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Evaluation of spatio-temporal resolution of MPI scanners with a dynamic bolus phantom

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Abstract

Magnetic particle imaging (MPI) is a tomographic imaging method to determine the spatial distribution of magnetic nanoparticles (MNP) within a defined volume. To evaluate the spatio-temporal resolution of existing MPI scanners, enabling a comparison of the performance of different setups, we developed dynamic MPI measurement phantoms. These segmented flow phantoms consist of a bolus of ferrofluid tracer material, pumped through a tube system. Using a hydrophobic organic carrier oil, cylindrically shaped bolus of different diameter, length, MNP concentrations, and flow velocity can be emulated. Moving boluses were imaged by MPI and the correlation of spatial resolution und velocity of the bolus was investigated. For all bolus dimension and flow velocity combinations, for increasing bolus velocity and decreasing bolus volume a decreasing spatial resolution and increasing blurring with was observed.

I Introduction

Magnetic Particle Imaging (MPI) detects the non-linear magnetization response of magnetic nanoparticles (MNP) exposed to an oscillating external magnetic field within a defined volume, which allows the reconstruction and visualization of an MNP distribution [1]. In the past years, a plenty of different scanner setups and data reconstruction algorithms were developed and presented [2]. To enable a comparison and assessment of the different MPI scanner setups which enables a comparison of results obtained from different scanners, reference objects with defined imaging properties are needed. At the moment, different types of measure¬ment phantoms are available for these investigations. Mostly, static phantoms, realized by a defined volume filled with a liquid tracer of known MNP concentration are used. Beside this, MNP embedded into a stiff matrix or 3D-printed magnetic materials are used for the preparation of such phantoms.

Independently from the MNP used for imaging within the matrix, these types of measurement phantoms only enable the investigation of the spatial resolution of MPI scanners and their sensitivity regarding the signal strength and tracer concentration. Such phantoms do not offer the possibility to assess the time dependent properties of signal acquisition and data analysis. For the investigation of these parameters, which determine the temporal resolution of the scanner system, dynamic measurement phantoms are needed [3]. Measurements with such phantoms allow to determine the velocities of moving objects [4] that can be imaged and reconstructed by a scanner without remarkable loss of spatial resolu-

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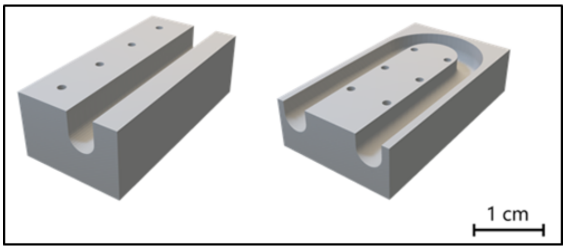

Figure 1: Overall design for (left) a straight and (right) a curved trajectory of the moving bolus within the FOV of the MPI scanner.

tion and to investigate deviations occurring in spatial resolution for velocities above this limit.

Therefore, we developed a dynamic bolus phantom, which provides moving liquid objects of different size, tracer concentration, and velocity.

II Material and methods

This dynamic phantom is based on segmented flow of a cylindrically shaped bolus (MNP dispersion) within a liquid carrier material. The dynamic phantom consists of a flexible tube system with different diameters. The tube is filled with a hydrophobic liquid (carrier) in which an aqueous bolus of a liquid MNP dispersion (tracer) is added. The tracer bolus will not mix with the carrier due to the high surface tension between both liquid phases. Due to the wetting of the inner surface of the tube with the hydrophobic carrier, the aqueous tracer will not interact with the tube system, which leads to a very stable geometry of the tracer segment within the tube system. This tracer segment can be moved accurately trough the scanner by pumping the hydrophobic carrier liquid. By a variation of tube diameter, bolus volume, tracer concentration, and carrier flow velocity, the temporal resolution of MPI scanners can be tested. Different geometries (trajectories) of the moving bolus were realized by mounting the tube into two different 3D-printed tube holders (see figure 1). Fiducial markers (filled with tracer fluid) in the holders enables a reproducible positioning of the phantom.

By measuring the contact angle of a ferrofluid drop on the surface of the tube, the hydrophobicity of the tube material was tested. The hydrophobicity should be as high as possible to prevent an adhesion of the tracer to the inner tube wall. For the selection of a tube material that shows a minimum adhesion of tracer material at the inner wall of the tube, several tube systems were tested. It was found that, "TYGON® E-3603" (Reichelt Chemietechnik, Heidelberg, Germany) was the most suitable material. From this material, tubes with different inner diameters were used for the experiments. As the hydrophobic carrier liquid, silicon oil (M10, Carl Roth, Karlsruhe, Germany) was selected to guarantee the phase separation between tracer bolus and carrier liquid. Due to its high performance for MPI and the use of perimag® (LOT 01718102-04, micromod Partikel¬technologie, Rostock, Germany) in our previous phantom studies [5], this tracer material was used for the setup of the dynamic bolus phantom again.

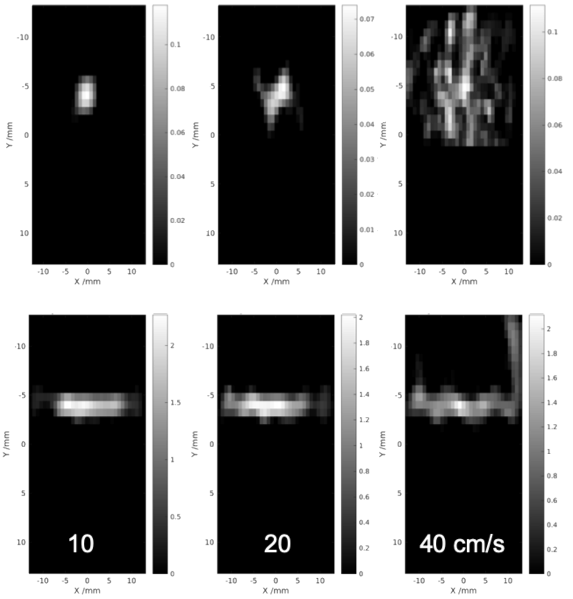

Figure 2: Reconstruction of boluses with a diameter of 0.8 mm (upper row) and 3.2 mm (lower row) for a bolus length of 3 times the tube diameter and flow velocities from 10 to 40 cm/s confirm a decreasing spatio-temporal resolution for increasing flow velocities of the boluses and decreasing bolus size/volume. Shown pictures were obtained for imaging the straight phantom within MPI 25/20 FF scanner. The color bar is coding the reconstructed signal intensity.

In a previous study it was tested, which static bolus sizes of perimag® can be imaged in the scanner with a sufficient temporal resolution. From these studies we determined the here used bolus aspect ratio to be 1, 3, and 10 times the tube diameter (denoted as 1D, 3D, 10D) for tube diameters of 0.8, 1.6, 3.2, and 4.8 mm (denoted as 08, 16, 32, and 48).

For the setup of the dynamic phantoms, tubes of all four diameters were connected to a syringe pump (Legato 100, KD Scientific, Holliston/MA, USA) and the carrier oil was moved continuously through the tubes with adjustable flow velocity. An injector needle was mounted to the tube and connected to a second pump, which injects the tracer into the carrier, and depending on tube diameter and corresponding tracer volume, tracer bolus segments of desired length (1D, 3D, and 10D) are formed. The velocity of moving boluses was defined to be 1, 5, 10, 20, and 40 cm/s, which represent realistic blood flow velocities within the body [6]. These moving boluses within the dynamic phantom were imaged by two different MPI scanner types: an MPI 25/20FF (Bruker, Ettlingen, Germany) operated at Charité University Medicine and the Würzburg TWMPI prototype (V1, 2.5 T/m, SSM, Würzburg) [7, 8]. With both devices the spatial resolution as a function of bolus velocity was investigated.

III Results and discussion

Moving boluses were imaged successfully by means of both scanners. For all tube diameters it was possible to reconstruct the moving bolus up to flow velocities of 40 cm/s, see figure 2. Higher flow velocities can't be realized with the present dynamic bolus phantom due to the maximum volumetric flow rate of the pump. For all bolus dimension and flow velocity combinations, a decreasing spatial resolution and increasing blurring with increasing bolus velocity and decreasing bolus volume was observed. This means that, the obtained temporal imaging resolution is defined by the dimensions of the bolus and the used spatial resolution and vice versa. The here presented phantom is able to assess the correlation of spatial and temporal resolution for moving objects of different size and velocity.

IV Conclusions

A dynamic bolus phantom system for evaluation of the temporal resolution of MPI scanners was developed. Within the presented measurement phantom, tracer boluses of adjustable size, volume, concentration, and flow velocity can be provided in a range which is representable for medical applications. Due to high surface tension in the segmented flow system, the boluses show a very good stability against leaching into the carrier liquid. In both MPI scanner systems moving boluses were imaged successfully and a clear dependency of the spatial resolution on the velocity of the moving bolus was found. The developed dynamic phantoms enable to evaluate the temporal-spatial resolution of existing MPI scanners.

Author's Statement

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