

Vogel, Patrick,; Rückert, Martin; Kampf, Thomas; Herz, Stefan; Stang, Anton;
Wöckel, Lucas; Bley, Thorsten; Dutz, Silvio; Behr, Volker

Vascular MPI: visualization and tracking of rapidly moving samples

Original published in: International journal on magnetic particle imaging. - Lübeck : Infinite Science Publishing. - 9 (2023), 1, art. 2303044, 3 pp.
Original published: 2023-03-19
ISSN: 2365-9033
DOI: [10.18416/IJMPI.2023.2303044](https://doi.org/10.18416/IJMPI.2023.2303044)
[Visited: 2023-08-22]



This work is licensed under a [Creative Commons Attribution 4.0 International license](https://creativecommons.org/licenses/by/4.0/). To view a copy of this license, visit <https://creativecommons.org/licenses/by/4.0/>

Proceedings Article

Vascular MPI: visualization and tracking of rapidly moving samples

P. Vogel^{a,e,*} · M. A. Rückert^a · T. Kampf^{a,d} · S. Herz^c · A. Stang^b · L. Wöckel^b · T. A. Bley^c · S. Dutz^b · V. C. Behr^a

^aDepartment of Experimental Physics 5 (Biophysics), Julius-Maximilians University, Würzburg, Germany

^bInstitute of Biomedical Engineering and Informatics, Technische Universität Ilmenau, Ilmenau, Germany

^cInstitute of Diagnostic and Interventional Radiology, University Hospital Würzburg, Würzburg, Germany

^dDepartment of Diagnostic and Interventional Neuroradiology, University Hospital Würzburg, Würzburg, Germany

^ePure Device GmbH, Rimpf, Germany

*Corresponding author, email: Patrick.Vogel@physik.uni-wuerzburg.de

© 2023 Vogel *et al.*; licensee Infinite Science Publishing GmbH

This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

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.

1. Introduction

Magnetic Particle Imaging (MPI) is based on the non-linear 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 reconstruc-

tion 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

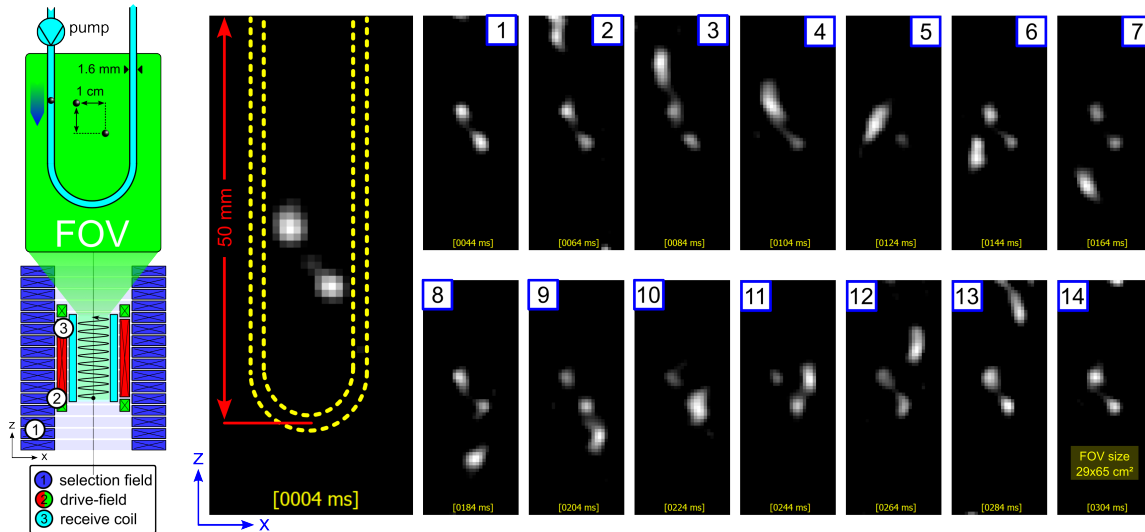


Figure 1: Left: Sketch of the dynamic bolus sample in a TWMPI scanner. The tube is fixed in an U-shape on a 3D-printed holder. In the tube a point-like bolus is prepared, which can be moved by a pump at adjustable velocity. Right: Results of the measurement of a bolus of SPIONs traveling through the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

$$T_{SSM} = \frac{1}{2} \cdot \frac{1}{f_1} . \quad (1)$$

For image reconstruction within a continuous data stream, at least the minimal number of data points $S_{f1,min} = \text{samplingrate}/2f_1$ 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® (Micro-mod 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 $125 \cdot 10^6$ 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.

Acknowledgments

Research funding: This work was supported by German Research Council (DFG) in the frame of the project quantMPI (DU 1293/6-1) and partially by the German Research Council (DFG) under Grant VO 2288/1-1, VO 2288/3-1, and BE 5293/1-2.

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.

References

- [1] B. Gleich & J. Weizenecker, Tomographic imaging using the nonlinear response of magnetic particles, *Nature*, 435(7046), 1214–7, 2005.
- [2] M. Graeser et al., Towards Picogram Detection of Superparamagnetic Iron-Oxide Particles Using a Gradiometric Receive Coil, *Sci. Rep.*, 7:6872, 2017.
- [3] P. Vogel et al., Micro Traveling Wave Magnetic Particle Imaging – sub-millimeter resolution with optimized tracer LS-008, *IEEE Trans Magn*, 55(10):5300207, 2019.
- [4] Z.W. Tay et al, In vivo tracking and quantification of inhaled aerosol using magnetic particle imaging towards inhaled therapeutic monitoring, *Theranostics*, 8(13), 3676–87, 2018.
- [5] P. Vogel et al., Superspeed Traveling Wave Magnetic Particle Imaging, *IEEE Trans Magn*, 51(2):6501603, 2015.
- [6] J. Weizenecker et al., Three-dimensional real-time in-vivo magnetic particle imaging, *Phys Med Biol*, 54(5), L1–L10, 2009.
- [7] P. Vogel et al., Low latency Real-time Reconstruction for MPI Systems, *Int. J Magn Part Imaging*, 3(2):1707002, 2017.
- [8] T. Knopp & M. Hofmann, Online reconstruction of 3D magnetic particle imaging data, *Phys Med Biol*, 61(11), N257–N267, 2016.
- [9] S. Herz et al., Magnetic Particle Imaging guided real-time Percutaneous Vascular Angioplasty: A phantom study, *Cardiovasc Intervent Radiol*, 41(7), 1100–5, 2018.
- [10] S. Herz et al, Magnetic Particle Imaging-Guided Stenting, *J Endovasc Ther*, 25(4), 512–9, 2019
- [11] J. Salamon et al., Magnetic Particle / Magnetic Resonance Imaging: In-vitro MPI-Guided Real Time Catheter Tracking and 4D Angioplasty Using a Road Map and Blood Pool Tracer Approach, *PLoS One*, 11(6): e0156899, 2016.
- [12] P. W. Goodwill & S. M. Conolly, The x-Space Formulation of the Magnetic Particle Imaging process: One-Dimensional Signal, Resolution, Bandwidth, SNR, SAR, and Magnetostimulation, *IEEE TMI*, 29(11), 1851–9, 2010.
- [13] P. Vogel et al., Flexible and Dynamic Patch Reconstruction for Traveling Wave Magnetic Particle Imaging, *Int. J. Magn Part Imaging*, 2(2):1611001, 2016.
- [14] P. Vogel et al. Real-time 3D Dynamic Rotating Slice-Scanning Mode for Traveling Wave MPI. *Int. J. Magn Part Imaging*, 3(2): 1706001, 2016.
- [15] D.A. Bluemke et al, Magnetic Resonance Angiography and Multidetector Computed Tomography Angiography, *Circulation*, 118, 586–606, 2008.
- [16] P. Vogel et al, Traveling Wave Magnetic Particle Imaging, *IEEE TMI*, 33(2), 400–407, 2014.
- [17] P. Vogel et al., First in-vivo traveling wave magnetic particle imaging of a beating mouse heart, *Phys Med Biol*, 61(18), 6620–34, 2016.
- [18] P. Vogel et al., Superspeed Bolus Visualization for Vascular Magnetic Particle Imaging, *IEEE TMI*, vol. 39(6), pp. 2133–9, 2020
- [19] S. Dutz et al., A Dynamic bolus phantom for the evaluation of the spatio-temporal resolution of MPI scanners, *J Magn Magn Mater*, vol. 519:167446, 2020.
- [20] S. Dutz et al., Evaluation of spatio-temporal resolution of MPI scanners with a dynamic bolus phantom, *IJMPI*, vol. 6(2):2009011, 2020.