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Research Article

Detection of flow dynamic changes in 3D printed aneurysm models after treatment

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Abstract

Treatment success and potential relapse of intracranial aneurysms need to be followed-up by regular imaging. However, the metallic material inside treated aneurysms can cause artifacts in MRI, CT and DSA possibly compromising clinical interpretation. Furthermore, frequent follow-ups with X-ray based imaging methods seriously increase the patient's exposure to ionizing radiation. Thus, magnetic particle imaging (MPI) may be beneficial for patients with treated aneurysms. The purpose of this work was to demonstrate the capability of MPI to depict the change of the contrast agent dynamics of aneurysms after treatment. Realistic aneurysm models before and after treatment with different approaches were connected to a peristaltic pump with a physiologic flow (250 ml/min) and pulsation rate (70/min). Contrast agent curves over time were measured during injection of a 3 ml bolus within 3 s of an aqueous solution of 50 mmol(Fe)/L. MPI was able to detect the expected delay and dispersion of the contrast agent in the treated aneurysm as well as reduced filling with contrast agent, if densely packed material was present inside the aneurysm. The delay was estimated based on the MPI contrast agent curves to be in the order of about 1 s. Thus, MPI is capable to detect delay and dispersion of the contrast agent dynamics after aneurysm treatment with clinical standard metallic material.

I. Introduction

Magnetic particle imaging (MPI) is capable of acquiring 3D datasets with high temporal resolution [1, 2], which may be especially beneficial for *in vivo* hemodynamic imaging. We recently demonstrated the capability of MPI to clearly depict contrast agent dynamics of an untreated 3D printed aneurysm model with much higher temporal resolution compared to magnetic resonance imaging (MRI) and without the use of ionizing radiation compared to digital subtraction angiography (DSA) [3]. The use of a realistic, patient specific, aneurysm model with physiological flow and pulsation rates translates the, so far only pre-clinically available, MPI towards clinically realistic conditions.

The treatment success and potential relapse of intracranial aneurysms need to be followed-up by regular imaging. Current clinical practice is to use DSA for the first year of follow-up together with MRI. All later follow-ups are typically conducted using MRI only, if the

findings are stable and inconspicuous. However, metallic material inside the treated aneurysm can cause artifacts in MRI, CT, and DSA compromising the clinical interpretation [4]. Furthermore, frequent follow-ups with X-ray based imaging methods, i.e., CTA and DSA, seriously increase the patient's exposure to ionizing radiation. Thus, an imaging methodology without ionizing radiation, like MPI, may be beneficial for patients with treated aneurysms. The purpose of our study was to test, whether MPI is capable of depicting the change of the aneurysm's contrast agent dynamics after treatment.

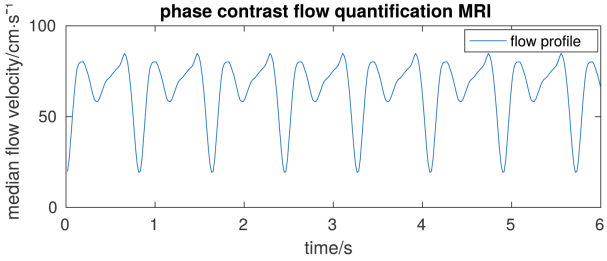

Figure 2: Flow pulsation pattern of the peristaltic pump measured by phase contrast flow quantification MRI.

II. Methods

3D printed aneurysm models were derived from a static 3D rotational angiography of a patient with an incidental Internal Carotid Artery (ICA) aneurysm of saccular morphology (ca. 5 mm diameter). The model was printed with 254 μm thick layers of acrylonitrile butadiene styrene at fused deposition modeling using the HP Designjet 3D printer and surfaces were sealed with Nano-Seal (Jeln Imprägnierung, Schwalmstedt, Germany) [5] (Fig. 1, left). The aneurysm model was connected to a peristaltic pump (Model type 10-00-00, Sorin Group Deutschland GmbH, formerly Stöckert, Munich, Germany), which was set to deliver a physiological flow and pulsation rate of about 250 mL/min and 70/min, respectively. It should be noted that, due to the peristaltic nature of the pump, the pulsation profile is not directly comparable with real human physiology (Fig. 2).

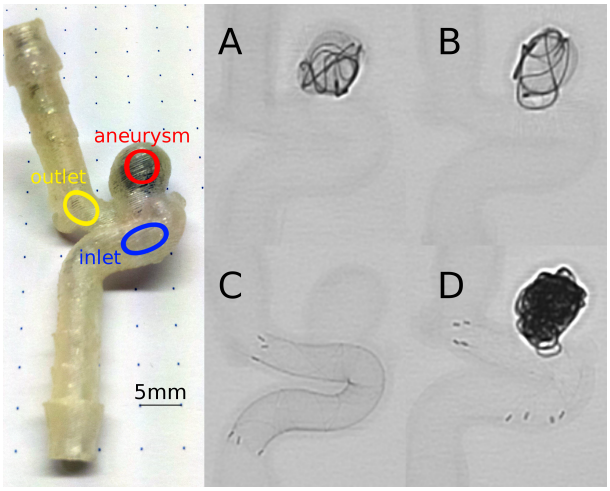

Figure 1: Photograph with locations of analyzed regions of interest (left) and X-ray images of 3D printed aneurysm treated with Medina devices (A, B), flow diverting stent (C), and stent assisted coiling (D).

Five identical aneurysm models were used for the experiments. Four of these models were treated with different endovascular materials by two trained neuroradiologists (A.F. and J-H.B.) using an AlluraClarity Xper FD20 angiography system (Philips Healthcare, Best, Netherlands). Two models were treated by the same interventionalist with identical Medina embolization devices (Medtronic, Dublin, Ireland) (Fig. 1, A, B), which allow a fast treatment of an aneurysm with just one device [6, 7]. One model was treated with a flow diverting stent (DERIVO, Acandis, Pforzheim, Germany) (Fig. 1, C), which also allows a fast treatment with just one device [8] and one model was treated using stent assisted coiling (Fig. 1, D) [9]. The single untreated aneurysm model served as pre-treatment control for all treated models.

MPI was performed using a pre-clinical MPI scanner (Bruker Biospin/Philips) acquiring 1 mm isotropic 3D data with 21.5 ms temporal resolution. The selection gradient field of the MPI scan was 2.5 T/m in the z-direction (1.25 T/m in the x- and y-direction), the amplitude of the drive field was equal to 14 mT resulting in a FOV of 22.4×22.4×11.2 mm^3. To prevent artifacts at the FOV boundaries the calibration scan was captured for a larger volume of 32×32×18 mm^3. Images were reconstructed based on an iterative reconstruction scheme that solves a first order Tikhonov regularized least-squares functional [10]. This is also known as the Kaczmarz algorithm.

A bolus of 3 ml aqueous solution of 50 mmol(Fe)/L (MM4, TOPASS GmbH, Berlin, Germany) was administered within 3 s using a syringe pump and an angiographic catheter with 1 mm inner diameter. The tip of the catheter was placed close to the aneurysm model (~5 cm upstream) to reduce bolus dispersion.

To reduce smearing of the short and small volume contrast bolus caused by the inertness of the injection system (syringes and lines), a three-way stopcock was placed directly at the inlet of the angiographic catheter and opened shortly before the injection pump was manually started and closed immediately after the programmed injection pump stopped moving.

Post processing was done employing in house written software using MATLAB (The Mathworks, Natick, MA, USA). Regions of interest (ROIs) were placed in the parent vessel before (inlet), after (outlet), and inside the aneurysm (Fig. 1, left). Median signal of these ROIs was plotted over time and visually compared between control and different treatments.

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III. Results

Maximum projections of the mean contrast filling of the models during bolus injection nicely resample the anatomy of the models (Fig. 3). The projection of the models treated by stent assisted coiling does not completely fill with contrast agent.

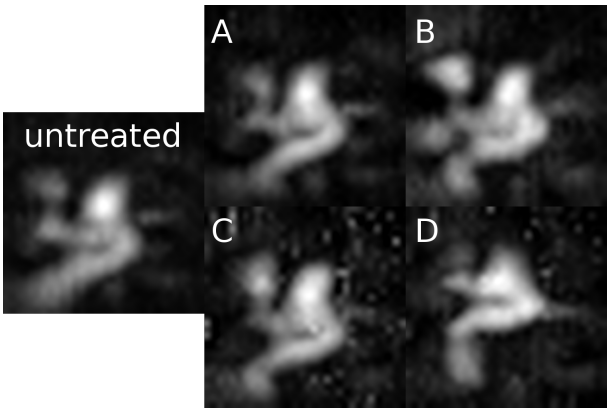

Figure 3: Maximum projections of mean contrast filling of the models during bolus injection. Untreated aneurysm model (left) and models treated with Medina devices (A, B), flow diverting stent (C), and stent assisted coiling (D).

The contrast over time curve of the parent vessel (inlet as well as outlet ROI) was similar for all models (Fig. 4). The amplitude of the contrast curve of the outlet ROI is lower than the inlet ROI for all models, whereas the contrast amplitude of the aneurysm ROI is similar or slightly higher than the inlet ROI, except for the aneurysm treated with stent assisted coiling (Fig. 4, D). In the latter case, the contrast curve is similar to the lower amplitude of the outlet ROI. Furthermore, the temporal distance (about 0.86 s) between the local peaks, which are clearly visible on top of the inlet ROI contrast curve, allow the estimation of the parent flow pulsation.

The duration of the contrast bolus flowing through the parent vessel is about 4 s, which is longer than the 3 s bolus injection duration (Fig. 4). Despite the gradual contrast increase at the beginning of the bolus, the end of the bolus shows a sharp drop, which allows a good visual estimation of the delayed contrast dynamics of the aneurysms before and after treatment. A delayed contrast agent outflow from the aneurysm is visible for all models, but it is clearly longer (about 1 s) for all treated models compared to the untreated case. The first model, treated with the Medina coil, (Fig. 1 and Fig. 4, A) shows the longest delay of the contrast agent outflow from the aneurysm.

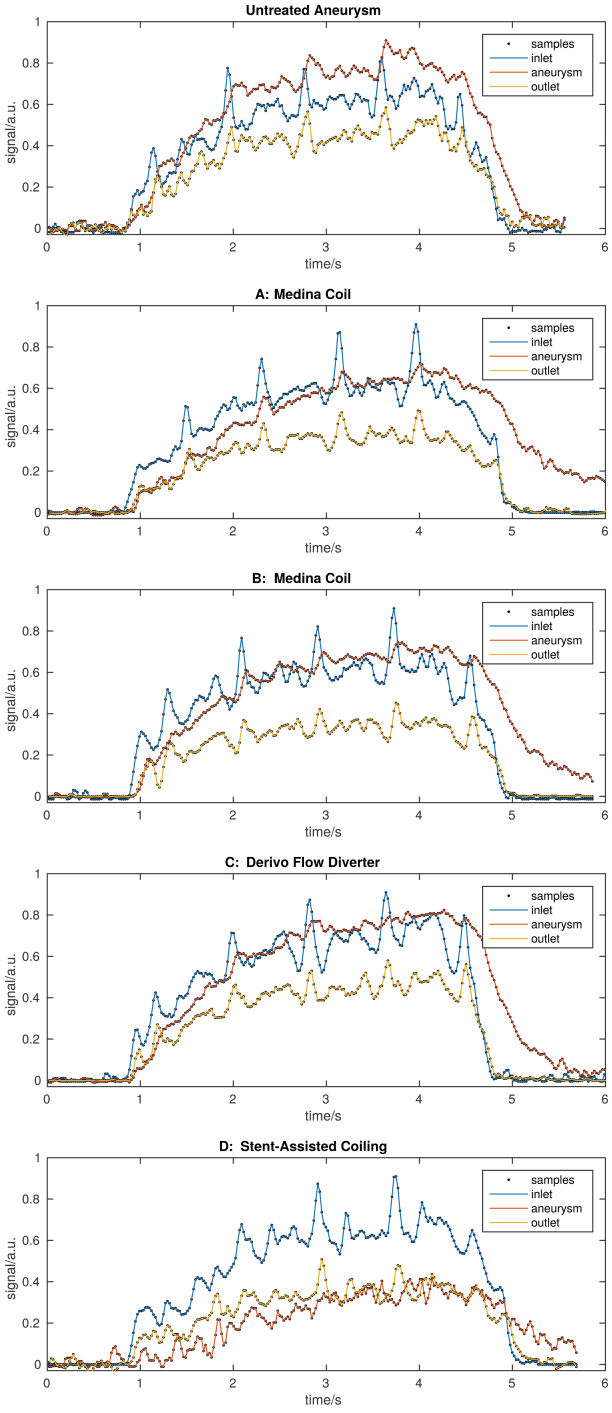

Figure 4: ROI analysis shows a distinct pulsation which is in agreement with the employed pulsation rate. A prolonged delay of the contrast agent outflow of the aneurysm is clearly visible after treatment.

IV. Discussion and Conclusion

MPI was able to detect the expected delay and dispersion of the contrast agent dynamics of the treated aneurysm models. The minimal delay of the untreated aneurysm is caused by a naturally occurring vortex inside of the

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empty aneurysm as shown previously [3]. The delay of the contrast outflow was clearly prolonged for all treated models, which shows the direct treatment effect. The contrast dynamics of the two models treated with the Medina coils (Fig. 1, A and B) was not identical. The first model showed a slower outflow than the second model, which can be interpreted as more effective treatment (Fig. 4, A and B). This effect may have been caused by different configurations of the device's metallic petals across the aneurysm's orifice, which may affect inflow and outflow. However, the aneurysm contrast outflow of model B is still comparable to the model treated with the flow diverter (Fig. 4, C).

Furthermore, the treatment material placed inside the aneurysm displaces volume otherwise occupied by the contrast agent causing a lower magnitude of the contrast curve. This was especially visible for the model treated by stent assisted coiling, where the densely packed coils occupy a large fraction of the aneurysm volume. On the other hand, the low magnitude of the contrast curves of the outlet ROI of all models are most likely caused by partial volume effects, since the vessel caliber here is smaller than compared to the inlet or aneurysm ROI.

The overall longer contrast bolus in the model compared to the injection duration may be caused by dispersion and mixing of the contrast agent upstream of the aneurysm model as well as by the inertness of the injection system. This is especially apparent by the gradual contrast increase at the beginning of the bolus. This may be caused by some contrast leaking out of the catheter tip after opening the stopcock and before the injection system effectively pushes contrast agent into the stream. However, closing the stopcock immediately after the injection pump stopped, effectively blocked the contrast flow into the stream and produced a sharp drop at the end of the bolus. Due to the gradual contrast increase at the beginning of the bolus, the inflow dynamics of the contrast agent is not clearly visible. The same limitations of our injection system were also visible in other imaging modalities, i.e. MRI and DSA, already shown in an earlier work [3]. Thus, the accuracy of the dynamic contrast bolus measurements, regardless of the applied imaging modality, depends on the precision of the injection system. Suboptimal contrast bolus injections may increase the variability and systematic errors to the analysis of the dynamic contrast agent measurements.

The different metallic endovascular materials had no influence on signal noise. The spikes and background signal visible in Fig. 3 are caused by instabilities of the scanner hardware, which will be further improved in collaboration with the manufacturer. Thus, MPI seems capable for measuring flow dynamic changes of aneurysms after treatment.

Water at room temperature was used for the circulation system, which has a 3-4 times lower viscosity than blood. Thus, the contrast agent dynamics of the treated aneurysms will be even slower and, therefore, better detectable, if a liquid matching the viscosity of blood is been used. Furthermore, the slowed down flow dynamics inside the treated aneurysms allow for blood coagulation. Thus, less contrast agent can enter the aneurysm, resulting in lower contrast curves similar to the model treated by stent assisted coiling.

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Disclosures

J. Fiehler consults for Company Microvention, Stryker, Codman and is speaker for Medtronic. J. Buhk consults for Microvention, Sequent Medical, Acandis, Codman and Medtronic. The other authors report no conflicts.

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