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MPI visualization of hybrid implant fibers using different system matrices

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Abstract

Hybrid stents can be used in cardiovascular applications and in hollow organ tumor therapy. They open the occluded area and can induce local hyperthermia by application of an alternating magnetic field (AMF) destroying cancer cells. Here, we investigate hybrid fibers made of polypropylene (PP) fibers with incorporated magnetic nanoparticles (MNP) via magnetic particle imaging (MPI). An influence of the MNP mobility and MNP agglomeration state as well as the orientation of elongated MNP agglomerations with respect to the drive field of the system matrix reference on the image reconstruction were determined. Best image resolution for a phantom consisting of two parallel fibers was achieved with reconstructions using system matrices of a fiber where MNP agglomerations point in the same direction as the ones of the phantom with respect to the drive field. Changes in MNP mobility, agglomeration state and their preferred directions have effects on the resulting image quality and must be considered in future measurements of complex structures of hybrid fibers.

I. Introduction

Hybrid stents made of polypropylene (PP) fibers with incorporated magnetic nanoparticles (MNP), so called hybrid fibers, can be used in cardiovascular applications and in hollow organs. They open the occluded site and can induce local hyperthermia treatment. The surface temperature of the hybrid stent is adjusted in a controlled manner by application of an alternating magnetic field (AMF) [1]. Hyperthermia treatment is used to treat restenosis, to remove plaques or to destroy tumor tissue. Specifically, apoptosis of tumor cells occurs at temperatures of about 43 °C for exposure times of 30-60 min. At temperatures of 40-45 °C, healthy tissue remains unharmed for same exposure durations [2]. This allows tumor tissue in close vicinity to the stent to be destroyed.

In this study, we investigate the visualization of hybrid fibers *via* magnetic particle imaging (MPI). For this, different measurements are performed showing a clear influence of the MNP mobility, agglomeration state and orientation of elongated MNP agglomerations of the system matrix reference on image reconstruction.

II. Material and methods

PP fibers with a diameter of (450 ± 80) µm were produced by melt spinning of PP pellets mixed with 7 wt% freeze-dried MNP (PP@7%MNP). The MNP had a core diameter of (10.2 ± 2.4) nm and a saturation magnetization of (99.4 ± 0.8) $\mathrm{Am^2/kg(Fe)}$. The MNP synthesis and further characteristics are described in [3,4]. The exact MNP concentration inside the fibers was investigated by

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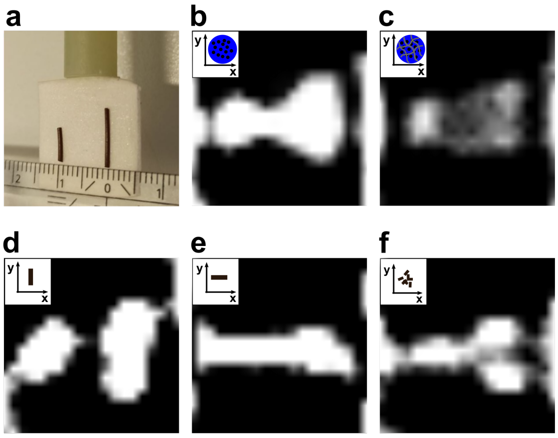

Figure 1: (a) Photo of two parallel hybrid fibers PP@7%MNP at a distance of d = 1 cm. (b-f) MPI images reconstructed with system matrix of (b) dispersed MNP, (c) immobilized MNP, as well as PP@7%MNP fiber oriented in (d) y-direction, (e) x-direction and (f) randomly distributed. The insets illustrate the orientation of the system matrix sample.

thermogravimetric analysis (TGA).

MPI measurements were performed using a commercial imaging system (MPI 25/20 FF, Bruker BioSpin MRI GmbH, Ettlingen, Germany).

A phantom of two hybrid fibers (1 cm and 0.5 cm in length) parallel fixed at an initial distance of 1 cm was used (Figure 1a). The distance between the fibers was gradually reduced up to 0.5 cm. For calibration measurements, various MNP configurations including hybrid fibers which are differently oriented or randomly distributed in the sample holder used to record the system matrix. For that, small parts of PP@7%MNP (2 mm) were either placed in x- or y-direction, as well as randomly oriented. Also system matrices acquired using samples of freely dispersed and immobilized MNP were tested. A volume of V = 8 µL of in water dispersed and in hydrogel (1.5 wt% agarose) immobilized MNP was used, respectively. All measurements were performed with a maximum gradient field in z-direction of Gz = 2.5 T/m, a drive field amplitude of BDx,y,z = 14 mT and a system matrix FOV = (20 x 20 x 8) mm^3. A dedicated receive coil (Micro coil) with a bore diameter of 65 mm (Bruker BioSpin MRI) was used for signal acquisition in x-direction. For reconstruction, the Kaczmarz algorithm with 50 iterations was used. In this framework, the signal-to-noise ratio (SNR) threshold was 4, the maximum mixing order 25 and the regularization parameter was set to 10^{-4}.

III. Results and discussion

TGA measurements yield an MNP concentration of (7.2 ± 0.2) wt% for the hybrid fibers PP@7%MNP. Figure 1a shows a photo of the two parallel fibers at distance of 1 cm. Figure 1b-f show MPI images reconstructed with different system matrices. The best image resolution was achieved when the PP@7%MNP fibers in the reference sample are aligned along the y-direction, which is the same direction as the two fibers that were imaged (Figure 1d). The image shows clearly distinguishable structures with different lengths. Image reconstruction was not possible using system matrices of in water dispersed and in agarose immobilized MNP (Figure 1b-c) or with system matrices of PP@7%MNP fiber parts in x-direction or randomly distributed (Figure 1e-f). These differences in image resolution can arise due to several reasons.

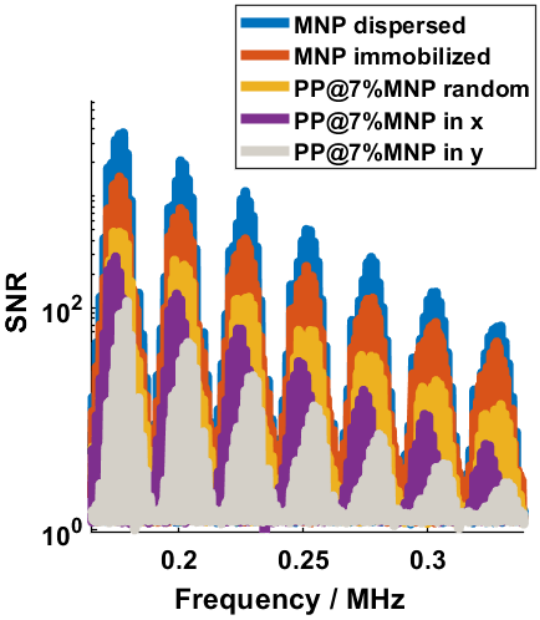

Figure 2: SNR of the system matrices of dispersed MNP, immobilized MNP, as well as PP@7%MNP fiber randomly distributed and oriented in x- and y-direction. The frequency bands shown are in the range of (0.16-0.34) MHz.

First, the relaxation dynamics of the reference sample used to measure the system matrix differ from those of the fiber. As previously reported, MNP are agglomerated inside the fibers inducing dipole-dipole interactions, leading to different magnetic response to an AMF compared to that of dispersed or immobilized MNP [1]. Second, the MNP agglomerations are elongated with elliptical shapes and show a preferred direction [4]. Changing the fiber orientation in x-, y- or random direction also changes the orientation of the MNP agglomerations with respect to the direction of applied AMF. As previously reported, a change of the angle between drive field direction and the easy axis of an immobilized MNP chain influences the frequency components of the received system matrix [5]. Such differences are also observed in the SNR spectra of the system matrices measured. Compared to the frequency bands of dispersed MNP, immo-

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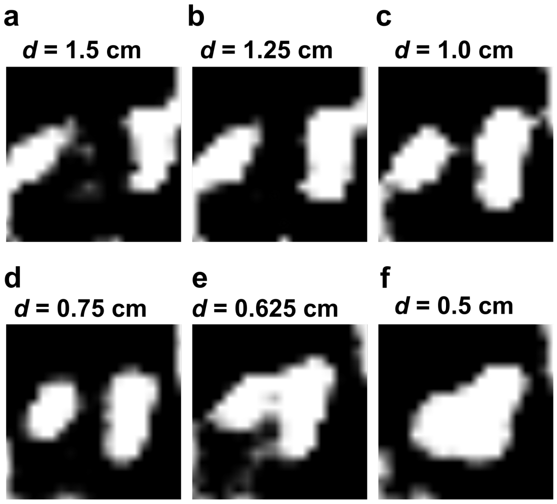

Figure 3: MPI images of parallel hybrid fibers PP@7%MNP placed at a distance of (a) d = 1.5 cm, (b) d = 1.25 cm, (c) d = 1.0 cm, (d) d = 0.75 cm, (e) d = 0.625 cm and (f) d = 0.5 cm. All images were reconstructed using a system matrix of PP@7%MNP hybrid fiber sample oriented in y-direction.

bilized MNP and of PP@7%MNP randomly distributed, the peaks of PP@7%MNP oriented in x- and y-direction are shifted (Figure 2). In hyperthermia applications, a similar dependency of magnetic response regarding the MNP chain orientation to the direction of AMF has been reported [6]. Since hyperthermia and MPI rely on the non-linear dynamic magnetic susceptibility, the same behavior is expected for both techniques [7]. Third, by using the *Micro coil*, the signal of the higher harmonics in x-direction is higher compared to the other directions. This could be an additional effect apart from the observed directional image resolution.

Figure 3 shows MPI images of parallel hybrid fibers PP@7%MNP placed at different distances from d = 1.5 cm to d = 0.5 cm. All images were reconstructed using a system matrix of PP@7%MNP hybrid fiber sample which was oriented in y-direction. The hybrid fibers can no longer be delineated below a distance of d = 0.75 cm.

IV. Conclusions

In this study, MPI measurements of hybrid implant fibers were performed to investigate the influence of the image resolution on the type of system matrix that is used for reconstruction. A clear dependency of the resulting image resolution on the selected reference sample, namely dispersed, immobilized or agglomerated MNP, was observed. Best image resolution could be obtained with reconstructions using system matrices of a fiber where MNP agglomerations are oriented in the same direction as the fibers that were imaged with respect to the drive field direction. This is probably due to the dependency of the MNP magnetization response on the MNP immobilization and agglomeration state as well as their preferred direction with respect to the drive field. Furthermore, the use of a Micro coil can also influence the image quality. Two parallel fibers could be delineated up to a critical distance of d = 0.75 cm. To visualize a more complex structure of the fibers (e. g. a stent), the dependency of the MPI signal on the orientation of MNP agglomerations with respect to the direction of the drive field must be further investigated and carefully taken into account in image reconstruction. For that a multi-channel technique could be a promising approach [8].

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Author’s statement

Conflict of interest: Authors state no conflict of interest.

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