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A microrobot for endovascular aneurysm treatment steered and visualized with MPI

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Abstract

The steering of microrobots by using magnetic fields offers applications for minimally invasive surgery or for establishing drug delivery scenarios. On the one hand, magnetic particle imaging (MPI) offers a tomographic, real-time visualization of the used magnetic microrobots. On the other hand, an MPI scanner can apply magnetic fields, which a microrobot can be steered with. Hence, MPI is of great interest for realizing the tracking and navigation of microrobots. Here, we show that a microrobot, which has been coated with superparamagnetic iron oxide nanoparticles (SPIONs) can be steered through a patient specific phantom of the middle cerebral artery into an aneurysm, where it should occlude the aneurysm and can be potentially used for a triggered drug release or a hyperthermia treatment. The acquired MPI images show that a tracking accuracy of 0.68 mm is achieved.

I. Introduction

A brief introduction into magnetic microrobotics as well as a description on how to apply magnetic fields with an MPI scanner for the actuation a microrobot will be given. The medical background about the treatment of cerebral aneurysm motivates the intended application of the presented microrobot.

I.I. Magnetic microrobotics

For a precise and individual treatment of patients, microrobots are of interest. Tiny robots, in the scale of only a few millimeters to several micrometers, enable e.g. a targeted drug delivery or a local application of hyperthermia in regions of the body which are barely accessible by catheter guided interventions.

The use of magnetic fields for navigating the microrobots seems beneficial as the needed field configurations do not provoke any side effects, such as toxic fuel reagents, and the penetration depth is not limited as it is the case for e.g. light or ultrasound induced actuation techniques [1].

There are different strategies to couple the rotation of a magnetic microrobot with its forward movement. Many robots therefore feature either a flexible flagellum or a helical shape.

For a safe in vivo and clinical application of microrobots in the future, a precise tomographic real-time monitoring is essential [2], which MPI can provide.

I.II. Navigation of microrobots with MPI

A magnetic microrobot can be steered by homogeneous magnetic fields with a rotating field vector. Typically, field strengths of only a few militesla and rotation frequencies of less than 100 Hz are applied. Such fields can be generated with the focus fields of an MPI scanner [3, 4]. Sinusoidal currents are applied to the three orthogonal coils. If a movement of a helically shaped microrobot is intended in the direction of

$$\vec{v} = v \begin{pmatrix} \cos\phi \sin\theta \\ \sin\phi \sin\theta \\ \cos\theta \end{pmatrix} \tag{1}$$

in spherical coordinates with the azimuth angle ϕ and the polar angle θ, the plane of rotation of the field vector needs to be applied perpendicular to $\vec{v}$. The magnetic field then reads

$$\vec{B}_{rot}(t) = B_{rot} \begin{pmatrix} -\sin\phi \cos\omega t \\ \cos\phi \cos\omega t \\ -\sin\omega t \end{pmatrix} \tag{2}$$

for a movement of the microrobot in the horizontal xy-plane.

The magnetic moment of a microrobot tends to align with the applied magnetic field vector. The generated torque has the form

$$\vec{T} = \vec{m} \times \vec{B}_{rot} \tag{3}$$

with $\vec{m}$ being the magnetic moment. Therefore, the microrobot follows the rotation and due to its helical shape, a forward velocity is induced.

I.III. Treatment of cerebral aneurysms

A cerebral aneurysm is an outward bulging of a vessel wall in the brain. A rupture which leads to severe bleeding is potentially life threatening. Nowadays, treatment scenarios are either a minimal surgical clipping or an endovascular embolization. For the latter, metallic devices or coils are inserted via a microcatheter into the aneurysm, which induces blood coagulation. Thus, the aneurysm sac is detached from the blood circulation.

However, the advancement of the micro-catheter into the cerebral aneurysm is a critical intervention especially for aneurysms located far peripherally or when a patient anatomy is difficult to probe.

II. Material and methods

A magnetic microrobot, featuring a helical Savonius shape was 3D-printed (Form2, Formlabs) with a size of 3 mm length and 1.2 mm width (see Fig. 1). It was coated with SPIONs (synthesized by the coprecipitation method)

Figure 1: The magnetic microrobot has a helical Savonius shape. It is coated with SPIONs and the tip contains NdFeB particles. It is 3 mm long and therefore smaller than a grain of rice.

and NdFeB microparticles (Magnequench). The microrobot was inserted into a cerebral aneurysm phantom, which was manufactured from patient's CT data (see Fig. 2 left). For details refer to [5]. The phantom was filled with a water-glycerol mixture with a mixing ratio of 2:1, such that the fluid had a viscosity of about 3.5 mPa·s to mimic the viscosity of blood. The path through the middle cerebral artery of the phantom into the aneurysm was approximated by four straight path segments. The magnetic field was then calculated according to equation 2 and applied with a preclinical MPI scanner (Bruker BioSpin) by using a field strength of 3 mT and a rotation frequency of 5 Hz. MPI images of the microrobot were acquired sequentially between each path segment and superimposed by the phantom's angiogram, for which the phantom was filled with 1:100 diluted Resovist (I'rom Pharmaceuticals). Drive field amplitudes of 12 mT have been applied in x-, y- and z-direction and a gradient strength of 0.625 T/m in x- and y-direction and 1.25 T/m in z-direction was set. For determining the tracking accuracy images at 27 dedicated spatial positions of the microrobot were acquired and the center of mass of the reconstructed images was calculated. For more information refer to [6].

III. Results and discussion

The microrobot has been successfully steered through the middle cerebral artery of the phantom into the aneurysm. A video still as well as one of the MPI images of the microrobot are shown in Fig. 2 where it is superimposed by the phantom's angiogram showing the middle cerebral artery.

From the center of mass calculations of 27 images it can be stated that the microrobot can be located with an accuracy of 0.68 mm.

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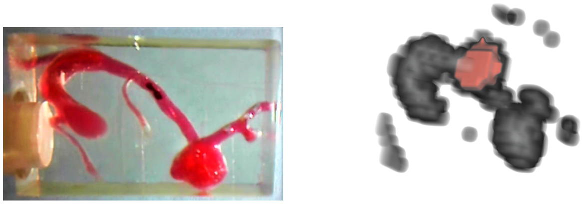

Figure 2: The microrobot was steered through a middle cerebral artery in a human phantom into the aneurysm. The phantom is filled with a red tinted water-glycerol mixture. A video still is shown (left). An MPI image of microrobot at the corresponding position was acquired and superimposed by the angiogram of the phantom (right).

IV. Conclusions

A preclinical MPI scanner has been successfully used for the navigation of a microrobot through an aneurysm phantom. For this, a magnetic field with rotating field vector was calculated according to the path the microrobot has to cope and applied with an MPI scanner. The reconstructed images show the microrobot at different positions inside the phantom. The center of mass calculations of the MPI images prove, that the microrobot can be tracked with a sufficient accuracy. The demonstrated study paves the way towards using an MPI scanner as an actuator and for a real-time feedback for realizing a closed loop control.

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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. 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.

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