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Investigation of the spatial resolution and penetration depth of a single-sided MPI device in three-dimensional imaging

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Abstract

A one-sided arrangement of the components relevant for magnetic particle imaging leads to improved patient access, as the object size can be unlimited. In this paper, we further investigate the properties of the single-sided MPI system published earlier. A phantom with up to five positions filled with Perimag particles was rotated to evaluate the spatial resolution depending on the orientation of the receive coils. The reconstruction was done with a Kaczmarz algorithm and a Tikhonov regularization with individually calculated regularization parameters for each measurement. The penetration depth and the spatial resolution in the y-, z-plane were evaluated.

I Introduction

MPI has been introduced the first time in 2005 by B. Gleich and J. Weizenecker [1]. The design of the single-sided MPI setup was first proposed by Sattel et al. in 2009 [2]. Compared to the conventional design, all relevant components are arranged on one side, which leads to the possibility of measuring unlimited patient or object sizes. However, the unique design leads to different challenges such as inhomogeneous magnetic fields or a limited penetration depth [3]. In order to overcome these difficulties, the system boundaries must be evaluated. Therefore, various characterization processes must be done to fully describe the system. Building on an investigation, where the linear system response has been evaluated [4], the spatial resolution of the system in z- and y-direction is evaluated and a possible dependence of the orientation of the receive coils on the reconstruction results is investigated in this work.

II Material and methods

II.I Scanner configuration

The single-sided scanner consists of four sending coils providing three-dimensional imaging. A receive coil for each channel is implemented. A base frequency of $f_b = 2.5$ MHz was used for excitation. The frequency dividers $f_{Dx} = 99$, $f_{Dy} = 96$, $f_{Dz} = 93$ lead to the excitation frequencies $f_x \approx 25.25$ kHz, $f_y \approx 26.04$ kHz and $f_z \approx 26.88$ kHz for the three channels respectively. Spatial encoding can be implemented using a field free line (FFL) [5] or a field free point (FFP). The arrangement of the coils of this scanner produce an FFP which moves on a Lissajous trajectory due to the selected excitation frequencies.

II.II Phantom and measurements

A square phantom with 7 x 7 holes holding a volume of 7 μl respectively was used for the three-dimensional measurements, where in a first step two holes with a distance of 14 mm to each other were filled with Perimag

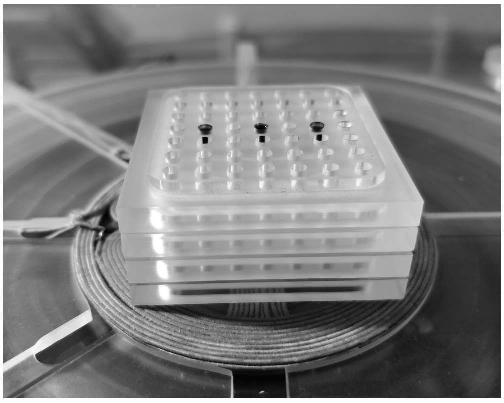

Figure 1: The used phantom with four layers lying on the scanner surface. Each layer has a thickness of 3.5 mm and only the uppermost layer has been used to fill in particles.

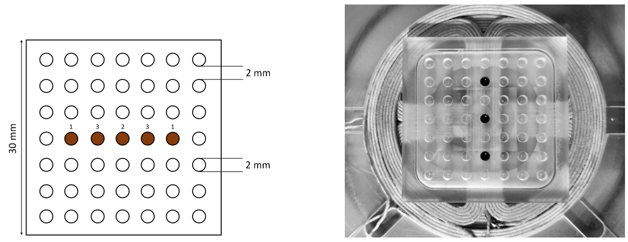

Figure 2: (left) Sketch of the used phantoms with dimensions and the marked filling order. (right) Image of the phantom on the scanner surface rotated by 90° around the x-axis.

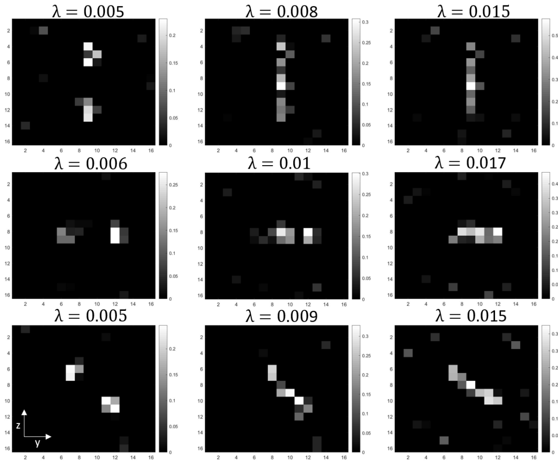

Figure 3: Reconstruction of the phantom in the first layer with the respective regularization parameters λ. (left) two, (center) three and (right) five holes filled with particles. (top) 90°, (center) 0° and (bottom) 45° rotation around the x-axis.

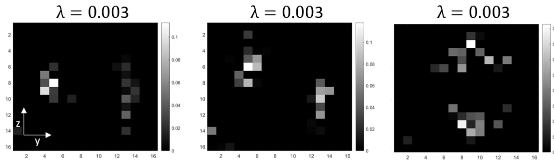

Figure 4: Reconstruction of two filled holes in the phantom in the uppermost layer. (left) 0° rotation, (center) 45° rotation and (right) 90° rotation around the x-axis.

(micromod, Rostock, Germany) nanoparticles. One ml of Perimag contains 8.5 mg iron, which results an iron content of 0.0595 mg per 7 μl. The measurements were averaged 150 times. The phantom consists of several layers, whereby only the top layer was used to fill in particles to find out the maximum penetration depth. Each layer has a thickness of 3.5 mm, so the particles were measured at a distance of 3.5 mm to 14 mm from the scanner surface (Fig 1).

At each distance, the phantom was rotated by the angles 0°, 22.5°, 45° and 90° to the x-axis starting with 0°. The dimensions and the filling order as well as the shape of the phantom and its orientation is shown in Fig 2.

First, each angular position in each layer was measured with two filled positions in the phantom. Afterwards one additional hole was filled and finally five filled positions were measured for each layer and each angular position resulting in 12 measurements for each phantom layer.

II.III Reconstruction

To reconstruct the measured phantom data, the system matrix approach was used. Therefore, a three-dimensional system matrix with Perimag nanoparticles was acquired, recording 150 measurements per frame for averaging. An 8 μl cube-shaped phantom was moved by a robot (isel Microstep Controller C 124–4, iselautomation, Eiterfeld, Germany) to measure each position in a field of view (FOV) of 16 mm x 32 mm x 32 mm and a shape of 8 x 16 x 16 positions.

As a first step, a background correction was applied. Therefore, the middle layer of the FOV was measured again without particles and these were subtracted from the system matrix. For selecting frequency components from the system matrix measurement an SNR threshold had to be determined. Therefore, the center plane of the FOV was measured with the system matrix phantom. Different SNR thresholds were applied, and the best reconstruction result evaluated. The determined threshold was used to select frequency components for the reconstruction of the phantom measurements. An empty measurement was subtracted from the sample measurement for a background correction as well. An iterative Kaczmarz algorithm with 200 iterations was used to reconstruct the images. A Tikhonov regularization was used to stabilize the results, whereby the regularization parameter λ was calculated individually for each measurement [3].

III Results and discussion

Fig 3 shows a selection of reconstructions of the phantom at a distance of 3.5 mm from the scanner surface. Three rotation angles and two to five with particles-filled holes of the phantom are shown. The two filled holes with a distance of 14 mm to each other can be clearly distinguished. The rotation angle shows no significant change in spatial resolution or signal intensity for this layer. In Fig. 4 the uppermost layer is shown at two rotation angles, where two holes of the phantom were filled. The two dots with a distance of 14 mm can still be clearly distinguished in the fourth layer. Therefore, the penetration depth for a three-dimensional measurement is at least 14 mm. There are only small differences in the signal intensity when comparing the different angle positions. The signal intensity increases with the number of filled holes in the phantom, but the structure in the reconstructed images gets smaller and the dots cannot be distinguished anymore.

IV Conclusions

A connection between the arrangement of the receive coils and the spatial resolution in z- and y-direction could not be observed in the reconstruction results of the first layer. Due to coupling effects, the spatial resolution in three-dimensional imaging is lower than in two-dimensional imaging. With a three-dimensional measurement it is possible to achieve a penetration depth of 14 mm. Additionally, the spatial resolution in z- and y-direction is lower than the spatial resolution in the x-direction due to the excitation coil arrangement. Two holes filled with nanoparticles at a distance of 14 mm to each other could be distinguished in comparison to 4 mm in the y-direction of the two-dimensional imaging [6].

Acknowledgments

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