International Journal on Magnetic Particle Imaging
Vol 9, No 1, Suppl 1, Article ID 2303065, 3 Pages

Infinite Science Publishing

Proceedings Article

MPI-guided endovascular therapy of 3D printed human aneurysms

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Abstract

Endovascular treatment of human aneurysms with stent grafts is an established therapeutic strategy to treat ruptured and unruptured arterial aneurysms. These stents are covered with a membrane that blocks blood flow to the aneurysm and promotes healing of the vessel. To date, digital subtraction angiography (DSA) has been gold standard for image-guided stent graft application. However, DSA is associated with significant disadvantages including its invasiveness, the need for potentially nephrotoxic iodine-based contrast agents and exposure to ionizing radiation for patients and clinical staff. Magnetic particle imaging (MPI) is a fast and sensitive tomographic imaging technique that uses magnetic fields to visualize superparamagnetic iron-oxide nanoparticles (SPIONs). The advantages of MPI include the background- and radiation-free visualization of SPION-tracers. The aim of this proof-of-concept study was to demonstrate the potential of MPI for image-guided application of covered stents in a 3D printed realistic aneurysm phantom.

I. Introduction

An aneurysm is an abnormal enlargement of a blood vessel caused by a weakened vessel wall. Aneurysms typically occur in aortic, cerebral, mesenteric, splenic, and popliteal arteries. Their major complication is rupture, which is associated with high morbidity and mortality. Endovascular therapy of aneurysms is an established therapeutic approach and aims to prevent expansion and rupture, by excluding blood flow from the aneurysm wall using endovascular instruments such as coils and covered stents.

Digital subtraction angiography (DSA) is gold standard in visualization and image-guided treatment of human aneurysms. Drawbacks of DSA are the invasiveness, radiation exposure for patients and clinical staff and the need of potentially nephrotoxic iodine-based contrast agents.

Magnetic particle imaging (MPI) [1,2] could be an applicable radiation-free alternative for image-guided endovascular therapy. MPI visualizes superparamagnetic nanoparticles (SPIONs), which are non-nephrotoxic, very fast and sensitive. Recently, advances in experimental cardiovascular interventions such as MPI-guided PTA and stenting have been shown [3-6]. Moreover, interventional instruments such as metal stents seem not to relevantly alter image quality [6,7]. Thus, MPI has great potential for cardiovascular interventions.

II. Material and Methods

II.I. Scanner

All experiments were performed on a traveling wave MPI scanner system (TWMPI, isotropic resolution ~ 3 mm,

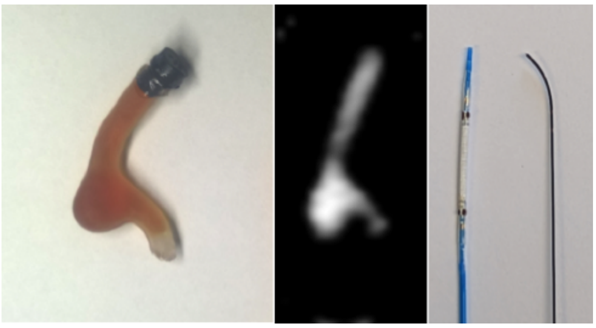

Figure 1: Left: Aneurysm phantom filled with diluted Ferucarbotran (1:50). Middle: Corresponding reconstructed MPI image (visualization speed 8 frames/s). Right: SPION-labeled interventional instruments (balloon-mounted covered stent and guide wire).

gradient strength ~ 1,5 T/m, FOV 65 mm length, 29 mm diameter, frequency f_1=1,050 Hz and f_2=12,150 Hz, 8 frames/s) [8-11].

II.II. Experimental setup

Aneurysms of different arteries were adapted from CT- and MRI scans and printed with a 3D printer (Form 2, formlabs, USA). Experimental MPI-guided endovascular treatment was performed using guidewires (Radifocus® Guidewire M, Terumo Interventional Systems, Tokyo, Japan) and covered stents (6/38 mm, BeGraft peripheral, Bentley InnoMed GmbH, Hechingen, Germany). Endovascular instruments were labeled (figure 1, right side) with a custom-made MPI sensitive lacquer based on Ferucarbotran (100 mmol (Fe)/l, Bayer, Berlin, Germany) for MPI-visibility [5,6]. Interventional procedures were performed under close MPI guidance. The lumen of the aneurysm was visualized with an MPI-angiography (MPA) by injecting diluted Ferucarbotran (5 mmol (Fe)/l). Then, a guidewire was passed through the vessel phantom. The stent graft was deployed over-the-wire in the target zone at the aneurysm neck.

III. Results and discussion

Aneurysm phantoms were displayed with good temporal and spatial resolution (Fig. 1). However, some anatomic distortions occurred especially along the z-axis, regardless of whether endovascular instruments were inserted or not. Dynamic visualization of MPI-guided applications of covered stents was performed at near real-time with ~115 ms latency time to visualization. Comparison with reference phantoms revealed that endovascular instruments and deployed stent grafts did not generate any relevant image artifacts that may have hampered lumen visualization. Correct positioning of the stent grafts was confirmed by a control MPA.

IV. Discussion

In this study 3D printed realistic aneurysm models were treated successfully with covered stents. Labeled interventional instruments, high image visualization speed and low latency time of the MPI scanner allowed for near real-time guidance of interventional procedures. Slight distortions of the depicted aneurysms can be reduced through optimized reconstruction algorithms.

Improved scanner hardware and tailored SPIONs bear potential for significant advancements such as spatial resolution far below 1 mm. However, advances in scanner design need to consider limitations in specific absorption rate (SAR) and peripheral nerve stimulation (PNS) [12].

Eddy currents potentially lead to heating of stents. In this proof-of-concept study the temperature of the stent grafts was not assessed. However, a recent study did show no or only minimal heating in stents of comparable topology and diameter [13]. Further investigations are necessary to fully assess heating effects in covered stents.

Blood flow, which may induce flow artifacts, was not included in the vessel phantom and should be assessed in future studies.

V. Conclusions

MPI-guided endovascular aneurysm treatment is feasible and may overcome disadvantages of established medical imaging modalities such as nephrotoxic contrast agent and ionizing radiation exposure in DSA. Further research and the development of dedicated human sized MPI scanners is required to evaluate MPI as a competitive method for clinical imaging.

Acknowledgments

Research funding: The work was supported by the German Research Council (DFG), grant numbers: VO-2288/1-1, VO-2288/3-1, and BE 5293/1-2. The authors especially thank Mrs. Hillburger from Bentley InnoMed GmbH for providing BeGraft Peripheral Stent Grafts.

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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10.18416/ijmpi.2023.2303065