma-Rich Breast Cancer Spheroids with Predominant Apoptotic Cell Death

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Magnetic fluid hyperthermia (MFH) is an emerging minimally invasive cancer therapy that uses magnetic nanoparticles to selectively heat tumors to $42\text{--}45^\circ \text{C}$ under an alternating magnetic field to kill cancer cells. Despite the therapeutic promise of MFH, the broader bench-to-bedside translation of MFH remains limited by heterogeneous nanoparticle distribution, inconsistent tumor heating, and difficulties with real-time thermal monitoring in deep-seated tumors, ultimately leading to variable therapeutic outcomes. This emphasizes the need to standardize key treatment variables at the in vitro level to improve predictive value and reduce trial failure. Monolayer cultures have been predominantly utilized in in vitro studies. However, these conventional models fail to recapitulate the structural and stromal complexity of solid tumors and thus can often overestimate therapeutic efficacy. To address these challenges, hetero-multicellular breast tumor spheroids were developed by co-culturing breast adenocarcinoma cells MCF-7 with non-cancerous murine fibroblasts McCoy at a 1:3 ratio using the liquid overlay technique. The developed breast cancer spheroids exhibited an in vivo-representative stroma-rich tumor microenvironment (TME), characterized by fibroblast activation, deposition of a collagen-rich extracellular matrix, and spatial arrangement of proliferative, non-proliferative, and necrotic cells. After identifying the most tumor-representative spheroid subtype, the hyperthermic potential of poly(acrylic acid)-coated $\text{Mn}_0.9\text{Zn}_{0.1}\text{Fe}_2\text{O}_4$ nanoparticle-based magnetic fluid was evaluated. A single MFH session induced significant cytostatic effects and apoptosis without substantial spheroid disruption, while two sequential MFH sessions led to near-complete spheroid eradication, a significant loss of viability, and prominent apoptosis. These findings suggest that repeated MFH sessions can overcome diffusion barriers and residual thermotolerance in complex TME, establishing a promising strategy for treating stromal-rich breast tumors.

Keywords: Magnetic fluid hyperthermia, Magnetic nanoparticles, 3D hetero-multicellular tumor spheroids, Breast cancer, Liquid overlay technique, Apoptosis.

Chemical coupling of biological magnetosomes with amine-functionalized antibody conjugates to improve immuno-associated cancer therapy

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Chemo- or radio- associated immunotherapy is a strategy that have been developed to overcome resistance to radiotherapy and chemotherapy. However, these conjugated antibodies are not able to complete several specificities, including a fast delivery and specific targeting, required to avoid unwanted side effects on healthy tissues. One strategy to overcome kinetic and targeting issues is to use magnetosome as vehicle to improve immune-associated therapy delivery into the tumor site. These magnetosomes are biogenic magnetic nanoparticles produced by magnetotactic bacteria that have the ability to be magnetically guided into tumor site and genetically or chemically modified by attaching specific tumor cell ligands on their surface leading to a fast kinetic delivery [1]. In addition, we have shown that magnetosomes are biocompatible theranostic agents surpassing synthetic nanoparticles in terms of ultrasensitive T2 contrast agents for magnetic resonance imaging but also sensitizers for cancer radiotherapy [2] and phototherapy [3].

The major challenge of this study lies in the fact that antibodies are mostly conjugate with drugs or radioelements using lysines residues that will impede amine dependent antibodies binding to magnetosome. To overcome the unavailability of antibody amine functions, we developed a new chemical strategy based on partial antibody reduction to use thiol groups as binding site. We demonstrated the efficiency and robustness of our magnetosome-antibody conjugates which is of primordial relevance for future *in vivo* experiments and opens up prospects for synergistic immunotherapy treatments associated with the theranostic properties of magnetosomes.

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Complex-Weighted Differential Harmonic Extraction in Magnetoresistance Sensor-Based Magnetic Particle Spectroscopy

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Magnetic particle spectroscopy (MPS) enables quantitative detection of magnetic nanoparticles (MNPs) for biomedical diagnostics and biosensing [1]. Giant magnetoresistance (GMR) sensors provide a compact alternative for magnetic detection [2] and have been explored in nanoparticle sensing applications [3]. In previous works, we investigated the integration of GMR sensors into an MPS platform. In Fig. 1(a), an anti-Helmholtz coil configuration creates a near-zero excitation field region that allows direct sensor integration, while a differential GMR sensor pair suppresses background signals such as excitation feedthrough. However, amplitude and phase mismatch between sensors limit the effectiveness of simple differential subtraction. We address this by implementing a complex-weighted differential algorithm. For harmonic h , the sensor phases derived from lock-in extraction $Z_{A,h}$, $Z_{B,h}$ are combined using a baseline-derived weight: $w_h = -\frac{(Z_{A,h} \cdot Z_{B,h}^*)}{(Z_{B,h}^2)_{baseline}}$, yielding the differential signal $Z_{diff,h}(t) = Z_{A,h}(t) + w_h Z_{B,h}(t)$, which compensates both gain and phase mismatch.

The algorithm is evaluated using concentration-sweeping measurements of 100 nm diameter MNPs (BNF, micromod Partikeltechnologie GmbH). The complex weighting significantly improves the linear concentration dependence of harmonic signals compared with single-sensor detection, as is shown in Fig. 1(b). In particular, for the third harmonic, the coefficient of determination improves from $R^2 = 0.048$ to $R^2 = 0.916$, demonstrating effective background suppression and recovery of monotonic nanoparticle response. While effective for background suppression, the method may attenuate signals, when both sensors detect strong nanoparticle responses, highlighting limitations of differential configurations. These results demonstrate the feasibility of combining differential GMR sensors with complex-weighted processing to improve signal extraction in compact MPS systems, potentially enabling GMR-based biosensing platforms.

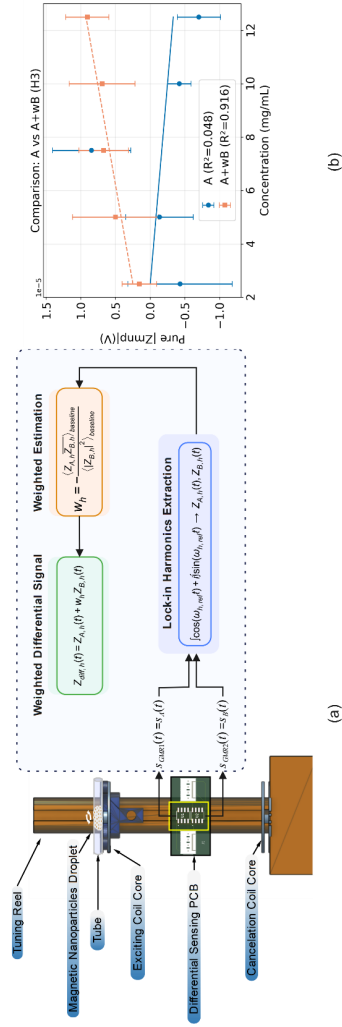


Figure 1. (a) Experimental setup and signal processing workflow of the giant magnetoresistance (GMR)-based magnetic particle spectroscopy (MPS) system. (b) Concentration-sweeping results for 100 nm magnetic nanoparticles showing improved linearity of third harmonic signal using complex-weighted differential combination (A+wB) compared with a single sensor (A).

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Design of Amino-Modified PLA Nanospheres as a Promising Platform for Nitric Oxide Delivery

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The therapeutic potential of nitric oxide (NO) in cardiovascular treatment and wound healing is well known, but its short half-life and high reactivity limit its clinical use. S-nitrosothione (GSNO), an endogenous NO donor, is a promising alternative; however, its hydrophilicity and rapid degradation complicate delivery. Poly(lactic acid) nanospheres (PLANS) are suitable drug carriers due to their biocompatibility and controlled degradation, but their hydrophobic matrix makes encapsulation of hydrophilic GSNO difficult. Therefore, surface engineering is necessary to enable stable drug binding instead of simple matrix incorporation.

In this study, two post-synthesis amino-functionalization strategies were developed to modify PLANS. The first involved coating with chitosan hydrochloride (CS-HCl) to bridge the polarity gap between PLA and GSNO, while the second utilized poly-L-lysine-modified magnetic nanoparticles (PLLMNPs). Optimal modification conditions were determined using Z-average and zeta potential measurements of the nanoparticles at different weight ratios. This led to an optimal CS/PLANS weight ratio of 0.4, whereas the best MNPs/PLANS weight ratio was 2.7 (Fig.1). The optimised systems were subsequently used for GSNO binding, achieving optimal GSNO loading capacities of 0.118 mg/mg for CS-PLANS and 0.127 mg/mg for PLLMNPs-PLANS. SEM and HRTEM analyses revealed the formation of spherical nanoparticles with an average diameter of < 200 nm (Fig. 1, insets).

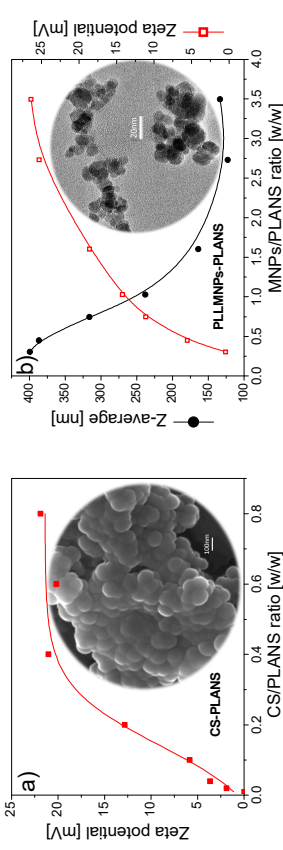


Figure 1: Zeta potential and Z-average of (a) CS-PLANS and (b) PLLMNPs-PLANS as a function of their input weight ratios. Insets represent (a) SEM and (b) HRTEM images of the related samples.

The magnetic performance of PLLMNPs-PLANS was also evaluated using quantitative MRI relaxometry, revealing strong transverse relaxation enhancement. The nanocomposites exhibit high T_2 (400 $\text{mM}^{-1}\text{s}^{-1}$) and T_2^* (~530–556 $\text{mM}^{-1}\text{s}^{-1}$) values with relatively low T_1 (~1.5–1.6 $\text{mM}^{-1}\text{s}^{-1}$), resulting in elevated T_2^*/T_1 ratios. The results revealed significant T_2 contrast enhancement. These findings demonstrate that the platform serves not only as a carrier but also as an effective T_2 -weighted contrast agent, enabling sensitive, real-time monitoring of nanoparticle distribution *in vivo*, *ex vivo* and *in vitro*.

The biological importance of the system was independently confirmed in *in vivo* rat models, demonstrating that GSNO-loaded nanoparticles effectively enhanced nitric oxide bioactivity, thereby improving endothelial function and conferring vasoprotective effects.

By combining controlled surface chemistry with high-performance magnetic nanoparticles (PLLMNPs), we have developed a versatile system that overcomes the challenges of NO delivery while offering theranostic capabilities.

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Design, fabrication, characterization and modeling of additive manufactured devices using novel magnetic nanoinks for label-free magnetic cell fractionation

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Cell fractionation separates cells based on physicochemical differences, and magnetic manipulation enables a non-contact, non-invasive control of particles and cells in microfluidic systems. In this research, label-free magnetophoresis enabled by additive manufactured magnetic nanoink-based devices is employed to fractionate cells into different fractions relying on differences in magnetic susceptibility. This technique allows separation of certain cell populations with distinct magnetic susceptibility without the need for antibody labeling or exogenous magnetic tags which can affect cell's functionalities. Thus, unlike conventional cell fractionation methods that rely on surface-marker targeting and chemical conjugation, label-free magnetophoretic separation exploits endogenous magnetic properties, thereby reducing sample preparation steps, minimizing biological perturbation, and preserving native cellular functionalities.

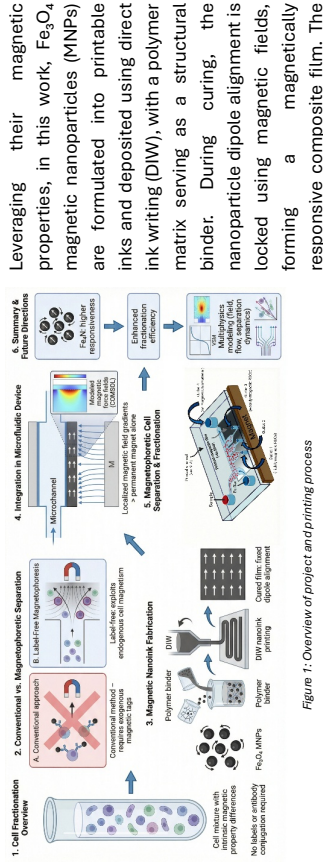


Figure 1: Overview of project and printing process

DIW process enables precise control of film geometry, allowing customizable magnetic structures to be seamlessly integrated with microfluidic devices. Once cured, the fixed dipole alignment generates strong localized magnetic field gradients when exposed to a constant field from an adjacent permanent magnet. The fabricated devices are characterized by using microscopy and magnetic measurement techniques through a vibrating sample magnetometer (VSM), and the printed films are modeled in COMSOL Multiphysics to quantify the magnetic force fields generated around the structures. Once the COMSOL simulations are validated, the optimization of the magnetic field gradients will be performed, and we will also explore other MNPs such as Fe₃N to further improve magnetic responsiveness and fractionation efficiency. When integrated alongside a microfluidic flow channel containing heterogeneous cell suspension, these films are anticipated to generate localized magnetic field gradients which are higher than what permanent magnets can create alone, which facilitate label-free magnetophoretic separation of cells, enabling effortless selective label-free fractionation. Ongoing work is focused on modeling the magnetophoretic system for the fractionation of red blood cells based on their intrinsic magnetic susceptibility and iron content. The project goal and methodology are summarized in Figure 1.

In Vivo Magnetorelaxometry of Iron Oxide Nanoparticles: Temporal Evolution of Relaxation Behaviour Following Injection

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Magnetic nanoparticles (MNPs) are widely investigated for therapeutics applications, where their efficacy depends on local concentration, degree of immobilisation, and interaction with the biological environment. Magnetorelaxometry (MRX), in which MNPs are magnetized by an external DC magnetic field and the decay of their net magnetic moment is recorded after rapid switch-off of the DC field, provides a sensitive and non-invasive probe of these properties. However, systematic *in vivo* MRX studies tracking the temporal evolution of nanoparticle relaxation behaviour after implantation remain scarce. Here, we present time-resolved *in vivo* MRX measurements performed with giant magnetoresistive (GMR) sensors to monitor changes in the relaxation signal of iron oxide nanoparticles over days following implantation in a mouse model.

RCL-01 iron oxide nanoparticles (Resonant Circuits Limited, UK) were administered by subcutaneous injection, and MRX measurements were recorded at day 0 (starting 17 minutes post-injection), day 3, and day 6. A GMR-based sensor setup (Figure 1) was used for detection of the MRX signal. A separate magnetic field generator delivering a time-varying magnetic field operating at 100 kHz was used to heat the implanted MNPs in a periodic pulse-and-probe cycle. For the data presented here the MNP temperature was in the range 36–38 °C throughout the measurements.

Figure 2 shows the mean MRX relaxation curves for the three time points. On day 0, the relaxation curve exhibits a high initial amplitude (ca. 1700 nT) with rapid decay, consistent with a substantial Brownian relaxation contribution from mobile particles. By day 3, the initial MRX amplitude had decreased to ca. 1000 nT while the relaxation time increased markedly, as evidenced by the much slower time-dependent decay of the magnetisation. We interpret this as being associated at least in part with the post-implantation immobilisation of the MNPs within the tissue, and a consequent shift toward Néel-dominated relaxation. On day 6, the MRX curve retained a similarly slow decay but showed a slight amplitude reduction compared to day 3, which we postulate may be attributed to partial material clearance or degradation.

Although these are very early measurements using an *in vivo* experimental set-up that is still being optimised, we believe that these results demonstrate that *in vivo* MRX can resolve meaningful changes in nanoparticle mobility and quantity over days following injection, providing information relevant to therapeutics planning and monitoring.

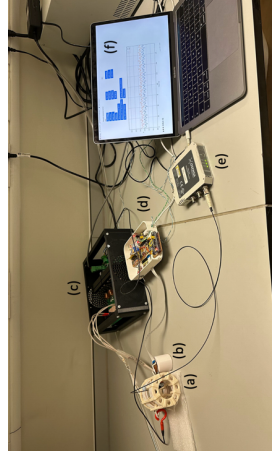


Figure 1. Combined magnetorelaxometry and magnetic hyperthermia measurement platform. (a) Helmholtz coil with 3D-printed sample holder; (b) GMR gradiometer on 3D-printed mount; (c) magnetic field generator operating at 100 kHz; (d) custom MRX pulse control and data acquisition electronics; (e) fibre optic probe for real-time temperature monitoring; (f) laptop running custom Python control software.

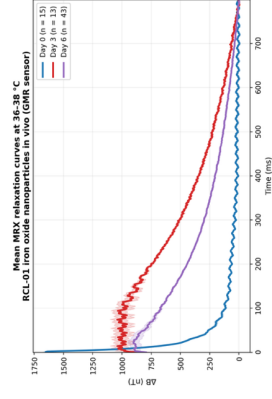


Figure 2. Mean MRX relaxation curves at an MNP temperature of 36–38 °C measured *in vivo* at day 0, day 3, and day 6 following injection of RCL-01 nanoparticles in a mouse model. Shaded regions indicate $\pm$ SEM. The rapid decay immediately after implantation on day 0 ($\tau \approx 20$ ms) reflects Brownian relaxation of mobile nanoparticles, while the progressively slower decays on days 3 and 6 ($\tau > 300$ ms) indicate immobilisation within tissue and a shift toward Néel-dominated relaxation.

Magnetic hyperthermia at the nanoscale

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Magnetic hyperthermia is one of the key applications of magnetic nanoparticles (MNPs) for catalysis or for biomedical applications¹. Evidences have been proposed for local effects of thermal activation, even at very low nanoparticle concentrations, and only at their vicinity². The local heat exchange around those nanoprobe is, however, still under controversy with too few evidences on its origin and even on its existence. Recently, we have investigated two different processes that are of prime importance to understand magnetic hyperthermia: the heat generation inside the nanoparticles and the direct thermal transfer at given distances from their surface. First, recent published worked demonstrated no thermal gradient around nanoparticles^{3,4}. This is, however, not in accordance with experimental evidences that a temperature gradient can be detected (fig.1). In a recent work, we analysed the detection of heat exchange on photosensitive ligands permanently and covalently bounded to the surface of maghemite nanoparticles. The measurement of rhodamine B lifetime allowed to evaluate the thermal increase, in very dilute nanoparticle dispersions, at 4 given distances ranging from 5 to 7 nanometres from the surface. We globally obtained coherent results compared to already published works achieved with thermolabile ligands^{4,6}, but without chemically cleavable groups at the surface of nanoparticles in solution. This whole strategy dedicated to a whole map of thermal transfer into and from the nanoparticles is the keystone to analyse more precisely the impact of heat exchange between magnetic nanoparticles and their surroundings.

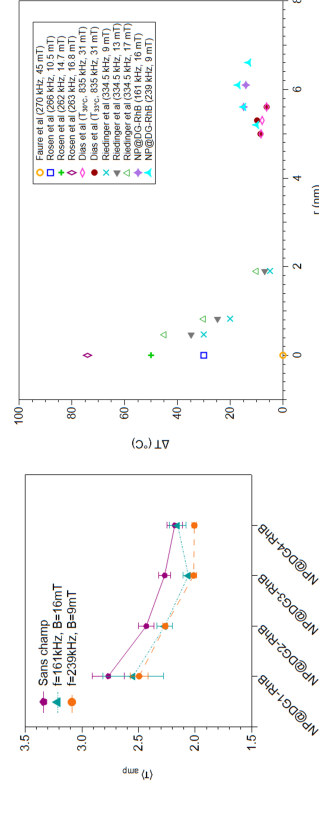


Figure 1: The lifetime of Rhodamine B grafted on MNPs under magnetic hyperthermia. Our data compared to literature with cleavable ligands.

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Framework for Assessing the Distinguishability of Magnetic Nanoparticles used in Color Magnetic Particle Imaging

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Magnetic Particle Imaging (MPI) enables highly sensitive and quantitative imaging of magnetic nanoparticles (MNPs). Color MPI (cMPI) has recently attracted significant interest as it enables not only the simultaneous differentiation of multiple nanoparticle types but especially to distinguish changes due to the local MNP environment within one single measurement. This capability opens new opportunities for advanced applications such as multiplexed tracer imaging, functional imaging, and the separation of signals originating from the MNP in different biological compartments and their resulting states (taken up by cells, attached to an extracellular matrix, accumulated in organs). However, selecting suitable MNP references for (calibration in) cMPI requires systematic characterization.

We developed a framework to evaluate the suitability of MNPs for cMPI based on Magnetic Particle Spectroscopy (MPS), as both MPI and MPS follow the same physical principle - the nonlinear dynamic magnetic response of MNP moments - for signal generation. By analyzing characteristic signal features of MPS spectra, we use quantitative metrics to assess different MNP systems with respect to their discrimination in cMPI. To this end, a principal component analysis (PCA) based on the real and imaginary parts of the harmonic spectrum is carried out.

To exemplify our methodology, we used four commercial MNP systems: one Synomag (COOH, 30 nm) and three differently coated Perimag systems (plain, NH₂ and COOH, 130 nm) all from Micromod Partikeltechnologie GmbH, GER. Furthermore, binary (25%/75%) mixtures out of them in different states (fluid, immobilized, aggregated) were investigated from which the distinct spectral signatures were investigated. Figure 1 shows the analysis of the four pure systems (circles) and six different mixtures in the fluid state (squares) where the spectral differences are visualized by the two main PCA components. They allow clear differentiation between pure systems, with their mixtures lying between the PCs of the pure systems. Interestingly, mixtures of all NH₂ Perimag systems show deviations from this behavior which is ascribed to interactions (aggregation) of the differently charged coatings.

The proposed approach enables rapid and reproducible assessment of MNP performance for cMPI without need of full imaging experiments.

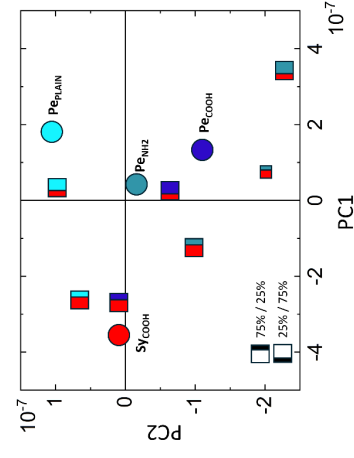


Figure 1: PCA analysis of 4 pure MNP systems and six binary MNP mixtures (25%/75%) in the fluid state. A smaller distance between points indicates higher spectral similarity and consequently reduced separability in cMPI. The circles refer to the pure systems (Synomag-COOH, Perimag-plain, -COOH, -NH₂) and the squares indicate the color-coded mixtures.

Magnetic Nanoflowers as MRI Contrast Agents: Shape, Coating and Size Effect on ¹H-NMR Properties

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In nanomedicine, iron oxide-based magnetic nanoparticles (MNPs) play a significant role in the diagnostic field, as contrast agents (CAs) for the magnetic resonance imaging (MRI) technique. The magnetic nature and high magnetization values induce sizeable inhomogeneities in the local magnetic field, perturbing the surrounding hydrogen nuclei present in the biological tissues of a particular region of interest (ROI). The perturbations at nuclear sites shorten the *spin-lattice* (T_1) and *spin-spin* (T_2) nuclear relaxation times, enhancing the contrast in the MRI images, an effect quantified by the nuclear longitudinal and transverse relaxivity ($r_{1,2}$). The spin dynamics of the MNPs depend on their morpho-structural features [1] and the present work focuses on the relaxometric properties of magnetic nanoflowers (NFs), which can be thought as clusters of single iron-oxide particles with cooperative magnetic behavior. The effect of changes in particle's shape, and in nanoflowers coating and size on the relaxivities was decoupled, highlighting a tunable feature of MNPs to improve MRI contrast efficiency.

The studied nanoflowers are composed of single cores of maghemite with a diameter $d = 10 \pm 2$ nm, clustered in flower-like particles with equivalent diameters of about 21, 25 and 34 nm (NF21, NF25 and NF34). They were synthesized by the polyol method (autoclave or MW), considering a non-classical pathway regulated by amines [2]. All sets were coated with poly(acrylic-acid) PAA, while NF25 was also coated with carboxymethyl-dextran CM-D. They were morpho-structurally characterized through TEM, XRD, DLS and IR measurements, and the magnetic properties were investigated by collecting M vs H curves at room temperature with a SQUID. The relaxometric properties were studied by acquiring ^1H -NMR longitudinal and transverse profiles in the 0.01 MHz < ν < 63.86 MHz Larmor frequency range. The Roch-Müller-Gillis heuristic model [3] was used to fit the relaxometric data and evaluate additional microscopic information about these systems. They were compared with single core spherical nanoparticles (NS) with a $d = 11 \pm 2$ nm. The differences in the relaxometric behavior were observed to depend on the shape, the coating and the flower size. A comparison with the withdrawn commercial contrast agent Endorem highlighted a promising enhancement of the image contrast, which might reduce the injected dose by up to a factor of ~ 5 .

Flower-like nanoparticles represent a relatively underexplored class, and the study of their spin dynamics provides a powerful tool that allows for fine-tuning of the nuclear relaxation mechanisms of these nanometric systems to enhance efficiency in a wide range of fields of application.

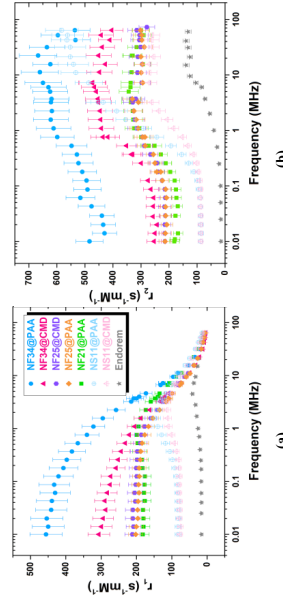


Figure. Longitudinal relaxivity r_1 (a) and transverse r_2 (b) ^1H -NMR-d profiles of the studied samples.

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Empirical evaluation of non-harmonic asymmetric waveforms magnetic hyperthermia with magnetic nanoparticles

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Magnetic hyperthermia for oncologic treatment is a therapy based on the increment of the temperature of tumoral cells. This is achieved by injecting magnetic nanoparticles into the cancerous cells and the application of an alternating magnetic field at a high frequency, typically from 100 kHz to 1 MHz. Consequently, the nanoparticles heat the medium and produce local hyperthermia which is particularly damaging for cancerous cells. Current research is focused on maximizing the efficiency of the heating, which is measured by the Specific Absorption Rate (SAR), either by optimizing the nanoparticles or applying more efficient waveforms.

Regarding the magnetic waveforms, the most important factors that affect SAR classically were the frequency and amplitude of the signal, both of which had to increase to improve heating efficiency. However, further research has shown that the shape of the signal is also a determining factor: non-harmonic signals with a higher slope at the transient phase (as square waves) have been proven to perform better than traditional sinusoidal waves not only in terms of SAR but also in the mortality of tumor cells in *in vitro* experiments. Moreover, calculations made in "Fine tuning and optimization of magnetic" by G.Barrera *et al*, suggested that asymmetrical non-harmonic waveforms might increase the effectiveness of the treatment even further, at the same frequency and amplitude. Asymmetric waveforms are characterized by having a different slope in the rising and falling part of the signal, as can be seen in Figure

This hypothesis has never been tested experimentally so we designed and fabricated a custom device that is able to generate a variety of non-harmonic asymmetrical waveforms. The device is capable of producing 6 different slope relationships (1:1, 1:2, 1:3, 1:4, 1:5, and 1:6) for frequencies between 100 KHz – 1Mhz. It is based on a MOSFET-based H-bridge that commutates two power sources across the coil. By modulating the timing of the MOSFETs and the voltage level of the power sources we are able to produce signals with different shapes and slope relationships. Some of them are shown in Figure A.

Using this newly home-made device, we tested the heating efficiency of different signals depending on the slope relationships between the rising and falling edge. However, due to the novelty of the device, the SAR assays with the nanoparticles are not complete at the time of this abstract. They will be finished by the time of the congress. Initial tests have been performed on un-coated spherical nanoparticles with a radius of 10 nm. The waveforms tested have 50 % of the period in the flat state 0% of the signal in that same state with a frequency of 100 kHz and field intensities of 0.9 mT, 1.8 mT and 2.7 mT. The slope relationships tested were 1:1, 1:3 and 1:6 and the first results suggest a positive relationship between slope relationship and SAR, although it requires high slope relationships (1:6) to attain a SAR increase of around 20%.

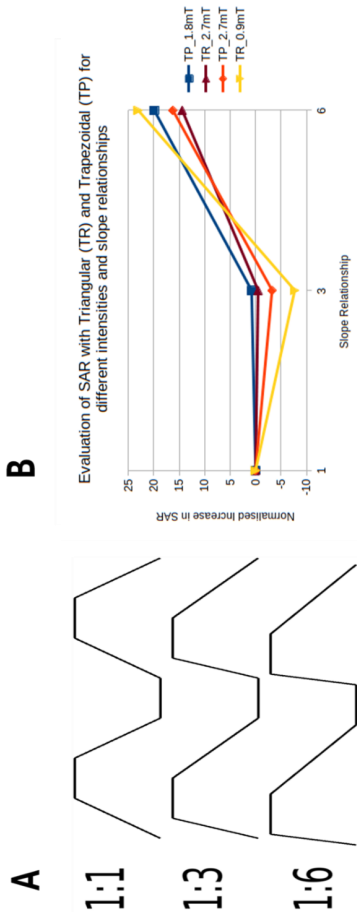


Figure. A) Diagram depicting the different waveforms used in the experiments. In this case the flatness part corresponds to the 50% of the signal and the slope relationship are 1:1, 1:3 and 1:6. B) Results of SAR normalization on spherical nanoparticles with trapezoidal and triangular waveforms at 100 kHz with different slope relationships and field intensities.

Magnetic hyperthermia treatment using pulsed-shaped waveforms in glioblastoma multiforme cell line using nanoflowers-shaped nanoparticles: Effects on cell death and cell migration

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Magnetic hyperthermia (MHT) is an emerging strategy for cancer therapy in which magnetic nanoparticles are used to produce localized heating when exposed to an alternating magnetic field, commonly operating within a frequency range of 100 kHz to 1 MHz. Traditionally, these fields have been applied using sinusoidal waveforms. However, recent studies have shown that trapezoidal pulsed alternating magnetic fields can provide a promising alternative, as they can improve the heating efficiency of the nanoparticles and produce a more effective thermal response during MHT treatments.

Glioblastoma multiforme (GBM) represents the most common and aggressive type of primary brain tumor. GBM is characterized by rapid proliferation and a strong capacity to infiltrate surrounding brain tissue, which significantly contributes to its poor prognosis and makes it one of the most lethal brain tumors.. Nevertheless, treatment remains challenging due to the pronounced molecular and cellular heterogeneity of the tumor, as well as the substantial variability observed both between patients and within different regions of the same tumor, factors that considerably complicate effective clinical management.

The MHT system used in this study was home-developed and represents a unique platform worldwide. Unlike conventional devices, it can generate a wide range of non-sinusoidal waveforms, from triangular to near-square shapes. This flexibility is achieved by modulating the flat segments of the waveform through precise control of the switching times in an H-bridge circuit. The system operates over a broad frequency range, spanning from 100 kHz to 1 MHz.

To assess the effectiveness of the MHT system *in vitro*, GBM mouse cells previously incubated with magnetic nanoparticles, are treated for 1 hour with a trapezoidal waveform of 200 kHz and 4.1 mT of field intensity. The nanoparticles employed are the Synomag-D nanoflowers, which are composed of iron oxide, have an average diameter of 50 nm and were used in a concentration of 3mg/ml.

After MHT treatment, cell viability and cell migration were evaluated. Results suggest that MHT treatments reduce cell viability (Figure A) and cell migration capacity (Figure B), which could imply a decrease in cellular motility and, thus, a lower likelihood of metastasis formation and a reduced ability to invade surrounding tissues. In addition, immunogenic cell death induced by the MHT treatment is being studied by analyzing thermal stress markers (HSP70). Staining for ICD markers is still ongoing, and the final results will be presented at the conference.

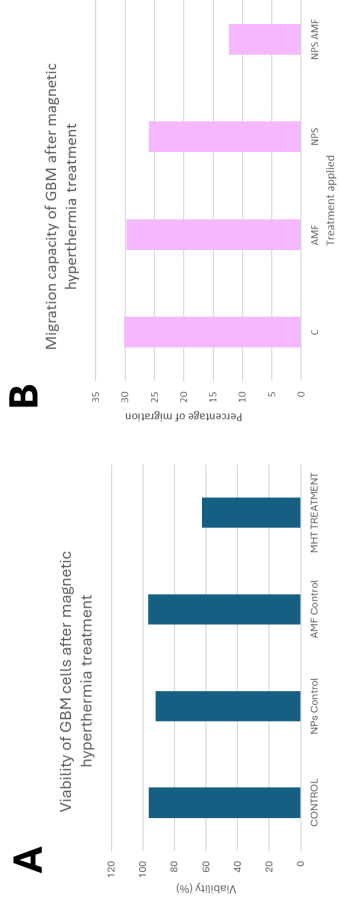


Figure. (A) Viability of the treatment with nanoflowers and trapezoidal waveform at 200 kHz and 4.1 mT (B) Bar graph of cell migration percentage of GBM cells under different conditions. C: control. AMF: cells exposed to alternating magnetic field, NPS: cells exposed nanoflowers nanoparticles, NPSAMF: cells exposed to nanoflowers nanoparticles and alternating magnetic field (standard magnetic hyperthermia treatment).

Urease-Powered Nanorobots Enhance Tumor Penetration and Hyperthermia Efficiency in 3D Cancer Cell Spheroids

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Magnetic fluid hyperthermia (MFH) of superparamagnetic iron oxide nanoparticles (SPIONs) is a promising approach for targeted cancer therapy, as it enables depth-independent energy deposition via magnetization losses [1]. Self-propelling nanoparticles, usually called nanorobots (NR), have been proposed as drug delivery systems capable of overcoming limited target accumulation and poor tumor penetration [2,3]. NR propel themselves through catalytic reactions of enzymes immobilized on their surface, consuming an enzyme-specific substrate as chemical fuel [4,5].

In this work, we show that urease-powered NR penetrate deeper into rat pancreatic cancer cell spheroids and generate higher temperatures during MFH than non-functionalized nanoparticles. These results highlight the potential of enzyme-powered NR in cancer therapy via MFH. The urease-powered NR used in this work were made from commercially available magnetic nanoparticles (Synomag®, Micromod, Rostock, Germany), which were functionalized with urease (Sigma-Aldrich, St. Louis, USA). Images were acquired using a laser scanning microscope (LSM 880, Carl Zeiss AG, Oberkochen, Germany). The uptake of nanoparticles in spheroids is demonstrated and shown in Figure 1 a,b. To enable spheroid loading with NR, the incubation time was reduced to prevent damage to the spheroids, likely caused by ammonia production during the catalytic reaction. Compared to non-functionalized nanoparticles, NR show a higher accumulation within the spheroids. MFH measurements were conducted using a custom-built magnetic hyperthermia device ($f=302\text{ kHz}$, $A_{MHF}=30\text{ mT}$). The results demonstrate that NR achieve higher temperatures than non-functionalized nanoparticles (44°C compared to 42°C). The presence of urea further increases the heating efficiency, leading to temperatures of up to 47°C (Figure 1 c). Furthermore, these nanorobots have the potential to be visualized by means of MPI.

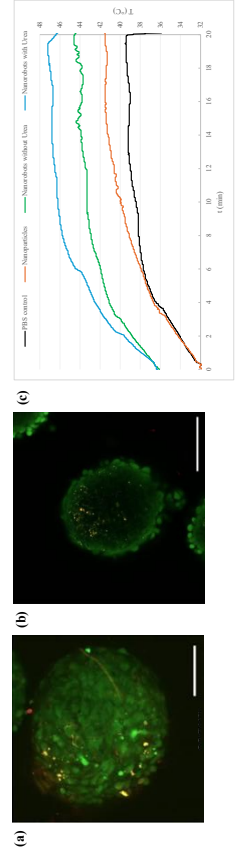


Figure 1: Uptake of nanoparticles (orange) in spheroids (a,b). MFH measurements reveal higher temperatures for NR, further enhanced by urea (c). The scale bar corresponds to 50 µm.

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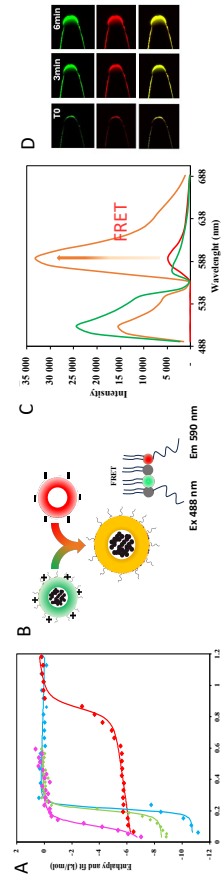
Fusion of Magnetic Liposomes with Model and Plasma Membranes: Towards Cytoplasmic Delivery

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Magnetic nanoparticles (MNPs), like many other nanoparticles, are internalized by cells via endocytosis and become confined within intracellular vesicles known as endosomes. However, for several bio-applications, such as cellular engineering or magnetic hyperthermia treatments, it is necessary that MNPs access the cell cytoplasm. This cytoplasmic delivery would minimize dipolar interactions between the MNPs and enhance their intracellular heating properties¹. In this study, we propose a novel strategy using **Magnetic Fusogenic Liposomes (MFLs)**. Fusogenic liposomes have the unique ability to fuse with the plasma membrane, and consequently deliver their contents directly into the cytosol.

MFLs composed of DOTAP/DOPE/PEGPE/TopfluorPE (45.5/45.5/4.5/4.5 molar ratio, 200 nm) were prepared by reverse phase evaporation. The fusion of MFLs was first studied on acceptor liposomes with well-defined charge (anionic or zwitterionic), size, and membrane composition. Fluorescence Resonance Energy Transfer (FRET), light scattering experiments, and isothermal titration calorimetry (ITC) demonstrated that fusion is initiated by electrostatic interactions and is strongly influenced by the lipid composition. Furthermore, the transfer of magnetic nanoparticles is assessed by magnetophoresis.² The fusion of MFLs was also studied on living cells. Confocal microscopy experiments confirmed the lipid fusion, while cell viability assays performed after magnetic hyperthermia cycles provided insights into the heating capacity of the magnetic nanoparticles.



(A) Binding enthalpies calculated from ITC thermograms as a function of the acceptor/fusogenic molar ratio for different formulations of cationic liposomes: DOTAP/DOPE (red), DOTAP/DOPE/TopfluorPE (green), DOTAP/DOPE/PEGPE (blue), and DOTAP/DOPE/TopfluorPE/PEGPE (pink), following consecutive injections of anionic liposomes (POPC/POPG). (B) Sketch of the FRET experiment. (C) Mean intensity fluorescence profiles (N = 150 vesicles) of magnetic fusogenic liposomes (MFLs) (Top Fluor emission) alone (green line), anionic liposomes (RhoPE emission) alone (red line) and MFLs incubated with anionic LUVs (orange line). (D) Magnetophoresis experiment

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A Theranostic Implant Concept for Advancing Magnetic Hyperthermia and Magnetic Particle Imaging Towards Clinical Use

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Magnetic particle imaging (MPI) is currently a technology at preclinical stage. Advancing this technology towards clinical application may involve combining it with magnetic hyperthermia therapy (MHT) into a theranostic framework. However, the translation into clinical practice requires the development of new treatment approaches. In this context, the application of magnetic nanoparticle (MNP)-loaded implants for hollow organ tumor treatment represents a particularly attractive concept. The implants are designed to perform reliably in both MHT and MPI. For this, beyond their intrinsic MNP properties, the MNP states within the implants are crucial. Using fibre-based stents as an example, we demonstrate that chain-like MNP agglomerations are particularly important for achieving strong performance in both modalities.

Stochastic simulations of various MNP agglomeration structures for MHT were performed and validated against experimental data. Complementary MPI measurements were conducted, accounting for different orientations of the MNP agglomerates within the MPI coordinate system. Excellent agreement between simulations and experiments was obtained only when both interparticle interactions and interactions with the applied magnetic field were included, underscoring their decisive influence on magnetic relaxivity. For specific MNP sizes and magnetic field strengths, chain-like agglomerates showed up to an eight-fold increase in MHT performance compared with dispersed MNP. In MPI, variations in fibre orientation – such as those expected in a braided stent – and thus changes in agglomerate orientation relative to the receive-coil direction produced similarly pronounced, orientation-dependent differences in signal intensity. As a result, distinct agglomerate orientations generated distinguishable MPI signal patterns. These findings demonstrate that accurate stent imaging requires multi-channel reconstruction strategies.

In summary, MNP agglomerates hold significant potential for advancing both MPI and MHT within a theranostic framework. When magnetic field parameters and reconstruction methods are specifically tailored to these structures, chain-like agglomerates can substantially enhance performance in both modalities.

Micro Powder Drying of Magnetic Nanoparticle Dispersions: Toward Re-dispersible Powder Formulations

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Magnetic nanoparticles (MNPs) have been extensively studied as in vivo magnetic imaging agents. Our previous work demonstrated that magnetic nanoparticles can be delivered to the brain via intranasal administration, highlighting the potential of non-invasive delivery routes [1]. However, nanoparticle suspensions suffer from limitations in stability, transportability, and achievable dosing concentration. Converting dispersions into dry powders while preserving their re-dispersibility and magnetic properties is therefore an important materials processing challenge.

Drying of nanoparticle dispersions generally induces irreversible aggregation due to capillary forces generated during solvent removal and collapse of surface-bound polymers. Conventional freeze-drying often results in dense secondary aggregates that are difficult to redisperse. To address this issue, we focused on the Micro Powder Drying (μPD) method, a vacuum-assisted spray-freezing process. In μPD, a liquid dispersion is sprayed into a vacuum chamber, where rapid solvent evaporation causes self-freezing of microdroplets. Subsequent sublimation under reduced pressure yields dry powders without prolonged liquid-solid compression.

In this study, FeM, a magnetic fraction of ferucarbotran (commercially known as Resovist), was used as a model magnetic nanoparticle dispersion. Prior to μPD processing, dextran (MW 40 kDa) and sodium decanoate were individually introduced to investigate their influence on powder formation and re-dispersion behavior. The obtained powders were characterized by SEM, dynamic light scattering (DLS), UV-vis spectroscopy, and vibrating sample magnetometry (VSM).

SEM observations revealed that μPD produced highly porous, fibrous powder structures rather than dense aggregates (Fig.1). Such a structure is expected to reduce capillary-induced collapse during drying and to facilitate rapid penetration of water upon contact with aqueous media, thereby promoting re-dispersion. UV-vis turbidity tracking and DLS measurements confirmed that both dextran and sodium decanoate improved re-dispersibility compared to FeM processed without additives. VSM analysis demonstrated that the magnetic properties of FeM were preserved after μPD processing and subsequent re-dispersion.

These results indicate that μPD is an effective materials processing strategy for converting magnetic nanoparticle dispersions into re-dispersible powder formulations. The formation of a porous microstructure plays a key role in enabling efficient re-dispersion without deterioration of magnetic performance, offering a promising platform for powder-based magnetic carrier applications.

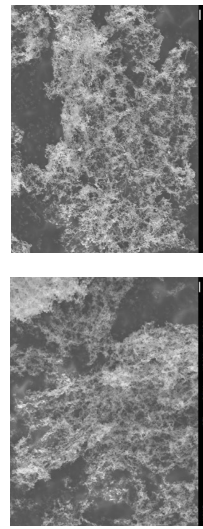


Figure 1. SEM images of powder samples obtained after μPD processing. Left: FeM with dextran addition. Right: FeM with sodium decanoate addition.

Reference [1] S. Seino et al.: *Journal of Controlled Release*, 367, 515 (2024)

ULF-Mag: A Compact Ultra-Low Frequency Electromagnetic Device for Magnetic Microsphere Applications in Cell Culture

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Magnetic microspheres are widely used for targeted delivery, mechanostimulation, and biosensing; however, controlled ultra-low frequency (ULF) magnetic field exposure in vitro systems remains challenging. We present ULF-Mag, a compact, user-programmable device operating at 1–30 Hz and compatible with 96-well plates, based on a 300-turn copper coil enclosing the culture area. Solenoid-based calculations and simulations indicate tunable field strengths from ~10 μT to ~2.9 mT with ±5% spatial uniformity, and ~1 mT RMS at intermediate currents. The system enables precise, user-defined control of frequency and amplitude, and ongoing validation will assess microsphere positioning and cellular responses under 4 and 8 Hz stimulation. To our knowledge, ULF-Mag provides a biologically compatible platform for reproducible ULF magnetic stimulation in standard in vitro microsphere-based applications.

Time-course simulations integrating an NRF2–ferritin–labile iron pool (LIP) regulatory module were performed to assess frequency-dependent cellular responses to ultra-low frequency electromagnetic field (EMF) exposure. Overlay analysis of EMF=0 (sham), EMF=1 (4 Hz), and EMF=2 (8 Hz) conditions revealed a monotonic, EMF-level–dependent upward shift in ferritin protein abundance. Both FTH1 and FTL exhibited higher baseline levels and sustained accumulation with increasing EMF, accompanied by a concomitant reduction in the labile iron pool and enhanced NRF2 activity. The 4 Hz condition was characterized by a mild adaptive response, whereas the 8 Hz condition was predicted by the model to elicit a more pronounced cytoprotective and regulatory phenotype. These frequency-dependent differences should be interpreted as model-derived, hypothesis-generating predictions that warrant experimental validation under controlled in vitro conditions. Collectively, these findings support a regulatory rather than structural mode of action for low-frequency EMF effects on ferritin dynamics, suggesting that EMF exposure may bias macrophage iron homeostasis toward ferritin-mediated sequestration through redox- and NRF2-associated signaling pathways.

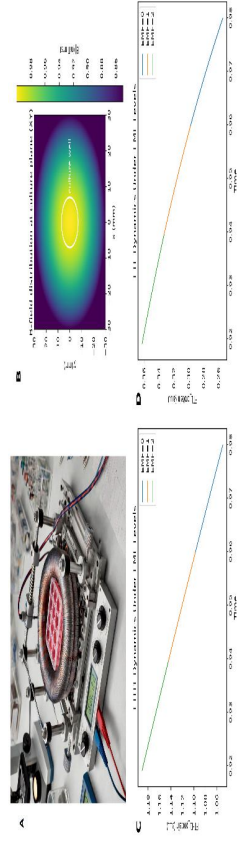


Figure 1. Design and in silico-experimental integration of the ULF-Mag system for frequency-dependent ferritin regulation.

(A) Photograph of the custom-built ULF-Mag device consisting of a 300-turn copper coil enclosing a standard 96-well cell culture plate, designed to deliver ultra-low frequency (1–30 Hz) electromagnetic stimulation. (B) Simulated spatial distribution of the magnetic flux density (|B|) at the culture plane (XY), showing an approximately uniform field (±5%) across the central well region at ~1 mT RMS. (C) Time-course overlay of FTH1 (H-ferritin) protein dynamics under sham (EMF=0), 4 Hz (EMF=1), and 8 Hz (EMF=2) conditions, demonstrating a frequency-dependent upward shift in protein abundance. (D) Corresponding time-course overlay of FTL (L-ferritin) protein dynamics under the same EMF conditions, revealing sustained accumulation and consistent modulation of ferritin subunit balance in response to increasing EMF frequency

Microtron Electron-Beam Defect Engineering of Ultrasmall Ceria Nanoparticles for Tuning Optical and Magnetic Properties

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Cerium oxide nanoparticles (CONPs) represent attractive nanoscale materials because their properties are strongly governed by the Ce⁴⁺/Ce³⁺ redox couple and oxygen-vacancy defect chemistry. In ultrasmall nanoceria, where the surface-to-volume ratio is very high, even subtle changes in defect populations can markedly alter optical absorption, electronic structure, and magnetic response of the material. Thus, post-synthetic defect engineering represents an intriguing route to tune nanoceria properties without altering their composition. We present a dopant-free post-synthetic strategy using high-energy microtron electron-beam irradiation to control the defect landscape of ultrasmall colloidal CONPs.

CONPs were synthesized by thermal decomposition of the Ce precursor in a high-boiling solvent with a mixture of aliphatic surfactants. By carefully setting up procedures, we achieved reproducible preparation of crystalline 2–3 nm CONPs with a fluorite structure. The as-synthesized CONPs were irradiated with a high-energy electron beam for up to 80 min. Structural, spectroscopic, optical, and magnetic characterization was carried out, showing CONPs retained their fluorite cores after irradiation, while their defect chemistry was substantially modified. XPS and TEM-EELS indicate the formation of irradiation-induced Ce³⁺ species and oxygen-vacancy-related states (Figure 1). The optical response exhibited a non-monotonic trend: the apparent optical band gap decreased at intermediate irradiation, then partially recovered at the longest irradiation. This behavior was accompanied by changes in the Urbach tail, suggesting competition between defect generation and partial near-surface reorganization at high irradiation levels. In parallel, the room-temperature saturation magnetization increased markedly in the highly irradiated samples, consistent with enhanced defect-related magnetic response.

As such, our results demonstrate that microtron electron-beam irradiation provides an effective post-synthetic tool for defect engineering in ultrasmall ceria nanocrystals. The method enables changing optical and magnetic properties while preserving the nanoscale fluorite framework, and offers a promising route for the design of defect-controlled oxide nanomaterials for future catalytic, optical, and functional nanotechnology applications.

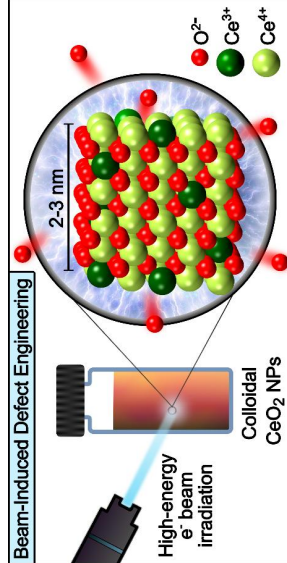


Figure 1. Schematic representation of the CONPs' high-energy irradiation process showing the generation of the defect oxygen vacancies and mixed valence Ce⁴⁺/Ce³⁺ sites in the crystalline fluorite ceria nanostructure.

Transition-Metal-Doped Iron Oxide Nanoparticles: Synthesis, Phase Composition, and Structural Evolution

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Transition-metal-doped iron oxide NPs are attractive for magnetic applications because their structural disorder, dopant distribution, and oxidation state can be exploited to tune the magnetic response. In this work, we prepared and investigated a series of Co(II) and Co(II)/Ni(II)-doped iron oxide NPs prepared by the thermal decomposition method in high-boiling organic-phase Fe and transition-metal precursors in the presence of a mixture of aliphatic surfactants (e.g., oleic acid), ethers, and aldehydes. Synthetic optimization primarily aims to control NP morphology to promote cubic shape and NP size. ICP-OES confirmed successful incorporation of Co and Ni in the prepared NP dispersions, with Fe-dominant compositions and measurable Co/Ni contents across the sample series. Powder X-ray diffraction showed that the products are predominantly spinel iron oxide-based materials, with several samples refining primarily to magnetite-like phases, while others showed partial oxidation to maghemite. A representative Co-containing sample was assigned as cobalt ferrite, whereas some Ni-containing phase assignments require further verification. Together with STEM, EDS mapping, hysteresis, and ZFC/FC measurements acquired for the series, these results define a practical framework for linking precursor chemistry and reaction engineering with dopant incorporation, phase purity, and the emergence of magnetically relevant ferrite nanostructures.

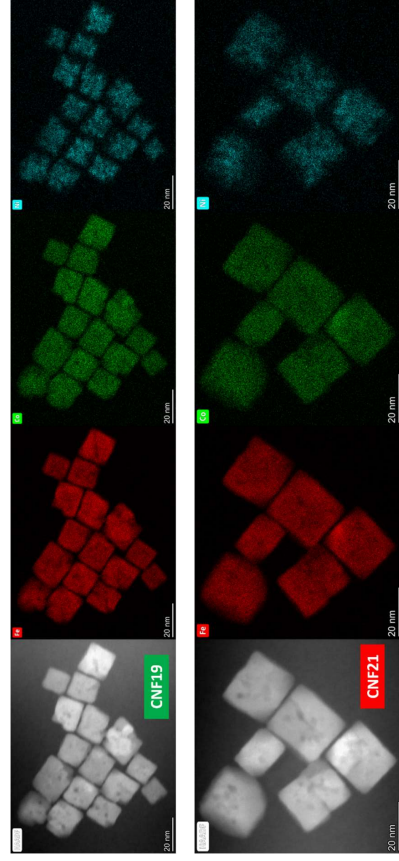


Figure 1. HRTEM images and EDS mapping of the prepared Co/Ni-doped iron oxide nanoparticles showing the element distribution in 1.9 nm and 2.1 nm samples.

CODERAM: Coating-dependent Relaxation Model for Prediction of MRI Relaxivities of Iron Oxide Nanoparticles with Different Coatings

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Iron oxide nanoparticles (IONPs) are extensively studied as negative contrast agents in magnetic resonance imaging (MRI), characterized by relaxivity values (r_1 , r_2 , r_2^*). While the influence of the magnetic core on relaxivity determination is usually well understood, the role of surface coatings remains insufficiently quantified. In this work, we present a simple descriptor-based model that quantitatively links coating properties of IONPs to MRI relaxivity.

A theoretical framework, based on outer-sphere relaxation theory [1], was developed to describe coating-dependent relaxivity using three physically motivated descriptors derived directly from experimental data (DLS, TEM, magnetic, and zeta potential measurements): (i) effective shell thickness (δ); (ii) diffusion factor (ϕ_D), and (iii) aggregation index (ξ). Relaxivities were modeled by scaling reference values using multiplicative factors that account for coating-induced changes in proton-core distance, diffusion dynamics, and nanoparticle aggregation. Experimental datasets included different coatings (Table 2 in [2]). Model parameters were fitted using nonlinear least-squares optimization in MATLAB.

The proposed model in most cases (**Figure 1**) successfully reproduced experimental relaxivity trends across diverse coating systems at T, demonstrating that coating effects can be decomposed into three physically distinct contributions: **distance effect (δ)**, **diffusion effect (ϕ_D)**, and **aggregation effect (ξ)**. The only exception is PLL-coated IONPs, where the polymer-rich shell introduces strong local diffusion heterogeneity and diffusion-hindrance-amplified relaxation, which compete with reduced proton accessibility as predicted by the model.

Nevertheless, the approach provides a quantitative bridge between colloidal nanoparticle properties and MRI relaxation properties, enabling the prediction of coating-dependent contrast efficiency. The simulations are still in progress and will soon incorporate other experimental datasets. This framework provides a quick, simple tool for the rational design and optimization of MRI nanocontrast agents.

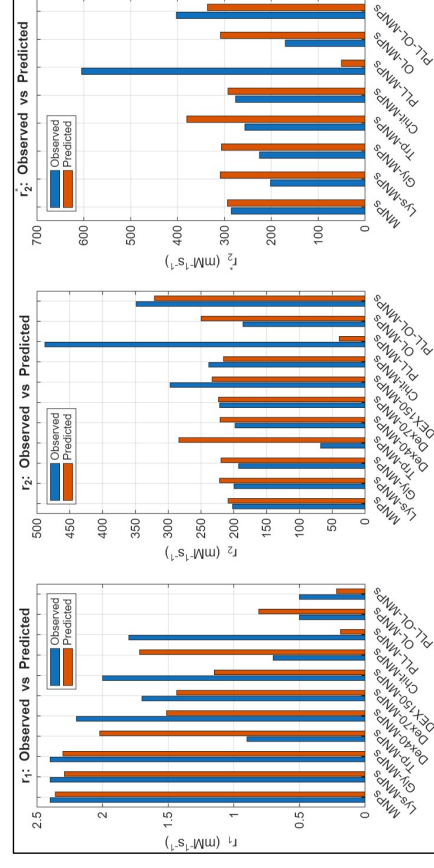


Figure 1: Observed vs. predicted relaxivity values for different coatings.

- [1] *Vuong QL et al., WIREs Nanomed Nanobiotechnol* **2017**, 9:e1468.
- [2] *Antal I et al., Nanomaterials* **2023**, 13, 1831.

Magnetic Relaxation Switch for Non-Invasive Detection of Inflammatory Bowel Disease Biomarkers

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Inflammatory bowel disease (IBD), mainly Crohn's disease and Ulcerative Colitis, consists of chronic inflammatory conditions of the gastrointestinal tract with an unknown cause and a relapsing course. Current methods to assess disease activity, such as blood and fecal biomarkers or endoscopy with biopsy, have limitations because they lack sensitivity, spatial information, or are invasive and costly. While computer tomography imaging is commonly used, it exposes patients to radiation. Therefore, magnetic resonance imaging (MRI) is becoming a safer and more promising diagnostic tool, especially for children. However, there is a need to further develop MRI-based approaches for IBD detection and monitoring.

Superparamagnetic iron oxide nanoparticles (SPION) have revolutionized the field of biomedicine. SPION can be used as MRI contrast agents due to their ability to shorten the T2 relaxation times, which causes regions that have SPION present appear darker in the images. SPIONs are a useful alternative to gadolinium-based contrast agents for imaging patients who require repeated contrast-enhanced studies, such as those undergoing monitoring of IBD progression, where minimizing cumulative gadolinium exposure is desirable. Therefore, SPION hold significant potential as contrast agents for the non-invasive diagnosis and monitoring of IBD.

In this project, polyclonal antibodies specific to IBD biomarkers were conjugated to the surface of superparamagnetic iron oxide nanoparticles using click chemistry. In the presence of the target antigen, lactoferrin, the nanoparticles aggregate around the biomarker. This aggregation alters the nanoparticles' relaxation dynamics, thereby affecting the T2 contrast in MRI. The conjugated nanoparticles serve as a magnetic relaxation sensor (MRS), where the T2 contrast signal in MRI can be correlated to IBD biomarker quantities. The MRS is characterized in vitro and in vivo. The performance of the biosensor was evaluated by assessing its T2 relaxivity using a MRI scanner, while dynamic light scattering was used to characterize aggregation behavior and determine aggregate size. To test the biosensor's responsiveness, varying concentrations of lactoferrin are introduced in vitro, and the resulting aggregation was analyzed using both MRI and DLS measurements (Figure 1a and b). Then, an in vitro model consisting of Caco-2, HT-29 MTX cells, and THP-1 derived macrophages were inflamed with different cytokine cocktails to produce controlled amounts of lactoferrin. The MRS is encapsulated in alginate-based hydrogel beads and exposed to the cell culture, and the resulting MRS response is characterized using MRI. Finally, an established dextran sodium sulfate-induced mouse model of IBD will be employed to evaluate the magnetic resonance sensing system in vivo. Quantitative mass spectrometry will be used to measure biomarker levels and validate the performance and accuracy of the MRS detection approach.

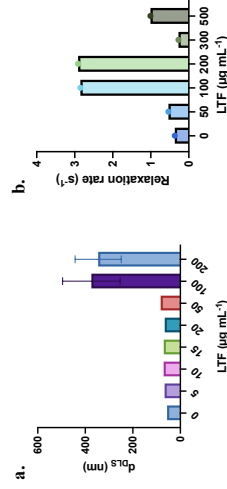


Figure 1. a. Hydrodynamic diameter (DLS) changes of the MRS when exposed to different lactoferrin (LTF) concentrations. **b.** Relaxation rate changes (1/T2) of agar phantoms containing the MRS when exposed to different LTF concentrations.

Influence of Interparticle Spacing on AC Magnetic Losses in Magnetic Nanoparticle Assemblies

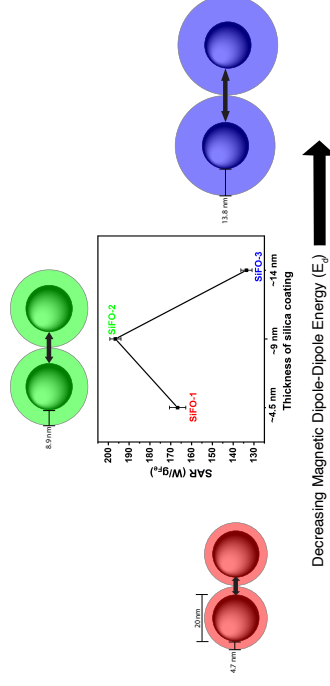
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Controlling alternating current (AC) magnetic losses in magnetic nanoparticle assemblies is critical for applications ranging from energy-efficient devices to biomedical therapies such as magnetic hyperthermia. While intrinsic particle properties, such as shape, size and magnetic characteristics have been widely explored, the influence of interparticle spacing and dipolar interactions on AC energy losses remains debated. In this work, we establish a platform for understanding and controlling AC magnetic losses in magnetic nanoparticle assemblies by precisely tuning interparticle spacing without altering particle size and composition. Using silica-coated Fe₃O₄ nanoparticles as a model system, we demonstrate that energy dissipation exhibits a pronounced non-monotonic dependence on interparticle spacing, with a clear maximum at an intermediate separation. By combining DC magnetometry, AC susceptibility analysis, and AC magnetic hysteresis measurements, we directly correlate this behavior to changes in effective magnetic anisotropy and dipolar interaction strength. Magnetic measurements reveal a systematic reduction in effective magnetic anisotropy (K_{eff}) with increasing interparticle spacing. AC magnetometric measurements show a pronounced non-monotonic dependence of specific absorption rate (SAR) on spacings, with a clear maximum at intermediate separation. Strong dipolar interactions at small spacings suppress heating efficiency, while increased particle separation reduces collective magnetic response. These results demonstrate that optimal AC magnetic losses arise from a balance between dipolar coupling and single-particle relaxation, providing clear insights into how nanoparticle assemblies dissipate energy under alternating magnetic fields and that the optimal energy dissipation arises from a balance between collective magnetic coupling and single-particle relaxation, rather than from intrinsic particle properties alone.



BacBots: Engineering bacteria-based biohybrid microrobots for torque-driven actuation

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The use of bacteria in cancer immunotherapy has resurged as promising modality in oncology, with recent efforts increasingly focused on improving tumor targeting through external control strategies. Magnetic fields are well suited for wireless energy transfer in human tissue and have been extensively explored to remotely actuate magnetically responsive microrobots. Conjugating magnetic nanoparticles (MNPs) to bacteria turns them into such microrobots, here dubbed 'BacBots', leveraging synergies between biological targeting and external control. While most systems rely on gradient-based pulling forces or magnetically guided flagellar locomotion, rotating magnetic fields (RMFs) enable torque-driven actuation with improved energy transfer and tissue penetration. However, achieving sufficient torque is challenging as the magnetically enhanced bacteria require a certain degree of anisotropy.

Here, we present a functionalization strategy that enables tuning the externally applied torque through a combination of crystalline alignment and consideration of shape anisotropy [1]. Leveraging the biocompatible strain-promoted azide alkyne cycloaddition (SPAAC), 25 nm sized magnetic NPs were conjugated to a probiotic *E. coli* Nissle 1917 strain (a). Markov Chain Monte Carlo simulations of 50 – 200 NPs on a bacterial body were carried out to compare the effects of random versus oriented magnetocrystalline alignment of the particles (b). The results show that the anisotropy originating from crystalline alignment surpasses the torque obtained from fourfold higher magnetic particle content without alignment (c). Experiments in which the NP conjugation was performed in the presence of a directing magnetic field further support these computational findings, achieving sufficient magnetic anisotropy for stable rotation at frequencies of several hertz when exposed to an RMF. This rotational motion ultimately resulted in enhanced BacBot accumulation in 3D tumor spheroids, laying the groundwork for improved bacterial cancer therapies.

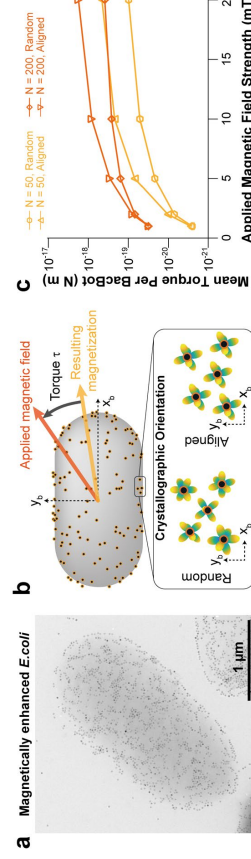


Figure: (a) TEM image of an *E. coli* Nissle 1917 bacterium functionalized with 25 nm sized magnetic NPs dubbed "BacBot". (b) A representative simulated geometry with $N = 200$ spherical MNPs randomly distributed on the surface of a 2 μm long, 1 μm diameter cylinder; particle core diameter = 25 nm, hydrodynamic diameter = 50 nm. (c) Magnitude of the expected torque on a BacBot as a function of applied magnetic field.

Synthesis and Characterization of Co-doped Iron Oxide Nanoparticles for Torque-based Actuation

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Magnetic nanoparticles are widely used in biomedical applications as diagnostic tools, for targeted drug delivery, or for treatments like magnetic hyperthermia. Beyond these applications, their ability to convert the input of external magnetic fields into mechanical motion makes them ideal candidates for torque-based magnetic microrobots that can be guided through the body and can exert mechanical forces on tissues. The key property enabling torque generation in these microrobots is the magnetic anisotropy of the particles, which determines the maximum magnetic torque that can be applied to them by rotating magnetic fields, and which can be tuned through particle shape and composition. In particular, incorporating small amounts of cobalt into iron oxide nanoparticles is a known way to strongly increase their magnetocrystalline anisotropy.

In this work, we present a reliable and reproducible synthesis of iron oxide nanoparticles with a series of progressive Co doping levels, obtained by using different ratios of Co and Fe oleate precursors. We show the effect of the increased anisotropy on hysteresis curves obtained by performing vibrating sample magnetometry (VSM) on magnetically oriented dispersed samples in solidified matrices. We use this technique both as a qualitative assessment of a sample's anisotropy through the different magnetization pathways obtained with different orientations as well as a method to estimate the anisotropy field.

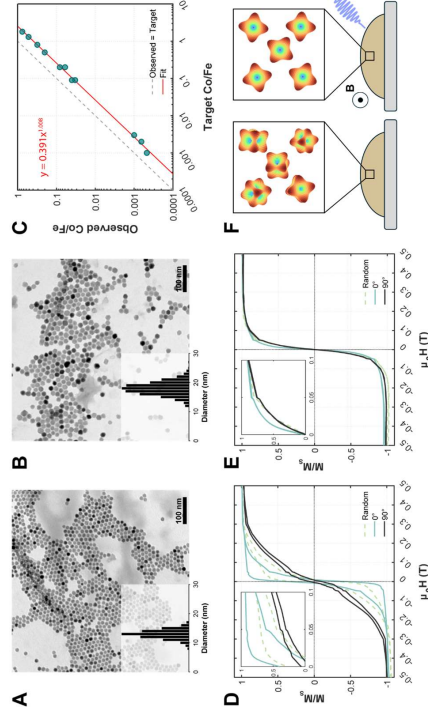


Figure. TEM images of nanoparticle samples with high Co doping ($\text{Co}_{0.6}\text{Fe}_{0.4}\text{O}_4$ in picture A) and low Co doping ($\text{Co}_{0.1}\text{Fe}_{0.9}\text{O}_4$ in picture B). (C) Co/Fe molar ratio observed in the synthesized nanoparticles versus the target molar ratio based on the mix of Co and Fe precursors used for the synthesis. The Co incorporated in the particles is consistently less than the precursors stoichiometry, with the doping efficiency staying around 40%. Representative VSM curves are shown for samples with (D) high doping and (E) low doping. VSM curves obtained from randomly oriented samples are compared to magnetically oriented samples placed parallel (0°) and perpendicular (90°) to the applied magnetic field. The different anisotropies of the two samples result in an observable difference in the orientation-dependent magnetization behavior. (F) The magnetically oriented samples are prepared by mixing the particles with an UV curable polymer and depositing them in a magnetic field so that the particles align one of their easy axes to the field. The deposited sample is then exposed to UV light so that the polymer hardens and traps the particles in their oriented state.

Magnetic Phenotyping of Red Blood Cells and Monocytes to Assess the Pain Severity and Risk of Vaso-Occlusive Crises in Sickle Cell Disease

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Sickle cell disease (SCD) is a hereditary hemoglobin disorder characterized by polymerization of hemoglobin S, leading to red blood cell (RBC) deformation, hemolysis, and recurrent vaso-occlusive crises (VOC) for which there is no rapid quantitative biomarker. RBCs exhibit oxygenation-dependent magnetic susceptibility due to the iron-containing heme groups in hemoglobin. We introduce Cell Tracking Velocimetry (CTV) for high-throughput magnetic phenotyping of individual RBCs under air saturated conditions from 22 healthy donors and 39 non-transfused SCD patients (Figure 1A). CTV simultaneously measures magnetophoretic mobilities (MM) and settling velocities under a high magnetic field gradient [1]. Significant differences were observed in the MM normal distribution of typically a few hundred cells in the sample: at the 1st percentile (SCD: $-1.12 \times 10^{-5} \text{ mm}^2/\text{TA} \cdot \text{s}$ vs. healthy: $-4.32 \times 10^{-6} \text{ mm}^2/\text{TA} \cdot \text{s}$; $p < 0.01$) and 99th percentile (SCD: $1.1 \times 10^{-5} \text{ mm}^2/\text{TA} \cdot \text{s}$ vs. healthy: $3.7 \times 10^{-6} \text{ mm}^2/\text{TA} \cdot \text{s}$; $p < 0.05$), especially for patients in VOC. Given these findings, we evaluated the feasibility of magnetic isolation of sickle RBCs using a commercial magnetic-activated cell separation (MACS) system (Miltenyi Biotec) under air-saturated conditions (Figure 1B) from 4 healthy and 4 SCD individuals. We further assessed whether patrolling monocytes (PMos)—which scavenge damaged sickle RBCs and accumulate iron-rich material—exhibit altered intrinsic magnetic properties and can act as potential biomarkers of disease activity. Results indicate that CTV may provide a label-free approach to associate RBC and immune cell biophysical heterogeneity with disease severity and VOC risk in SCD patients for future diagnostic and therapeutic applications.

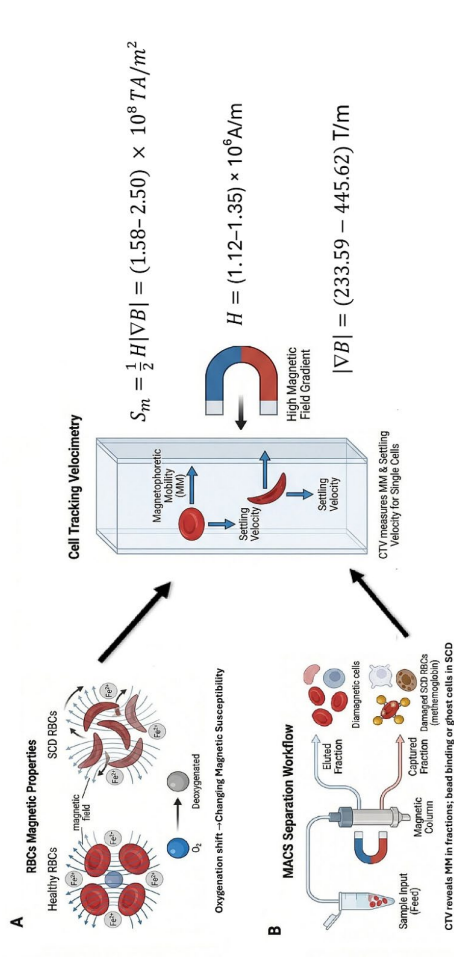


Figure 1. Schematic illustrating diverse applications of cell tracking velocimetry (CTV). (A) Measurement of oxygen-dependent magnetic susceptibilities in red blood cells (RBCs) and detection of pain status in sickle cell disease (SCD) via magnetic heterogeneity of RBCs. (B) Characterization of magnetic behavior in feed, eluted, and captured RBC fractions obtained from MACS separations, and assessment of magnetic properties of monocytes from healthy individuals and patients with SCD.

[1] J. Strayer, et al., Dissolved Oxygen-Dependent Magnetophoresis of Sickle Red Blood Cells and Proof-of-Concept Separation Using a Magnetic Column. ACS Measurement Science Au 2026. DOI: 10.1021/acsmes.3c00169.

Mussel-Inspired Janus Films Incorporating Polydopamine-Coated Magnetite Nanoparticles for Skin Cancer Therapy and Tissue Regeneration

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Magnetite nanoparticles (Fe₃O₄-NPs) have garnered significant scientific interest due to their exceptional magnetic, molecular, and structural properties. While broadly utilized in fields ranging from photocatalysis to biosensing, their magnetic responsiveness and surface functionalization capabilities make them particularly promising for advanced cancer diagnostics and therapeutics. In this study, highly crystalline and morphologically uniform cubic Fe₃O₄-NPs, with an average size of 17 nm, were synthesized via thermal decomposition (Figure (a)). These enhanced structural and magnetic properties are critical for improving drug-loading efficiency, facilitating magnetically guided delivery, and enabling magnetic hyperthermia for effective anticancer interventions.

To further enhance colloidal stability and anti-tumor efficacy, the synthesized Fe₃O₄-NPs were coated with polydopamine (PDA), a natural catecholamine-derived polymer recognized for its antioxidant and pharmaceutical benefits. The resulting PDA@ Fe₃O₄-NPs were subsequently incorporated into mussel-inspired, free-standing Janus films (Figure (b)) designed specifically for skin cancer applications. These functionalized films provide a synergistic therapeutic platform: they enable the controlled release of PDA@ Fe₃O₄-NPs under photothermal stimulation, generate reactive oxygen species (ROS), exhibit inherent antimicrobial activity, and actively promote tissue regeneration following oncological treatment.

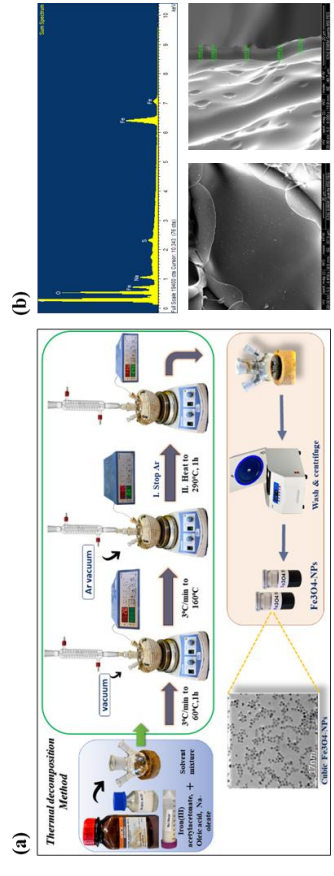


Figure. (a) Fabrication of Fe₃O₄-NPs via thermal decomposition method. (b) Functionalization of mussel-inspired free standing Janus film with PDA@Fe₃O₄-NPs.

Segmentation Strategies for Quantitative Biodistribution in Magnetic Particle Imaging

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Understanding magnetic nanoparticle (MNP) distribution in tumors is essential for advancing cancer nanomedicine. Meta-analyses indicate that a median of only ~0.7% of the injected dose reaches solid tumors, independent of MNP size, shape, composition or surface chemistry [1–3]. They also reveal that only a small fraction of reports include quantitative biodistribution measurements at several time points, as established imaging methods often lack the specificity and quantitative precision required to evaluate low MNP accumulation outside major clearance organs such as the liver. Magnetic Particle Imaging (MPI) is an emerging imaging modality that enables non-invasive and quantitative evaluation of MNP distribution *in vivo*. As with nuclear medicine imaging techniques, MPI typically requires multimodal image registration with anatomical imaging modalities such as Computed Tomography (CT). Defining regions of interest directly from MPI images can be difficult when organs are closely spaced and anatomical segmentation using CT can be challenging due to limited soft-tissue contrast.

In this work, we evaluated artificial intelligence (AI) assisted CT-based and MPI threshold-based approaches for the segmentation of internal organs to quantify MPI tracer biodistribution in mice. Animals were imaged using CT and MPI, with one cohort receiving MNPs only and another receiving both MNPs and the CT contrast agent ExiTron nano12000 [4]. A pilot study was conducted to determine optimal ExiTron nano12000 dosage. Brain, heart, liver and spleen segmentations were obtained from the CT images using SlicerNNInteractive within 3D Slicer [5], a deep learning framework for interactive 3D segmentation that enables rapid voxel-wise segmentation using 2D prompts. The resulting CT-based segmentations were compared with MPI-based threshold segmentations of MNP signal intensities and *ex vivo* organ shape to evaluate the correspondence between anatomical structures and MPI signal distribution (see Figure). Circulation half-life was obtained from the heart segmentations, whereas accumulation and elimination rates were calculated for other organs where the segmentation approach drastically affects results.

Combining CT contrast enhancement with AI-assisted segmentation enables reliable and reproducible delineation of high-accumulation organs while facilitating the distinction between strong organ signals and lower-accumulation regions such as tumors. Multimodal segmentation approaches improve quantitative analysis of MNP biodistribution and support the development of particle-based therapies.

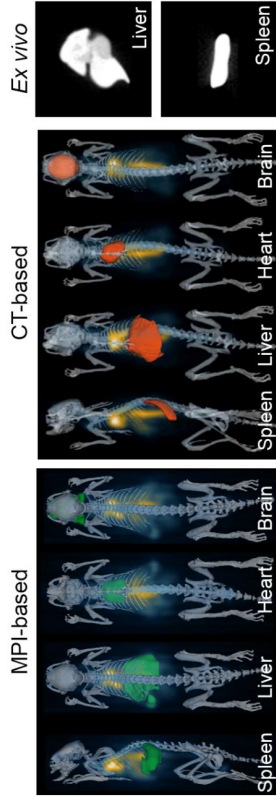


Figure. Maximum intensity projection of mouse MPI image superimposed with MPI-based threshold and CT-based SlicerNNInteractive segmentations and *ex vivo* shapes of organs. Skeleton shown for reference.

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Probing protein and drug interactions by nanoparticle dynamical magnetization phenomena

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Understanding interactions between proteins and drugs is essential for modern biomedical research and pharmaceutical development. Proteins are the main molecular targets of most therapeutic compounds, and their interaction with small molecules determines drug efficacy, specificity, and safety. Studying these interactions provides key insights into drug mechanisms and supports the rational design of new therapies. Moreover, potential off-target effects can be examined, contributing to safer treatments. Advances in structural biology, biophysics, and computational tools have improved our ability to characterize these processes at the molecular level, accelerating drug discovery and minimizing animal experimentation. In this scenario, novel approaches may provide further support to shorten drug screening process and keep reducing testing resources and times.

Here, we report on the potential of AC magnetometry to track protein and drug interactions. We have employed bovine serum albumin (BSA) to decorate commercial cobalt ferrite nanoflowers (MNFs) that were incubated with paclitaxel (PTX) or doxorubicin (DOX) at 25°C for 1 hour. Initially, we probed that the incubation of free BSA and drugs (PTX or DOX) leads to BSA conformational changes that can be tracked by circular dichroism. Next, we have checked that those BSA conformational changes can be monitored by AC magnetometry when 500 BSA proteins are covalently conjugated onto MNFs under AC magnetic fields (30 kHz, 24 kA/m). Indeed, the AC magnetic hysteresis area has been shown as extremely sensitive parameter to display BSA denaturation following molecular interactions at different DOX/PTX : BSA ratios. The AC magnetic area variations showed statistically significance of the protein-particle assemblies without being masked by the nanoparticle signal. Our experimental evidences underline the potential of dynamical magnetization measurements for monitoring BSA denaturation phenomena after interacting with PTX/DOX molecules. Our results underline the potential of magnetic transduction to effectively minimize drug screening procedures.

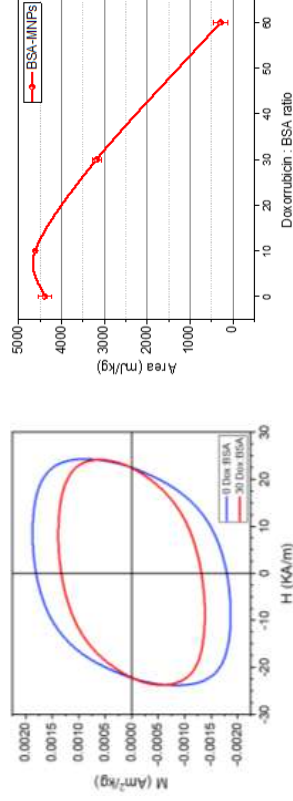


Figure 1 : (Left) AC magnetization cycles in BSA conjugated MNFs after incubation with 0 or 30 DOX molecules per BSA; (Right) Comparison of the AC magnetic area values at different DOX : BSA ratios obtained after incubation from AC magnetization cycles. Measurements performed at 30 kHz and 24 kA/m and [BSA-MNF] concentrations of 1 g/L.

Synthesis by Physics: Development of Superparamagnetic Thin Films Containing Nanoparticles via Magnetron Sputtering

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The synthesis of superparamagnetic nanoparticles in a reproducible and scalable way is necessary for potential biomedical applications. Chemical synthesis processes are often limited in their scalability and maintaining required properties of narrow size distribution and high saturation magnetization [1].

To overcome these limitations, we tested magnetron sputtering, a physical method, for synthesizing superparamagnetic nanoparticles. Magnetron sputtering is used in the semiconductor industry as a scalable method for producing very precise and tunable thin films. To evaluate the magnetron sputtering process, $\text{Co}_{40}\text{Fe}_{40}\text{B}_{20}$ and SiO_2 were co-sputtered onto Si wafers in varying ratios [2] and subsequently characterized at room temperature by magneto-optic Kerr effect (MOKE), superconducting quantum interference device (SQUID) and vibrating-sample magnetometer (VSM). The MOKE results for ratios between 35% and 68% $\text{Co}_{40}\text{Fe}_{40}\text{B}_{20}$ reveal no hysteresis, and the SQUID/VSM measurements also show no hysteresis, proving paramagnetic behavior. Samples with higher $\text{Co}_{40}\text{Fe}_{40}\text{B}_{20}$ contents of 55% and 68%, which were investigated by in-plane VSM, exhibit saturation magnetizations of 400 kA/m (see Figure 1a) and 500 kA/m (see Figure 1b), respectively. Based on the overlap between the Langevin fits and the magnetization measurements, it can be concluded that the magnetization behavior of the thin films corresponds to that of superparamagnetic nanoparticles with a maximum size of 5.40 nm for the 68% $\text{Co}_{40}\text{Fe}_{40}\text{B}_{20}$ sample, for example. These results suggest superparamagnetic thin films containing $\text{Co}_{40}\text{Fe}_{40}\text{B}_{20}$ particles separated from one another by insulating SiO_2 films. Furthermore, the size of the nanoparticles can be adjusted by varying the ratio of $\text{Co}_{40}\text{Fe}_{40}\text{B}_{20}$ to SiO_2 . Based on initial measurements using a magnetic particle spectrometer, the suitability of such thin films for medical applications, such as magnetic fluid hyperthermia, is discussed [3,4].

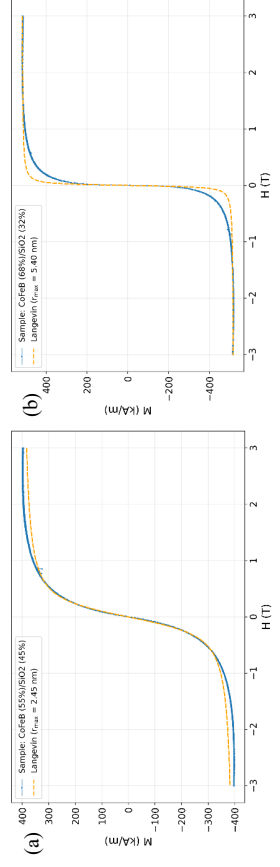


Figure 1: In-plane VSM measurements with approximately 1500 data points indicate no hysteresis. (a) Magnetization curve of 55% $\text{Co}_{40}\text{Fe}_{40}\text{B}_{20}$ and Langevin fit of particles $r_{\text{max}} = 2.45$ nm. (b) Magnetization curve of 68% $\text{Co}_{40}\text{Fe}_{40}\text{B}_{20}$ and Langevin fit of particles $r_{\text{max}} = 5.40$ nm.

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Harmonic Magnetic Response of Iron Oxide Nanoparticle Powders: Influence of Interparticle Dipolar Interactions

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Magnetic nanoparticles are widely used in magnetic particle imaging (MPI), magnetic separation, and drug delivery applications [1–3]. In biomedical applications they are typically used as colloidal dispersions, whereas in materials development and composite fabrication they are often recovered, stored, and handled as dry powders. In nanoparticle powder assemblies, the reduced interparticle distance enhances magnetic dipolar interactions and modifies the magnetic response of the nanoparticle assembly.

In this study, static magnetization, AC susceptibility, and harmonic magnetic responses of nanoparticle powders were experimentally investigated to clarify the influence of interparticle dipolar interactions in the absence of dispersion media.

Commercial iron oxide nanoparticle powders with different nominal particle sizes were examined. Static magnetic properties including saturation magnetization, remanent magnetization, and coercivity were measured using vibrating sample magnetometry. Differences in hysteresis behavior were observed among samples, which may reflect differences in dipolar interactions within the powder assemblies.

AC susceptibility measurements showed no clear peak in the imaginary component within the measured frequency range of approximately 50–200 Hz. Instead, a slope change around 100 Hz was observed, suggesting a distribution of relaxation times associated with particle size distribution and interparticle interactions.

The experimentally measured third-harmonic magnetic signal of the nanoparticle powders (Fig. 1) increased in the frequency range of approximately 50–100 Hz and decreased at higher frequencies. Samples showing relatively stronger hysteresis behavior tended to exhibit larger harmonic responses, suggesting that dipolar coupling contributes to the nonlinear magnetic response.

These results indicate that dipolar interactions and relaxation dynamics influence the frequency dependence of harmonic magnetic responses in nanoparticle powder assemblies.

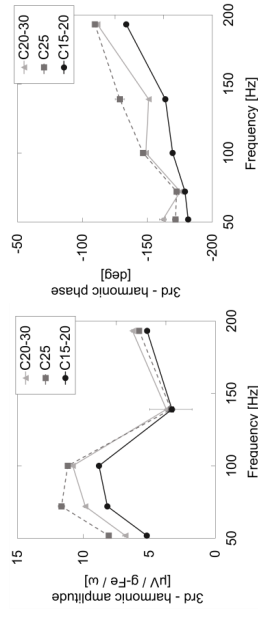


Figure. 1 Frequency dependence of the experimentally measured third-harmonic magnetic signal of iron oxide nanoparticle powders. The left shows the amplitude and the right shows the phase. Commercial iron oxide nanoparticle powders obtained from Nanostructured & Amorphous Materials, Inc. (USA) were used. The nominal particle sizes of the samples were C15–20 (15–20 nm), C20–30 (20–30 nm), and C25 (25 nm).

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Preparation of a binder-free electrode to assess magnetic nanocatalysts in a study of novel Cu₂O-IONP-clusters for electrochemical nitrate reduction

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Electrodes enhanced by nanocatalysts for electrochemical reduction have high potential for applications in synthesis, sensing or conversion reactions (e.g., CO₂) due to their high catalytic activity, selectivity and large surface area [1]. To enable these catalysts to work, they have to be conductively connected to a working electrode (WE) applying an appropriate electrical potential. A widely used approach is to use conductive polymer binders like poly-3,4-ethylenedioxythiophene (PEDOT) [2], which are expensive and raise environmental concerns. That is why the aim of this work was to present a binder-free platform for electrochemical catalysis by attaching catalysts magnetically to the WE as low cost, environmentally friendly alternative. As model system the electrochemical reduction of nitrate (NO₃⁻) on Cu-based catalysts was used as a promising method in environmental applications or synthesis of ammonia, widely needed e.g., in pharmaceutical or chemical industry [2].

As Cu-based catalysts show mostly diamagnetic behavior, in a first step magnetic nanocatalysts were prepared by coating ferrimagnetic large single domain iron oxide nanoparticles (IONP; prepared following [3] at 35 °C) with Cu-species. In a novel approach an electroless Cu deposition triggered by intensive light irradiation (adapted from [4]; white light LED (60 W) for 1 h) was performed, using photothermal and -electrical properties of IONP [5]. The resulting Cu₂O-IONP-clusters show a Cu-content of $\beta_{Cu} \sim 17 - 27$ wt-% (atom absorption spectroscopy (AAS)) and a spherical morphology with a fuzzy surface (d ~ 500 nm; see Fig. 1 a), transmission electron microscopy (TEM)), that consists of a mixture of CuO, Cu₂O and Cu(OH)₂ (X-ray photoelectron spectroscopy (XPS)).

To prepare a nanocatalyst enhanced electrode, these clusters were applied as a suspension on a masked glassy carbon holder with an exposed surface (see Fig. 1 b), Ø ~ 2.5 mm) equipped with a NdFeB permanent magnet on the back to hold the clusters in place. To evaluate the catalytic activity for NO₃⁻ reduction, the holder served as WE in an electrochemical setup (see Fig. 1 c); counter electrode: Pt; reference electrode: Ag/AgCl (sat.). Cyclic voltammetry (CV, dE/dt = 20 mV/s, E_{WE} = -0.5 to -1.2 V, 10 cycles) and chronoamperometry (CA, E_A = -1.2 V, for different times) were performed. In 0.5 M K₂SO₄ solution purged with argon, current densities in the µA/cm² range were obtained. Adding KNO₃ (0.01 M) resulted in higher current densities in the mA/cm² range, proving sensitivity for NO₃⁻. A shift to higher pH (ΔpH ~ 3) due to the consumption of H⁺-ions [6] was observed for longer durations of electrocatalysis. Faradaic efficiencies for the production of NH₄⁺ up to 94 % were measured photometrically with NH₄⁺-tests, proving a good catalytic performance.

As a proof of concept, it was possible to prepare a nanocatalyst enhanced electrode without using an additional binder. This setup can be used to investigate further magnetic nanocatalysts (e.g., Au-, Pt-, Ag-coated IONP, Co-ferrites) or catalytic reactions such as CO₂-reduction or oxidation of glucose.

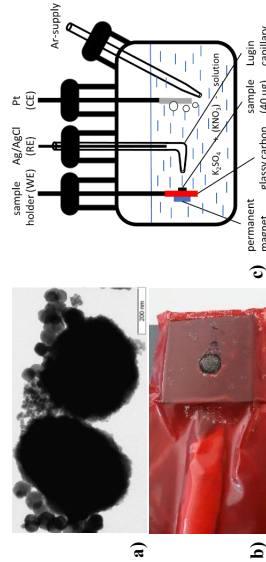


Fig. 1 a) TEM-image of Cu₂O-IONP-clusters b) loaded sample holder c) Electrochemical setup with loaded sample holder as WE

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Synthesis of Cobalt-Doped Ferrite Nanoparticles by Green Hydrothermal Synthesis: From Shape Anisotropic Particles to Chain-like Structures

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In hyperthermia applications, magnetic nanoparticles with high saturation magnetization values and Brownian relaxation behavior are exposed to an alternating magnetic field, whereby heat is generated in the surrounding media to destroy tumor cells locally. Among different types of ferrites, magnetite has the highest magnetic moment, which results in high saturation magnetization values. However, iron oxide tends to oxidize and is a soft magnetic material, and therefore, relaxes according to the Néel mechanism for particle diameters up to 20 nm. On the other hand, cobalt ferrite nanoparticles (CFNPs) have shown promise as they exhibit a higher magneto-crystalline anisotropy than iron oxide and show hard magnetic properties. Due to that, the Brownian relaxation mechanism is possible for CFNPs larger than 7 nm.

Therefore, our research focuses on the synthesis of cobalt-doped ferrite NPs, in which reduced concentrations of Co²⁺ ions yield high saturation magnetization values accompanied by a Brownian relaxation mechanism. By using a two-step method involving akaganeite nanorod precursors and an aqueous hydrothermal reaction without harmful surfactants or solvents, we synthesized cubic and spherical Co_{0.25}Fe_{0.75}O₄ nanoparticles (0.25 < x < 0.45). However, by upscaling this synthesis and varying the reaction parameters, such as pressure, molar ratio, temperature, and basicity, the particle shape and polydispersity can be influenced.[1,2] Moreover, chain-like structures are observed by exchanging the precursor system, which demonstrate a reversible chaining with a magnetic field.[3]

We will summarize the parameters that influence the particle shape and cobalt content as well as show their magnetic and magnetothermal behavior, thereby demonstrating their suitability for a range of applications.

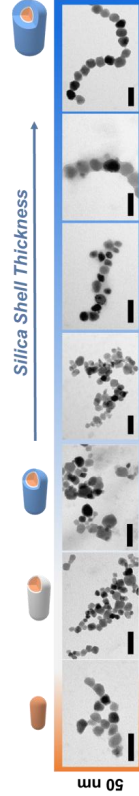


Figure 1: Top: Schematic illustration of the precursor used for the cobalt-doped ferrite synthesis. From left to right, pure akaganeite particles (orange), particles with a polyacrylate shell (white) and the precursors with increasing silica shell thickness (blue). Bottom: Transmission electron microscopy (TEM) images of the resulting cobalt-doped particles using the different precursor systems under the same hydrothermal conditions. (modified from Ref. [3]).

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Development of a continuous flow micromixer synthesis of hydrophobic magnetic nanoparticles for encapsulation in lipid nanoparticles for theranostic applications

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Magnetic nanoparticles (MNP) have a great potential for various biomedical applications such as magnetic particle imaging (MPI), Magnetic Fluid Hyperthermia (MFH), magnetic targeting and magnetic drug release. Thus, MNP represent a valuable component in the development of theranostic agents. For each specific application MNP must be designed and synthesized to achieve tailored functionality. Here, we report an adapted continuous synthesis for directly synthesizing hydrophobic MNP within an aqueous synthesis. Additionally, these hydrophobic MNP were used for encapsulation into lipid nanoparticles (LNP) by a continuous formulation process to enable the possibility of simultaneously monitoring by MPI, drug delivery and MFH.

Iron oxide nanoparticles were synthesized in a continuous flow micromixer setup by oxidation and precipitation from aqueous, alkaline solutions of iron salts and afterwards hydrophobic stabilization with an amphiphile (Figure 1A). Similar but smaller hydrophobic MNP were synthesized using a batch approach with the same amphiphiles. The hydrophobic MNP were encapsulated in LNP using a continuous micromixer setup for controlled self-assembly of lipid mix, MNP and a water component (Figure 1B).

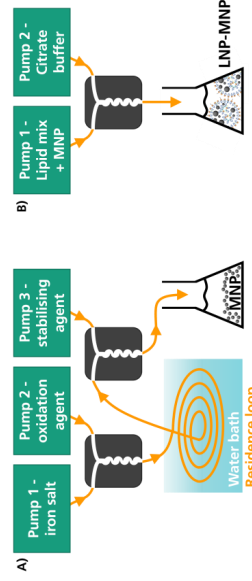


Figure 1: Schematic representation of A) the continuous flow micromixer setup for hydrophobic MNP synthesis and B) for formulation of LNP-MNP.

Magnetic characterization of the MNP was done to monitor the effects of encapsulation in LNP on the magnetic behavior. Magnetic Particle Spectroscopy (MPS) was used to evaluate the potential MPI performance of the MNP and the encapsulated MNP. With AC-magnetometry the suitability for MFH was assessed. In addition, size characterization was done using transmission electron microscopy.

In summary, we demonstrated a tunable, water-based and rapid continuous synthesis of hydrophobic MNP. Further, we showed that hydrophobic MNP can be encapsulated into LNP which can serve as a foundation for developing of theranostic hybrid systems.

pH-Modulated Adsorption and Desorption of BSA onto Mn/Zn/Co-Fe₃O₄ Magnetic Nanocarriers for Biomedical Applications

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Abstract

Magnetic nanoparticles, particularly metal-doped ferrites, are increasingly explored as versatile platforms for biomedical applications due to their tunable surface properties and superparamagnetic behavior. In this study, the adsorption-desorption behavior of 5% Bovine Serum Albumin (BSA) on bare Fe₃O₄ and Zn-, Mn-, and Co-doped Fe₃O₄ nanoparticles was systematically investigated under varying pH conditions. BSA was introduced into nanoparticle suspensions and incubated at room temperature for 24 h under continuous shaking (100 rpm) to evaluate adsorption performance. The results demonstrate that metal doping significantly enhances adsorption efficiency (EE) and loading capacity (LC) compared to bare Fe₃O₄. Among the dopants, Mn-doped Fe₃O₄ exhibited the highest performance (EE: 88.20%, LC: 4.42%), indicating that Mn incorporation most effectively improves protein-surface interactions. The adsorption process showed strong pH dependence, governed primarily by electrostatic interactions between BSA and the nanoparticle surface.

Structural and physicochemical characterization confirmed successful nanoparticle synthesis. X-ray diffraction (XRD) analysis revealed a cubic spinel structure for all samples while transmission electron microscopy (TEM) showed predominantly spherical nanoparticles with narrow size distributions (~10 - 25 nm depending on dopant). Vibrating sample magnetometry (VSM) indicated superparamagnetic behavior in all cases, with enhanced saturation magnetization upon doping.

These findings highlight the critical role of transition metal doping, particularly Mn, in modulating the surface and magnetic properties of Fe₃O₄ nanoparticles, thereby improving their protein adsorption capacity. This study provides valuable insights into the design of efficient magnetic nanocarriers for applications in drug delivery, bioseparation, and biosensing.

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Real-Time Prediction of Coupled Physical Parameters in Magnetic Particle Systems for Drug Delivery Monitoring

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Magnetic particles have attracted attention for targeted drug delivery due to their remote manipulation by external magnetic fields. Real-time knowledge of particle hydrodynamic radius (r_h), interfacial viscosity (η) and interfacial temperature (T) is essential for understanding transport dynamics and ensuring drug therapeutic efficacy. However, the three parameters are inherently coupled within the governing Langevin equation, which renders them inaccessible through simultaneous measurement.

This work presents a physics-informed machine learning (ML) paradigm to infer r_h , η , T from the motion signals of magnetically actuated particles. The paradigm integrates digital-twin simulations with ML to enable the estimation of latent parameters by combining physics-consistent reasoning with data-driven generalization. The digital-twin simulation grounded in the Langevin equation generates extensive motion datasets to address the scarcity of experimental data for ML training. To tackle parameter unidentifiability arising from a million-fold disparity in parameter influence scales, the designed hybrid ML architecture, RF-MBGA-Net, integrates a random forest (RF) regressor with a multi-branch gated attention (MBGA) network to form a two-stage prediction architecture. This design incorporates intermediate-prediction feedback and data augmentation, reducing parameter sensitivity disparity by 200-fold.

The proposed RF-MBGA-Net achieves outstanding predictive accuracy on simulated data ($R^2 > 99\%$; MAEs: $r_h = 3.9 \text{ nm}$, $\eta = 0.023 \text{ mPa} \cdot \text{s}$, $T = 1.5 \text{ K}$). Experimental validation on motion signals demonstrates robust agreement with independent measurements, including dynamic light scattering for r_h , rotational rheometer for η , and controlled temperature for T . Furthermore, the real-time predictions further reveal the inverse η - T coupling, biomolecular dissociation kinetics, and transient inter-parameter dynamics where particle aggregation-dispersion modulates the local apparent viscosity and heat dissipation.

By enabling real-time access to previously inaccessible coupled parameters (r_h , η , T) during particle motion, this work provides a foundation for closed-loop monitoring and control in magnetic drug delivery systems.

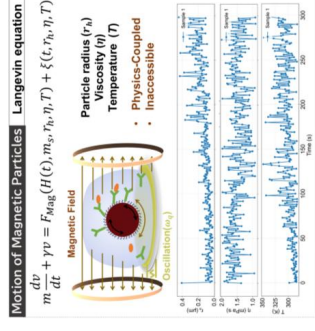


Figure. Schematic of the physics-informed machine learning for real-time inference of coupled physical parameters (r_h , η , T) from the motion signals of magnetically actuated particles.

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Magnebotix AG is a Swiss technology company founded in 2014. We are a spin-off of the ETH Zurich Multi-Scale Robotics Lab. The company develops and produces advanced **magnetic manipulation systems**, including high-precision magnetic field generators used for contactless control of nano- and microrobots, particles, and magnetic tools for biomedical, engineering, and research applications. Its product portfolio of magnetic field generators includes the MFG-100, OctoMag, and Navion. These cover a wide range of working volumes and support different applications in engineering, mechanobiology and surgical research. The team combines deep scientific expertise and engineering capabilities to enable wireless manipulation at micro- to human-scale levels. You can also check out MagnebotiX on their [LinkedIn](#) page.



nanotech Solutions

www.ntsol.es

Nanotech Solutions designs and manufactures user friendly AC magnetometers for quality control and/or exploiting the dynamical magnetization of nanomaterials in different applications. AC HysterTM Series measures AC magnetization cycles of magnetic nanoparticle powder, or dispersed in liquids (aqueous or organics), gels, or inside biological matrices at room temperature. Magnetic losses and magnetization harmonics are accurately determined in the field frequency range from 1 kHz to 350 kHz and field intensities up to 150 kA/m.



phase VISION GmbH

www.phase-vision.com

phase VISION GmbH is a young spin-off from the University of Würzburg dedicated to make Magnetic Particle Imaging (MPI) and magnetic nanoparticle characterization accessible for everyone. Building on over 15 years of academic MPI research and strong industrial engineering expertise, the company develops compact, flexible, and user-friendly instrumentation for research, education, and industrial applications.

With its **COMPASS system**, phase VISION provides a powerful tool specifically designed for the precise characterization of magnetic nanoparticles, enabling reliable analysis, reproducible measurements, and deeper insight into particle behavior across a wide range of applications.

By combining scientific innovation with robust engineering, phase VISION bridges the

gap between laboratory research and practical deployment, empowering researchers and developers worldwide to explore the full potential of magnetic nanoparticle technologies.



Magnetic Medicine

<https://www.sciencedirect.com/journal/magnetic-medicine>

Magnetic Medicine is the world's first journal dedicated to the clinical and biomedical applications of magnetic technologies and magnetic materials. Launched in 2025 as a quarterly gold open access journal with no article processing charges (APC), *Magnetic Medicine* aims to provide an academic platform for advancing research and clinical translation of magnetism in life sciences and healthcare.



Nanoscale Journal Family, Royal Society of Chemistry

[Nanoscale Horizons](#), [Nanoscale](#) and [Nanoscale Advances](#) are peer reviewed international journals publishing high-quality experimental

& theoretical work across the breadth of nanoscience & nanotechnology. Explore our recent themed collection highlighting [Magnetic Nanoparticles: From Massart Method to a Cascade of Innovations](#). Magnetic carriers are an important topic for our journals and we welcome submissions from the community showcasing their excellent research.



MSI Automation, Inc.

<https://www.msiautomation.com/m/>

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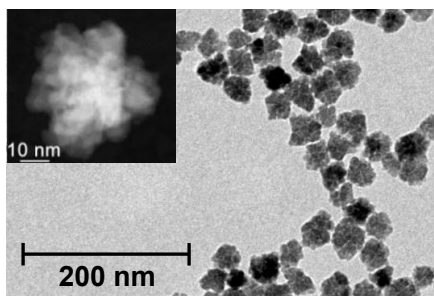


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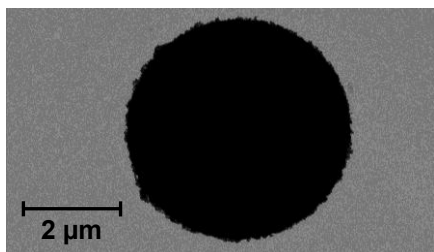
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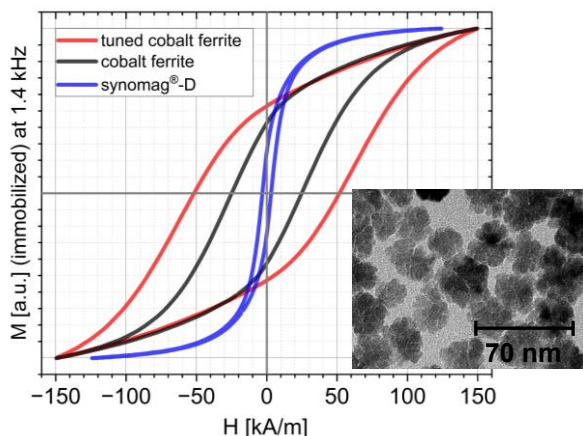
micromer[®]-M

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Cobalt ferrite

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Stay tuned – it is more to come in 2026!

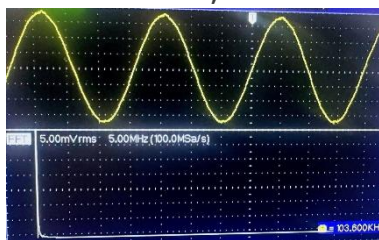
- [1] H. Carlton *et al.* Adv. Funct. Mater. 2025, 35, 2412321. (doi: 10.1002/adfm.202412321)
[2] B. Kunkel *et al.* IJMPI 2024, 10, 1. (doi: 10.18416/IJMPI.2024.2403032)
[3] A. Norrick *et al.* Stem Cell Research & Therapy 2021, 12, 194. (doi: 10.1186/s13287-021-02272-2)
[4] J. Borchers *et al.* Small Struct. 2024, 2400410. (doi: 10.1002/ssstr.202400410)



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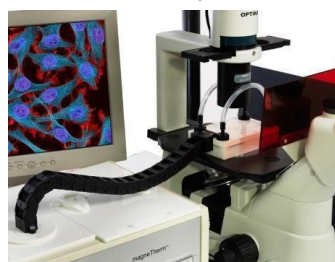
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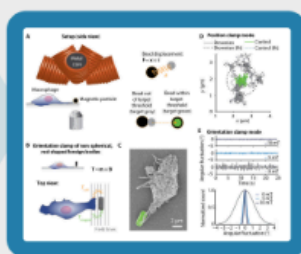
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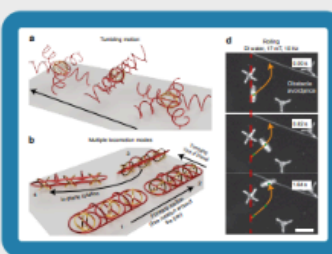
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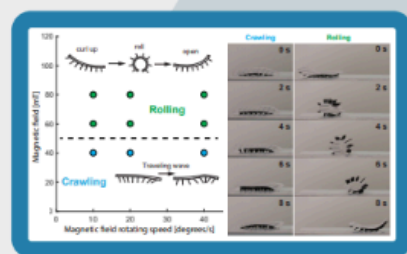
BIOLOGY & MEDICINE

A micromagnet is coated to resemble a bacterium and used to probe the mechanism of interaction with an immune cell¹



MATERIALS SCIENCE

A fabricated interlocked micromachine with multiple magnetic domains shows diverse modes for field-induced locomotion²



ROBOTICS

A magnetic cilia carpet shows field-dependent geometry and multimodal robotic locomotion from metachronal waves to rolling³



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MFG SETUP



NAVION



OCTOMAG

CITATIONS:

1. Simone Schuerle et al, Robotically controlled microprey to resolve initial attack modes preceding phagocytosis. *Sci.Robot.*2, eaah6094(2017). DOI:[10.1126/scirobotics.aah6094](https://doi.org/10.1126/scirobotics.aah6094)
2. Alcantara, C.C.J., Landers, F.C., Kim, S. et al. Mechanically interlocked 3D multi-material micromachines. *Nat Commun* 11, 5957 (2020). DOI:[10.1038/s41467-020-19725-6](https://doi.org/10.1038/s41467-020-19725-6)
3. Gu, H., Boehler, Q., Cui, H. et al. Magnetic cilia carpets with programmable metachronal waves. *Nat Commun* 11, 2637 (2020). DOI:[10.1038/s41467-020-16458-4](https://doi.org/10.1038/s41467-020-16458-4)

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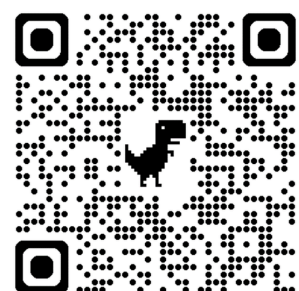
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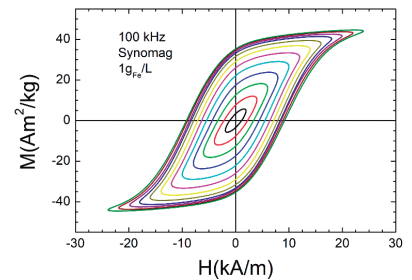
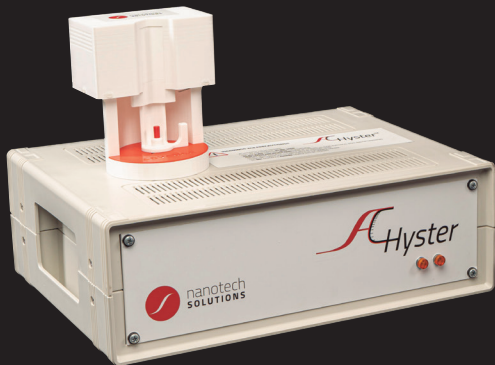
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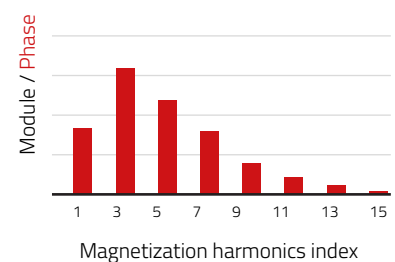
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Magnetic Particle

Spectroscopy

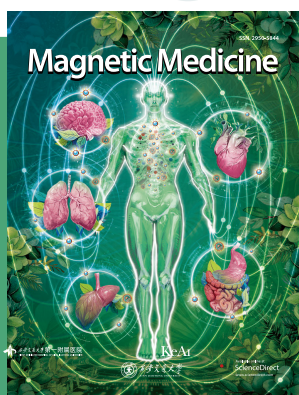


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Magnetic Medicine

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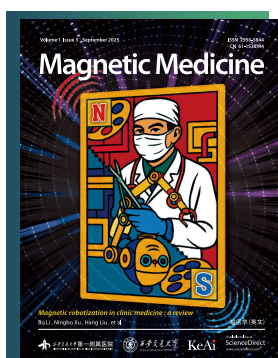


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Advancing Clinical Translation of Magnetic Technologies & Materials

- 01 Clinical Applications of Magnetic Technologies
- 02 Biomedical Magnetic Materials & Nanomaterials
- 03 Magnetic Particle Imaging (MPI) & Magnetic Bioimaging
- 04 Biological Effects of Magnetic Fields
- 05 Magnetically Actuated Medical Devices



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Nanoscale Nanoscale Advances

Magnetic Nanoparticles: From Massart Method to a Cascade of Innovations



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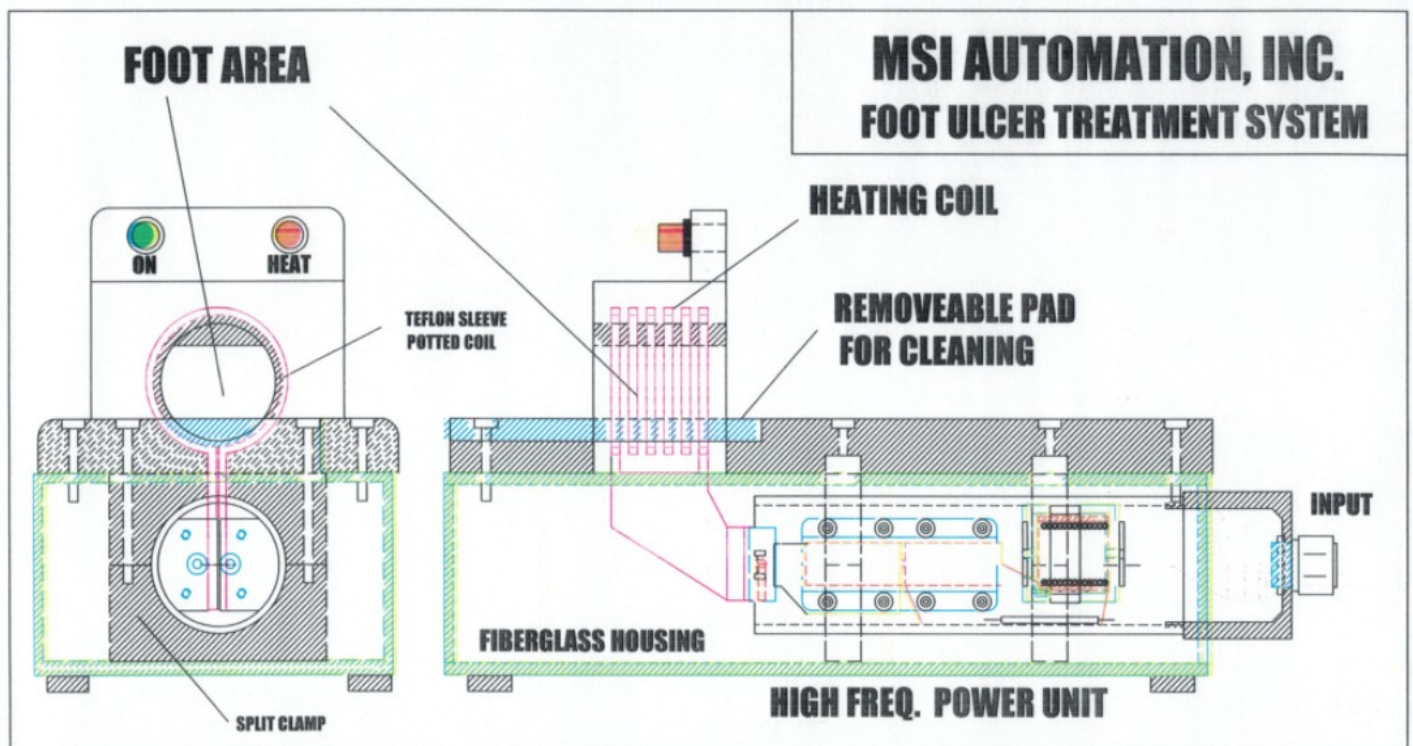
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