Transactions on Additive Manufacturing Meets Medicine
Trans. AMMM, Vol 3, No 1, 2021, Article ID 570

Fabrication of a steerable magnetic micro-robot

A. C. Bakenecker[1,2*], A. von Gladiss[1,3], H. Schwenke[4], A. Behrends[2], T. Friedrich[2], K. Lüdtke-Buzug[1], A. Neumann[1], Z. Penxová[1], J. Barkhausen[5], F. Wegner[5], and T. M. Buzug[1,2*]

[1] *Institute of Medical Engineering, University of Lübeck, Ratzeburger Allee 160, 23562 Lübeck, Germany*
[2] *Fraunhofer Research Institution for Individualized and Cell-Based Medical Engineering IMTE, Mönkhofer Weg 239a, 23562 Lübeck, Germany*
[3] *now with: Active Vision Group, Institute of Computational Visualistics, University of Koblenz-Landau, Universitätsstraße 1, 56070 Koblenz, Germany*
[4] *Department of Neuroradiology, University Hospital Schleswig-Holstein, Campus Lübeck, Ratzeburger Allee 160, 23562 Lübeck, Germany*
[5] *Department of Radiology and Nuclear Medicine, University of Lübeck, Ratzeburger Allee 160, 23562 Lübeck, Germany*
[*] *Corresponding author, email: {anna.bakenecker,thorsten.buzug}@imte.fraunhofer.de*

Abstract: A magnetic micro-robot is fabricated by a stereolithographic printing technique. It only measures 3 mm in length and 1.2 mm in width. After printing, the micro-robot was coated with a sealing lacquer, containing magnetic nanoparticles. Thus, magnetic properties could be introduced and the micro-robot becomes steerable by rotating magnetic fields and visible by Magnetic Particle Imaging. A model of the middle cerebral artery containing an aneurysm was chosen. This phantom was designed from patient's angiography and 3D-printed. The micro-robot could be successfully steered through the middle cerebral artery into the aneurysm of the phantom, demonstrating a future application scenario of treating aneurysms.

© 2021 Bakenecker; licensee Infinite Science Publishing

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.

I. Introduction

Micro-robots can improve a variety of therapies in terms of better accessibility, individual conformity and reduced side effects. One immense interest is to develop techniques, which are able to deliver therapeutics very precisely, such that the systemic dosage can be decreased, while the dosage at the targeted region can be increased [1]. Even though catheter guided interventions are less invasive then an open operation, it would be advantageous to develop an untethered operation technique, which can potentially reach regions of the body which are difficult to access by catheter guided interventions [2].

Magnetic micro-robots could be used in future to deliver drugs through the vasculature towards a targeted region, which could be a tumor, a vessel occlusion or an aneurysm. For the steering, rotating magnetic fields of only few millitesla are needed, which are harmless for the patient [3].

Here, we focus on the fabrication of the magnetic micro-robot as well as on the aneurysm phantom, through which the micro-robot has been steered. The steering and tomographic imaging, which is essential for a future application, are shown in [4].

II. Material and methods

In the following, the manufacturing of the micro-robot, including the 3D-printing as well as magnetic coating is described, followed by the manufacturing of the phantom.

II.I. Magnetic micro-robot

The micro-robot was 3D-printed by a Form2, which is a stereolithographic printing technique (Formlabs Inc., Somerville, USA) with a 25 µm layer thickness by using the "High Temp Resin" of the same manufacturer, because the coating procedure requires high temperatures (see below). Three micro-robots where printed at once on a platform. Each micro-robot stands on three pillars to easily remove them from the platform after printing and coating (see Fig. 1 top).

For the coating, water-soluble and dextran coated Fe_3O_4 nanoparticles were synthesized. 1 ml of the particle solution was mixed with 0.5 ml of an impregnating coating agent Nanoseal 180W (JELN Imprägnierung GmbH, Schwalmtal, Germany), which is typically used to seal additively manufactured devices. It was then filled into a basin with a volume of 1.1 ml, which was additively manufactured with the same printer and material as the micro-robots. This basin fits to the platform, on which the micro-robots were printed, such that the micro-robots dip into the coating solution. Everything was put into an oven for 100 min at 60 °C. The water of the coating solvent could evaporate through holes in the cap. This way a sufficiently thick and homogeneous magnetic coating of the micro-robots was realized. The used magnetic nanoparticles are a well suitable tracer material for the visualization of the micro-robot with Magnetic Particle Imaging [5].

DOI: 10.18416/AMMM.2021.2109570

Furthermore, Neodymium Iron Boron (NdFeB) powder with particles smaller than 5 µm (Magnequench, Singapore) were mixed with an acrylic paint (Lukas-Nerchau GmbH, Nürnberg, Deutschland) with 20 wt%, with which the micro-robot's tip was painted. It was immediately positioned onto a strong permanent magnet for drying. This way the NdFeB particles align with the magnetic field of the permanent magnet, and the micro-robot's tip itself becomes a small permanent magnet with an aligned magnetic moment. Thus, the magnetic tip enables the steering of the micro-robot by magnetic fields. A picture of the magnetically coated micro-robot can be found in Fig. 1 bottom.

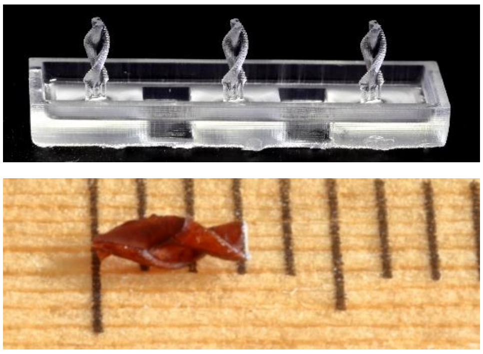

Figure 1: Three micro-robots were printed onto a cap fitting to a basin for the coating solvent. (top). The micro-robots were then dipped into a sealing agent, containing Fe_3O_4 nanoparticles. The tip was painted with an NdFeB containing paint. Each micro-robot has a length of 3 mm and a width of 1.2 mm, it is positioned on a mm-scale (bottom).

II.II. Aneurysm phantom

A 3D clinical rotational angiography with an Allura Xper FD 20/20 (Philips Healthcare, Best, Netherlands) of a patient was acquired, who suffered from an aneurysm located at the right middle cerebral artery.

The images were segmented using Analyze Pro 1.0 (AnalyzeDirect, Overland Park, USA) and arteries smaller than 0.1 mm were removed. The vessel structure was enclosed by a cuboid of 36.5 x 13.1 x 22.2 mm^3. The phantom containing the original size of the vasculature was printed with a stereolithographic printer (Form2) by using the "Clear Resin" of the same supplier. After post processing – washing and UV light curing – the phantom was coated with a clear coat to provide high transparency and water tightness (see Fig. 2). More information can be found in [6].

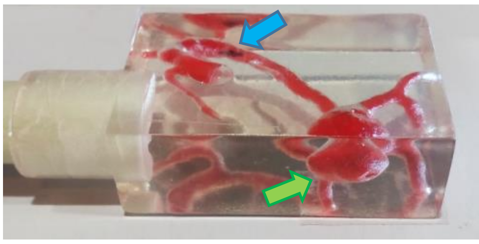

Figure 2: The phantom of a patient's middle cerebral artery featuring an aneurysm (green arrow). The phantom was 3D-printed by using a stereolithographic printing technique. The phantom was filled with red stained water for better visibility of the vasculature. The micro-robot (blue arrow) is positioned inside the middle cerebral artery of the phantom.

II.III. Steering in magnetic fields

By applying rotating magnetic fields, the micro-robot rotates with the same frequency as the magnetic field vector rotates (within certain field amplitudes and rotation frequencies). These rotating fields were applied with a Magnetic Particle Imaging scanner 25/20 FF (Bruker BioSpin, Ettlingen, Germany). Details about the magnetic field generation can be found in [4].

III. Results and discussion

A micro-robot was fabricated using a stereolithographic printing technique and a magnetic coating procedure. The micro-robot only measures a few millimeters (see Fig. 1) and is therefore suitable for the steering through the vasculature.

This was demonstrated using a model of the middle cerebral artery, which was 3D printed and served as a phantom. The micro-robot could be successfully steered through the phantom's vasculature into the aneurysm.

Inside the aneurysm the micro-robot should induce coagulation of the blood in order to prevent a rupture. In future, this could be triggered by applying hyperthermia or developing a drug release mechanism.

IV. Conclusions

With stereolithographic printing techniques and a magnetic coating procedure a micro-robot was fabricated, which can be steered by rotating magnetic fields. The applicability of the micro-robot for the treatment of cerebral aneurysms was demonstrated by using a 3D-printed phantom, which was manufactured from a patient specific data.

Acknowledgments

Research funding: Fraunhofer IMTE is supported by the EU (EFRE) and the State Schleswig-Holstein, Germany (Project: Diagnostic and therapy methods for Individualized Medical Technology (IMTE) – Grant: 124 20 002 / LPW-E1.1.1/1536). Further, the authors gratefully acknowledge the Federal Ministry of Education and Research, Germany (BMBF) for funding this project under grant numbers 13GW0230B (FMT), 13GW0069A (SAMBA PATI), 01DL17010A (IMAGINE) and 13GW0071D (SKAMPI).

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. Ethical approval: The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

References

[1] M. Sitti et al., Biomedical Applications of Untethered Mobile Milli/Microrobots, Proceedings of the IEEE, 103(2), 2015

[2] S. Lee et al., Fabrication and Characterization of a Magnetic Drilling Actuator for Navigation in a Three-dimensional Phantom Vascular Network, Scientific Reports, 8(2), 2018

[3] E. U. Saritas et al., Magnetostimulation limits in magnetic particle imaging. IEEE Trans. Med. Imaging. 32(9), 2013

[4] A. C. Bakenecker et al., Navigation of a magnetic micro-robot through a cerebral aneurysm phantom with magnetic particle imaging, Scientific Reports, 11(1), 2021

[5] B. Gleich and J. Weizenecker, Tomographic imaging using the nonlinear response of magnetic particles, Nature, 435, 2005

[6] H. Schwenke et al., High-precision, patient-specific 3D models of brain aneurysms for therapy planning and training in interventional neuroradiology, Trans. AMMM, 1(1), 2019