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Vascular MPI: visualization and tracking of rapidly moving samples

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Abstract

Magnetic Particle Imaging (MPI) is a fast imaging technique for the visualization of the distribution of superparamagnetic iron-oxide nanoparticles (SPIONs). For spatial encoding, a field free area is moved rapidly through the field of view (FOV) generating a localized signal. Fast moving samples, e.g., a bolus of SPIONs traveling through the large veins in the human body carried by blood flow with velocities in the order of 45 cm/s and higher, cause temporal blurring in MPI measurements using common sequences and reconstruction techniques. This hampers the evaluation of dynamics of rapidly moving samples. In this work, initial results of rapidly moving samples in form of SPION boluses visualized within an MPI scanner are shown.

I. Introduction

Magnetic Particle Imaging (MPI) is based on the nonlinear magnetization response to time-varying magnetic fields [1] and offers imaging with high sensitivity in the pico-molar range [2], good resolutions below 500 µm [3, 4] as well as short acquisition times (500 µs for 2D [5] and 22 ms for 3D [6]). The latter feature in combination with near real-time data reconstruction frameworks [7, 8] opens new ways for the treatment of coronary diseases, in particular for performing MPI-guided percutaneous transluminal angioplasty (PTA) or stenting [9, 10, 11].

Some applications in cardiovascular imaging require even higher temporal resolutions, e.g., in cardiac valve or coronary artery imaging [15].

Two fundamental reconstruction methods are available in the MPI community: the image-based reconstruction method [12, 13] and the Fourier-based reconstruction technique [6]. The usage of novel approaches can reduce computation time, which provide short latencies below 30 ms between data acquisition and visualization for 2D [3, 7] and below 150 ms for 3D [14]. These delay times are sufficient for near real-time visualization.

To achieve higher temporal resolutions, a continuous data streaming is used, which requires a robust and stable hardware design as well as a high-performance acquisition network for signal processing [7]. Furthermore, an MPI scanner providing a large field of view (FOV) and fast acquisition is required. The Traveling Wave Magnetic Particle Imaging (TWMPI) system [16] allows scanning a FOV with the length of 65 mm and a diameter of 29 mm at once with a temporal resolution up to 2000 frames per second (FPS) [5, 18].

In this work, a flexible reconstruction framework is utilized to study the influence on the image quality of rapidly moving samples within an MPI scanner. The

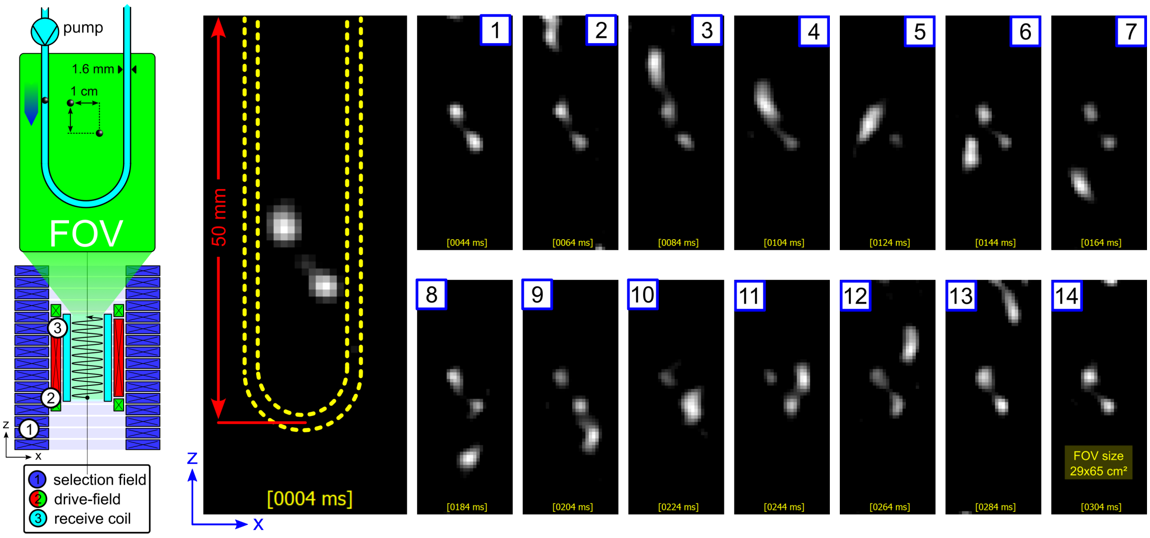

Figure 1: Left: Sketch of the dynamic bolus sample in a TWMPI scanner. The tube is fixed in an U-shape on a 3D-printed holder. In the tube a point-like bolus is prepared, which can be moved by a pump at adjustable velocity. Right: Results of the measurement of a bolus of SPIONs traveling through the FOV of a TWMPI scanner with the velocity of 40 cm/s.

adjustable processing of continuous signal streams provides image-series with adjustable temporal resolution offering smooth transitions of fast-moving samples.

II. Material and methods

II.I. Data reconstruction

The TWMPI system [16] is operating with four channels, Ch1 and Ch2 driving the main gradient system (dLGA) at the frequency f_1 and a phaseshift of 90° generating two field free points (FFP) traveling along the symmetry axis. Ch3 (f_2) and Ch4 (f_3) driving two perpendicular saddle-coil pairs, providing arbitrary 3D trajectories through the FOV [3, 5, 16]. For example, 2D imaging (slice-scanning mode – SSM), the sampled signals are rearranged on a 2D grid pixel-by-pixel depending on their time stamp generating a scanner-specific raw-image, which can be used for further image-based reconstruction processes [5, 13]. The shortest possible acquisition time T_{SSM}, which is required to scan one full slice, depends on the main frequency f_1:

$$T_{\text{SSM}} = \frac{1}{2} \cdot \frac{1}{f_1} \,. \tag{1}$$

For image reconstruction within a continuous data stream, at least the minimal number of data points $S_{f1,min}$=samplingrate/2f_1 corresponding to the acquisition time T_{SSM} are used and can be extended arbitrarily to more data points S_{data}, providing features such as averaging or higher pixel densities within the raw-images with the drawback of reduced frame rates [17].

II.II. Experimental setup

For initial measurements, a dynamic bolus utilizing a spherical sample filled with undiluted Perimag® (Micromod Partikeltechnologie GmbH, Germany) was prepared in a plastic tube (TYGON® E-3603, Reichelt Chemietechnik, Germany) with an inner diameter of 1.6 mm [19]. The aqueous bolus is formed within a hydro-phobic carrier of liquid silicone oil (Carl Roth, Germany) by segmented flow and the surface tension to guarantee the phase separation between SPION and carrier liquid. Connected to a syringe pump (Legato 100, kdScientific, UK), the carrier liquid can be transported with a specific velocity of up to 40 cm/s (1.6 mm tube) moving the point-like bolus through the U-shaped tube. As reference, two fiducial markers were positioned in the center of the sample and filled with undiluted Perimag®.

II.III. TWMPI scanner parameters

The TWMPI scanner parameters were set to f_1=1050 Hz and f_2=12150 Hz scanning the FOV of 65 mm in length and 29 mm in diameter with SSM sequence [5, 17]. The acquisition time for all measurements was 5 seconds at a sampling rate of 25 MS/s resulting in a data length of 125·10^6 samples.

III. Results and discussion

In Fig. 1 right, the results of an initial experiment with a bolus traveling at a velocity of about 40 cm/s inside an U-shaped plastic tube through the FOV of a TWMPI scanner is shown. The parameters for the reconstruction process were set to S_{data}=500k (20 ms, 50 FPS, 105 averages).

The large image indicates the position of the U-shaped plastic tube and of the two fiducial markers. The image series on the right shows the reconstructed images with the fiducial markers.

In comparison to other MPI scanners, e.g., MPI25/20FF (Bruker, Ettlingen, Germany), the image quality can differ dramatically [20]. With increasing velocity of the bolus, the blurring effect increases within non-TWMPI systems. However, it has to be emphasized, that the sequences and also the reconstruction process within this study has been optimized for TWMPI systems.

IV. Conclusion

The rapidly moving bolus traveling at a velocity of about 40 cm/s, which is in the range of venous blood flow in the human vena cava, could be clearly visualized. This provides the possibility of visualizing fast dynamics, such as bolus measurements in humans.

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Author's statement

Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study.

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