

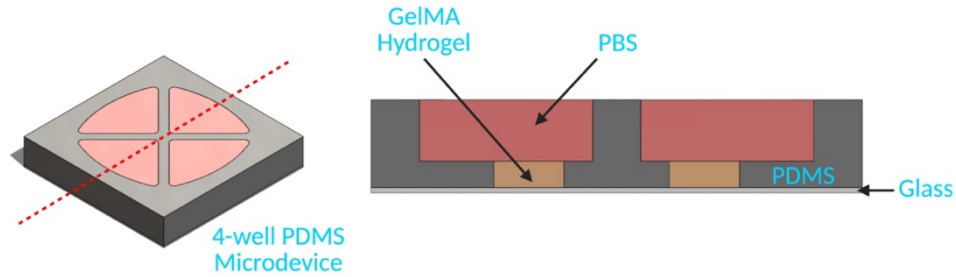
Supplementary Information

Supplementary Table S1. List of variables used in this work.

Variable	Definition	Unit
M	Magnetization Vector	A/m; emu/g
M_s	Saturation Magnetization Vector	A/m; emu/g
M _s	Saturation Magnetization (Magnitude)	A/m; emu/g
χ	Magnetic Susceptibility	-
H	Internal Magnetic Field Vector	
H^{sat}	Saturation Internal Magnetic Field Vector	A/m
τ_{mag}	Magnetic Torque	N m
V	Volume	m ³
B ₀	Applied Magnetic Field; in this work this is the applied MRI DC Field	T
D _a	Demagnetizing Factor, along the axis of symmetry	-
D _r	Demagnetizing Factor, radial	-
μ_0	Permeability of Free Space	H/m; N/A
β	Angle between Applied Magnetic Field and the Direction of Magnetization; in this case, along the rod axis of symmetry	Radians (rads)
β_0	Initial β	Rads
ϕ_{SPION}	Volume Percent of SPIONs in Rods	%
ρ_{SPION}	Density of SPIONs	g/cm ³
$\tau_{elastic}$	Elastic Torque	N m
G'	Elastic Shear (storage) Modulus	Pa
G''	Loss Modulus	Pa
ω_r	Angular Frequency for Rheological Tests	Rad/s
L	Rod Length	m
D	Rod Diameter	m
p	Anisotropy Ratio, L/D	-
g(p)	Dimensionless Function of the Anisotropy Ratio, p	-
θ	Rod Angle of Deflection with Respect to its Initial Angle, β_0 ; this initial angle is relative to the applied magnetic field direction	Rads
$\tau_{viscous}$	Viscous Torque	N m
η_0	Zero- shear Viscosity of Gel	Pa s
$\tau_{inertia}$	Inertial Torque	N m
I	Moment of Inertia	kg m ²
P	Power Generated in a Spherical Sample (in this work, due to RF field induced eddy current)	W
R	Radius	m
σ	Electrical Conductivity	S/m
D	Duty Cycle of RF Pulse	%
ω	Angular Frequency of the RF Magnetic Field	Rad/s
B ₁	RF Magnetic Field Amplitude	T
ΔT	Temperature Change	°C
Q	Heat Absorbed by Sample	J
m	Mass	kg
c	Specific Heat Capacity	J/ (kg K)
B _{eff}	Effective Rectangular Pulse Amplitude	T
PW	Pulse Width	s; ms
TR	Repetition Time	s; ms
θ_f	Flip Angle	Rads
γ	Gyromagnetic Ratio	Hz/T

I. PDMS Device Fabrication

a. 4-well chip

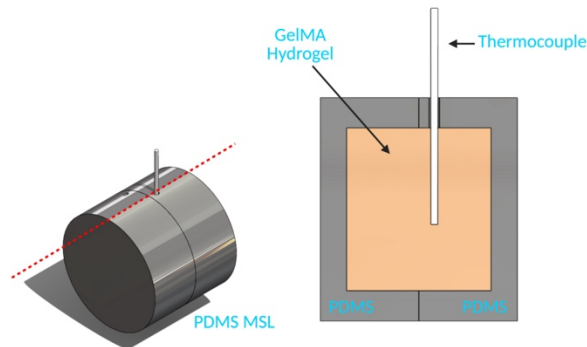


Supplementary Figure S1. Layers of 4-well microdevice. The microdevice consists of a Polydimethylsiloxane (PDMS) gasket with patterned well and reservoir features bonded to a glass coverslip. Each microdevice contains 4 independent hydrogel wells so that liquid GelMA can be loaded independently into each well but then simultaneously exposed to the same light source and magnetic field, sequentially. Overlying reservoirs can be filled with PBS to maintain hydration of the hydrogel during experimental scans. (Created in BioRender.

Bennet, T. (2026) <https://BioRender.com/agnd3h0>)

Polydimethylsiloxane (PDMS)-glass microdevices containing 4 independent microwells were fabricated through replica molding and assembled via oxygen plasma treatment. Each well contains a small central hydrogel reservoir (4 mm diameter, 1.65 mm height) with a larger media reservoir directly on top as shown in Fig. S1. To create the PDMS layers containing the well features, liquid PDMS (Sylgard 184, Dow Corning) mixed at a 10:1 (elastomer base: curing agent) ratio was poured into molds created using 3D printing (MiiCraft). A transparency film lid was placed over the PDMS-filled molds after degassing prior to curing to obtain a uniform thickness as previously described in ⁷². PDMS layers were cured overnight at 65°C.

b. Mock Spinal Lesion (MSL)

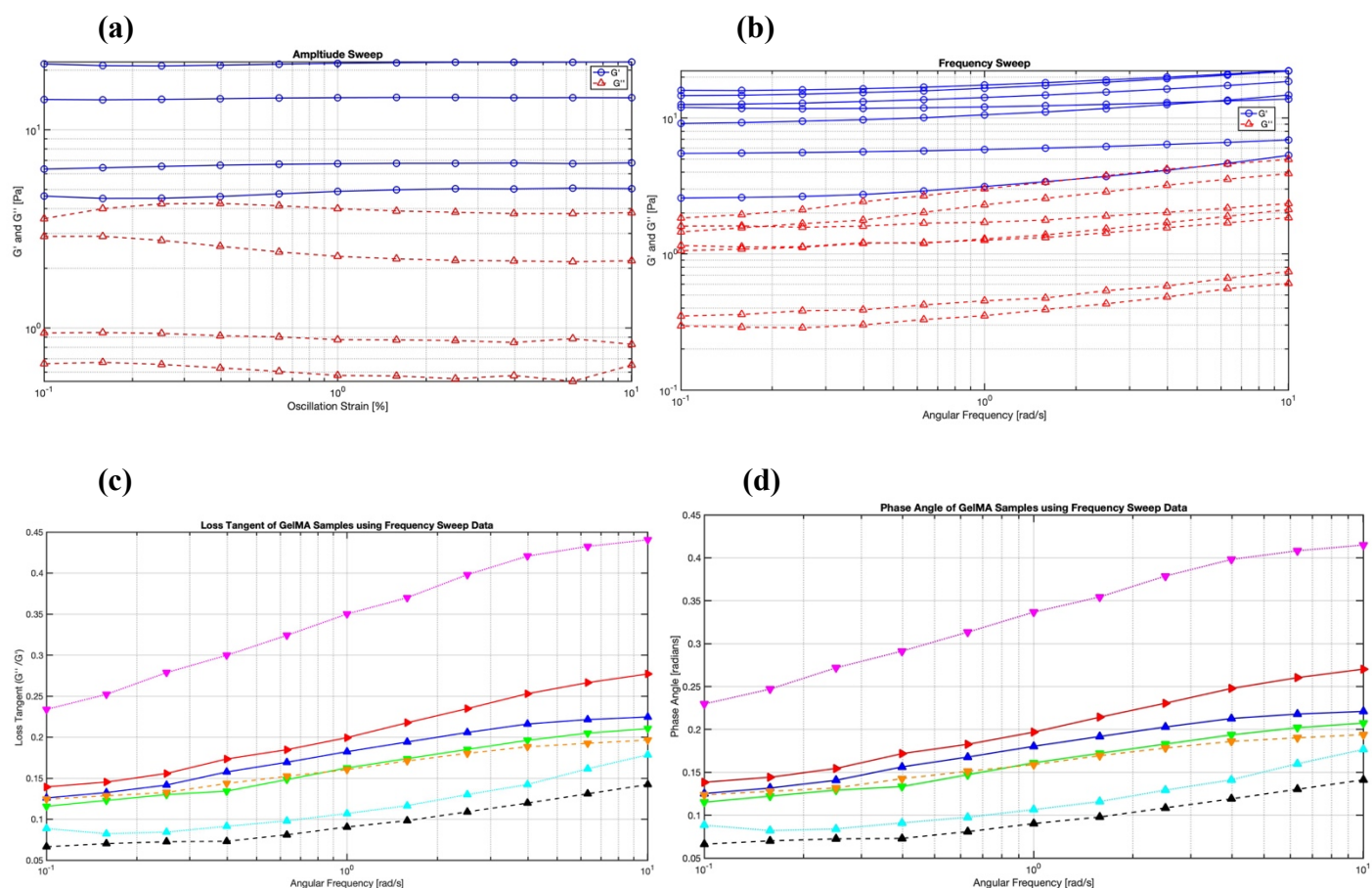


Supplementary Figure S2. Layers of Mock Spinal Cord Lesion (MSL). PDMS surrounds a GelMA filled cavity and contains an access point for the thermocouple. (Created in BioRender. Bennet, T. (2026)

<https://BioRender.com/085kpdt>)

As shown in Fig. S2, MSLs were fabricated from PDMS using replica molding. Due to the limitations of the replica molding process, MSLs were fabricated by bonding two PDMS layers with well-like features together to create an enclosed 1 mL empty lesion cavity that can be filled with the desired hydrogel. To facilitate insertion of a thermocouple for thermal measurements, a 20G dispensing tip (Outer diameter: 0.9 mm; Cat.75165A677, McMaster Carr) was inserted into a hole in the mold for the PDMS layer during the casting process. Once the mold was assembled and the needle inserted, liquid PDMS (10:1 ratio) was poured into the resin molds and degassed for 30-40 min in a vacuum chamber prior to curing. A transparency film lid was used as previously described to obtain uniform thickness and to facilitate assembly⁷². Once cured, the PDMS MSL halves were removed from the molds and bonded together. To prevent leakage, the assembled MSLs were enrobed in liquid PDMS. Care was taken to ensure no liquid PDMS entered the empty cavity through the thermocouple access point.

II. Gel Characterization Rheological Tests



Supplementary Figure S3. Rheological test results of 6% GelMA, 50% DoF. (a) Amplitude sweeps data ($n = 4$); (b) frequency sweep data ($n = 7$); (c) loss tangent using frequency sweep data ($n = 7$), (d) phase angle using frequency sweep data ($n = 7$).

III. Alignment State Study: Numerical Quantification Methods

Supplementary Table S2. Summary of numerical quantification methods used for pre- and post- MRI scan image comparison.

Method	Range	Highest Similarity Value	Comparison Metric	Mathematical Algorithm	Rationale for Use
RMSE	0 – 1	0	Pixel Intensity	Square root of average (difference in pixel intensity between the two images) ²	Widely used metric for comparison, based on the “error sensitivity philosophy” ⁷³ comparing the images pixel by pixel ⁷⁴ ; limitations as discussed in ⁷³
CC	-1 – 1	1	Pixel Intensity	Correlation Coefficient	Commonly used tool for image registration ⁶⁹ and template matching ⁶⁸ measuring the “degree of linear correlation in pixel-by-pixel intensity” ⁶⁷ ; additional advantages and limitations outlined in ⁷⁵

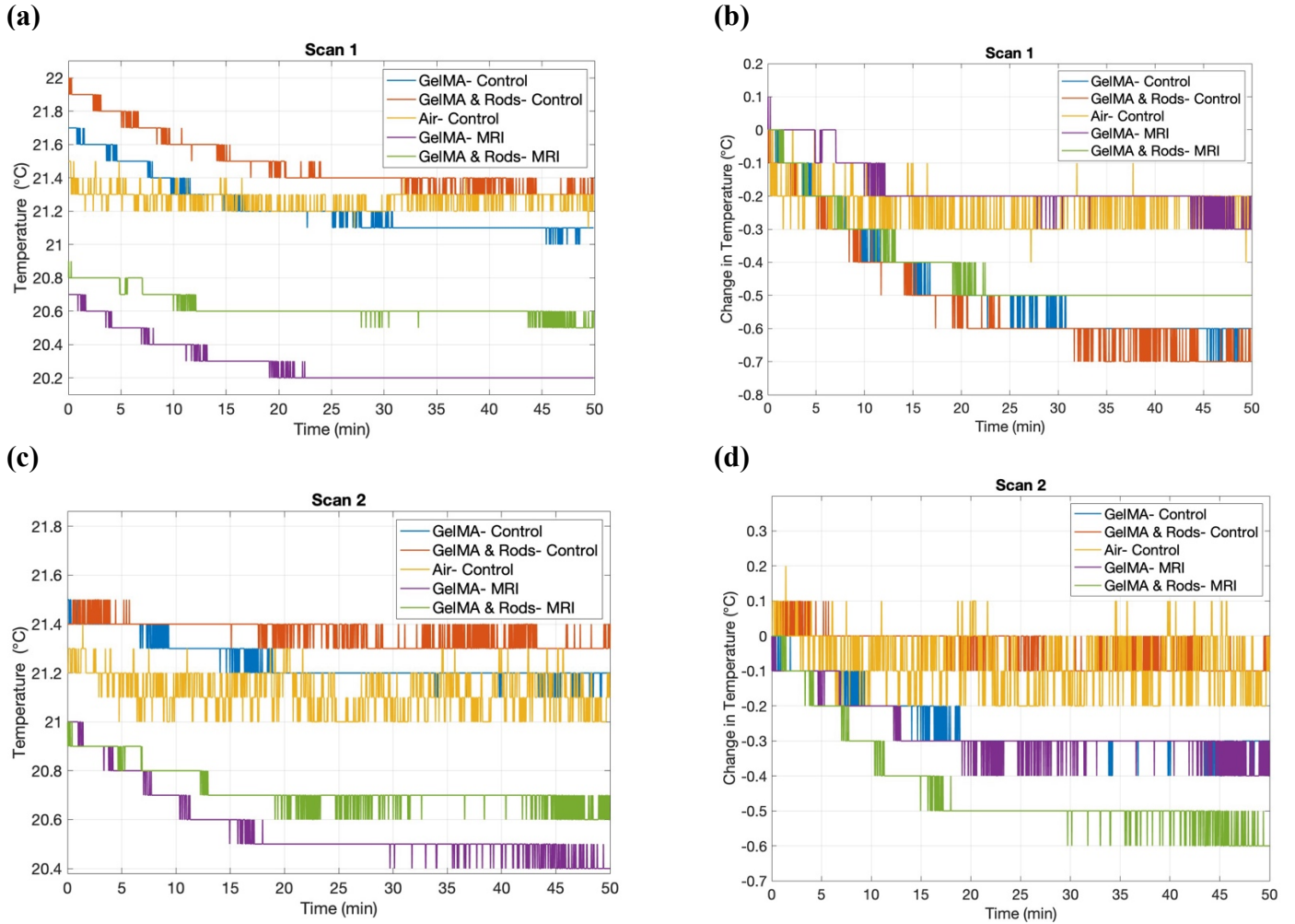
IV. Alignment State Study: Results

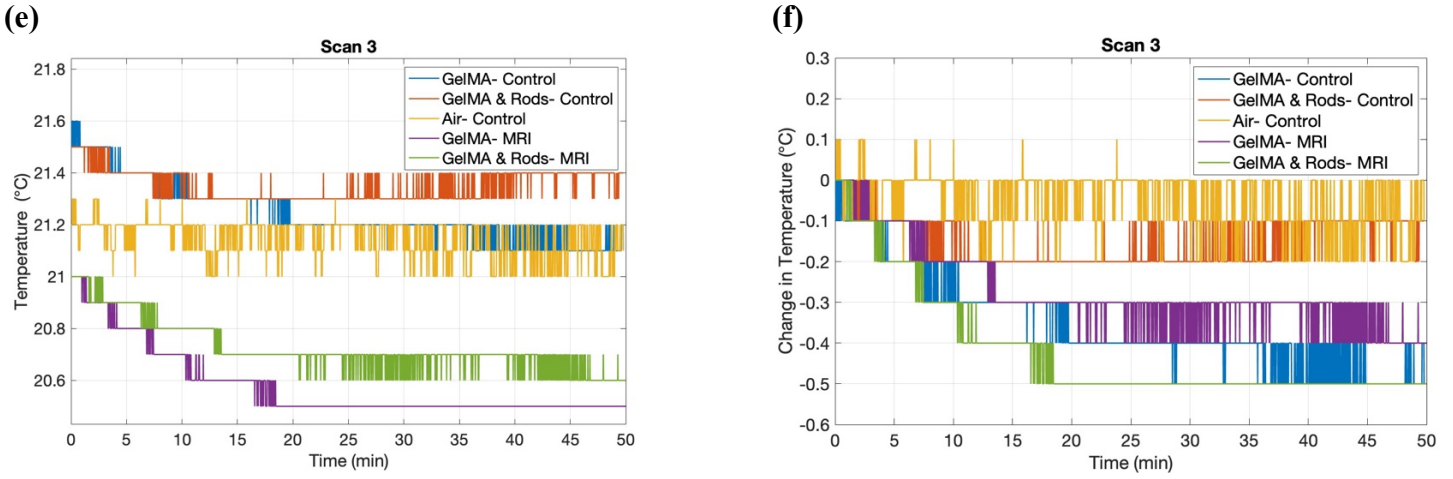
Supplementary Table S3. Numerical comparison values of chips 1-8 which underwent an MRI scan and the control chip (chip 9). This data is presented as the mean, with SD referring to standard deviation. The median can be found in Fig. 2(c).

Chip	Chip Condition	RMSE Average $\pm$ SD	CC $\pm$ SD
1, 5	Unaligned,	0.130 ± 0.056	0.69 ± 0.21
2, 6	Aligned,	0.15 ± 0.052	0.65 ± 0.22
3, 7	Unaligned, $\perp$	0.13 ± 0.044	0.70 ± 0.20
4, 8	Aligned, $\perp$	0.15 ± 0.053	0.57 ± 0.25
9	Aligned, no MRI (Control)	0.16 ± 0.050	0.58 ± 0.23

V. Heat Study: Results

Results from the three 45-minute MRI scans conducted can be seen in Fig. S3. The averaged results can be found in Fig. 3(b) in the main text.





Supplementary Figure S4. Temperature and change in temperature of the samples over the course of a 45-minute MRI scan. The time spans to 50 minutes as there are pauses in between scans leading to the total scan time being 50-minutes. The sampling rate of the measurements is 1 second. The change in temperature values is relative to the starting temperature of each sample respectively. **(a)** Temperature of samples in the first scan. **(b)** Change in the temperature of the samples in the first scan. **(c)** Temperature of samples in the second scan. **(d)** Change in the temperature of the samples in the second scan. **(e)** Temperature of samples in the third scan. **(f)** Change in the temperature of the samples in the third scan.

VI. Additional Rod Constants Calculations: Effective Magnetic Susceptibility

SPION Density (ρ_{SPION}) and Volume Fraction (ϕ_{SPION}) in PCL Rods:

Given the below constants:

- SPION weight percent of final rod weight, $w_{SPION} = 0.99$ weight(w/w) %
- SPION properties:
 - Initial volume magnetic susceptibility, $\chi_{SPION}^{vol} = 0.2$ (EMG 1200, Ferrotec)
 - Components (EMG 1200, Ferrotec):
 - Magnetite, Fe_3O_4 :
 - $w_{Fe_3O_4} = 60 - 80$ w/w%
 - density, $\rho_{Fe_3O_4} = 5.18$ g/cm³ ⁷⁶
 - Fatty acid coating (oleic acid):
 - $w_{OA} = 20 - 40$ w/w%
 - $\rho_{OA} = 0.89$ g/cm³ ⁷⁷
- PCL properties:
 - mass susceptibility, $\chi_{PCL}^{mass} = -7.5 \times 10^{-9}$ m³/kg ⁷⁸
 - $\rho_{PCL} = 1.145$ g/cm³ ⁷⁹
- Additional relevant constant:
 - vacuum permeability, $\mu_0 = 4\pi \times 10^{-7}$ H/m ⁸⁰

The volume magnetic susceptibility of the PCL is calculated as outlined in equation (S1) below ⁸¹:

$$\chi_{PCL}^{vol} = \chi_{PCL}^{mass} \rho_{PCL} = (-7.5 \times 10^{-9} \text{ m}^3/\text{kg}) (1.145 \text{ g/cm}^3) * 10^{-3} \text{ kg/g} * 10^6 \text{ cm}^3/\text{m}^3 = -8.59 \text{ ppm}, \quad (S1)$$

From the SPION properties listed above, the effective SPION density can be calculated using the rule of mixtures, equation (S2) ^{82,83}:

$$\rho_{composite} = \sum \phi_i \rho_i = \frac{1}{\sum \frac{w_i}{\rho_i}}, \text{ so } \rho_{SPION} = \frac{1}{\frac{w_{Fe_3O_4}}{\rho_{Fe_3O_4}} + \frac{1-w_{Fe_3O_4}}{\rho_{OA}}}, \quad (S2)$$

For $w_{Fe_3O_4} = 0.60$, $\rho_{SPION} = 1.77$ g/cm³, while for $w_{Fe_3O_4} = 0.80$, $\rho_{SPION} = 2.64$ g/cm³.

For SPION density, the average value is used for calculations: $\rho_{SPION} \sim 2.21 \text{ g/cm}^3$. Similarly, the density of a microrod can be calculated as shown in equation (S3):

$$\rho_{rod} = \frac{1}{\frac{w_{SPION}}{\rho_{SPION}} + \frac{1-w_{SPION}}{\rho_{PCL}}} \quad (S3)$$

Converting the weight% of SPIONs to volume% (vol%, ϕ)⁸²:

$$\phi_{SPION} = \frac{w_{SPION}}{\rho_{SPION}} \rho_{rod} = \frac{\frac{w_{SPION}}{\rho_{SPION}}}{\frac{w_{SPION}}{\rho_{SPION}} + \frac{1-w_{SPION}}{\rho_{PCL}}} \quad (S4)$$

$\phi_{SPION} \sim 0.0043 - 0.0064$ (0.43 - 0.64 vol%)

The average value is therefore used for the calculations: $\phi_{SPION} \sim 0.54 \text{ vol\%}$.

Rod Effective Magnetic Susceptibility:

The effective magnetic susceptibility of the rod can be determined by calculating the effective magnetic permeability of the SPIONs, PCL, and rod before converting the rod magnetic permeability to magnetic susceptibility. The effective magnetic permeability (μ_{eff} , ie. μ_{rod}) of a low concentration magnetic mixture with spherical magnetic particles can be calculated using the Maxwell-Garnett mixing model of magnetorheological fluids, as presented in equation (S5)⁸⁴⁸¹:

$$\mu_{rod} = \mu_{PCL} + \frac{3\phi_{SPION} \mu_{PCL} (\mu_{SPION} - \mu_{PCL})}{\mu_{SPION} + 2\mu_{PCL} - \phi_{SPION} (\mu_{SPION} - \mu_{PCL})}, \quad (S5)$$

where $\mu_i = \mu_0(1 + \chi_i^{vol})$ with i being PCL, SPION, and rod.

Given the range in volume fraction of SPIONs, the above equation leads to $\mu_{rod} = 1.258 \times 10^{-6} \text{ H/m}$ and $\chi_{rod}^{vol} = 0.00080 - 0.0012$.

Alternatively, using the volume% of SPIONs and PCL in the rods, along with the volume magnetic susceptibility of the SPIONs and PCL, the effective magnetic susceptibility of a single rod can be calculated using the rule of mixtures. The Maxwell-Garnett mixing model introduced earlier considers the demagnetization factor of the spherical SPIONs (1/3) and incorporates this into the equation. For a simple mixing model, the apparent magnetic susceptibility of the SPIONs considering the demagnetization factor needs to be calculated, as presented in equation (S6-7):

$$\chi_{SPION,APP} = \frac{\chi_{SPION}^{vol}}{1 + \frac{1}{3}\chi_{SPION}^{vol}}, \quad (S6)$$

$$\chi_{rod}^{vol} = \phi_{SPION} \chi_{SPION,APP}^{vol} + (1 - \phi_{SPION}) \chi_{PCL}^{vol} = 0.00080 - 0.0012, \quad (S7)$$

The two methods lead the same results: $\chi_{rod}^{vol} = 0.00080 - 0.0012$. For calculations, the average value of 0.0010 can be used.

Rod Demagnetizing Factors:

Approximating the rods as very slender prolate ellipsoids (in fact, prolate spheroids as two axes are equal), the demagnetizing factors of the rods, along the axis of symmetry and radially, can be calculated as $D_a = 0.0558$, $D_r = 0.4721$, respectively⁵⁴.

VII. MRI Scan Variables

Supplementary Table S4. MRI scan variables used to determine the expected heating, as shown in Table S5. θ_f : Flip Angle, PW: Pulse Width, TR: Repetition Time.

Scan Name	Excitation Pulse			Refocusing Pulse			Fat Suppression Pulse			TR (ms)
	θ_f (°)	PW (ms)	Pulses per TR	θ_f (°)	PW (ms)	Pulses per TR	θ_f (°)	PW (ms)	Pulses per TR	
FLASH 1,2,3: Initial three-slice localizer	10	1.1100	1	-	-	-	-	-	-	15.00
RARE 1: T2_TurboRARE_ax	90	2.1000	2	180	1.7000	9	-	-	-	2500.00
RARE 2: T2_Turbo_RARE	90	2.1000	2	180	1.7000	9	-	-	-	2500.00
RARE 3: T2_Turbo_RARE	90	2.1000	2	180	1.7000	9	-	-	-	2500.00
FLASH 1: T1_FLASH_3D_iso_quick	20	3.5000	1	-	-	-	-	-	-	50.00
FLASH 2: T1_FLASH_3D_iso	20	3.5000	1	-	-	-	-	-	-	50.00
EPI 1: SE_EPI	90	1.9091	1	180	1.5455	1	90	1.9571	1	1500.00
EPI 2: SE_EPI	90	1.9091	1	180	1.5455	1	90	1.9571	1	1500.00
DT-EPI: DTI_EPI_3D_40dir	90	2.7273	1	-	-	-	90	1.9571	1	2100.00
UTE 1: UTE2D	15	0.3938	1	-	-	-	-	-	-	30.00
UTE 2: UTE3D	5	0.0043	1	-	-	-	-	-	-	4.24

Supplementary Table S5. Expected temperature rise by scan type. Explanation of the scans can be found in the *Methods* (Section 4.4.1).

Scan Name	Total Average RF Power, P (μW)	Total Time of Scan (s)	Heat, Q (mJ)	ΔT (°C)
FLASH 1,2,3: Initial three-slice localizer	0.328	43.00	0.0141	3.37×10^{-6}
RARE 1: T2_TurboRARE_ax	3.92	80.00	0.313	7.49×10^{-5}
RARE 2: T2_Turbo_RARE	3.92	80.00	0.313	7.49×10^{-5}
RARE 3: T2_Turbo_RARE	3.92	40.00	0.157	3.74×10^{-5}
FLASH 1: T1_FLASH_3D_iso_quick	0.125	89.00	0.0111	2.66×10^{-6}
FLASH 2: T1_FLASH_3D_iso	0.125	2.00	0.000250	5.97×10^{-8}
EPI 1: SE_EPI	1.07	2.00	0.00214	5.11×10^{-7}
EPI 2: SE_EPI	1.07	450.00	0.481	1.15×10^{-4}
DT-EPI: DTI_EPI_3D_40dir	0.185	840.00	0.155	3.71×10^{-5}
UTE 1: UTE2D	1.04	13.00	0.0135	3.23×10^{-6}
UTE 2: UTE3D	75.0	55.00	4.12	9.86×10^{-4}