Adapting MRI Systems to Propel and Guide Microdevices in the Human Blood Circulatory System

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Abstract—**Magnetic Resonance Imaging (MRI) systems are widely used to gather non-invasively images of the interior of the human body. This paper suggests that an MRI system can be seen beyond being just a tool for imaging purpose but one that can propel and guide special microdevices in the human body to perform specific medical tasks. More specifically, an MRI system can potentially be used to image the region of interest, propel a microdevice through the generation of magnetic gradients, determine the location of the device, compute the corrective actions through feedback control algorithms and adjust the generation of the magnetic gradients accordingly to navigate such a microdevice in a pre-planned path. This paper presents an introductory description of the proposed techniques, the main issues to consider, and some preliminary data indicating the validity of this approach.**

Keywords—**Microdevice, magnetic resonance, magnetic gradient, propulsion, positioning, blood vessels**

I. Introduction

Although modern medical procedures rely on instruments such as the catheter to reach remote regions inside the human body, many sites are still inaccessible to minimally invasive medical instruments. Accesses to these remote locations can have a relatively large impact on modern medicine by providing a method that would allow new procedures to be considered. These procedures may include but are not limited to highly localized drug delivery for chemotherapy, thermal treatment of tumors through magnetic modulation at selected sites, MRI image contrast agents for early detection at pre-selected sites, carriers for biosensing applications, in vivo molecular imaging by MRI from magnetic nanoparticles at target sites, diagnostic tools to measure various properties at pre-selected sites, minimally invasive procedures such as reopening of encumbered arterial ways, novel methods to treat aneurysm, and many more. Ideally, a tool in the form of a wireless microdevice specially designed for a particular task and propelled within the human body would offer many advantages in term of accessibility to remote sites compared to existing tools.

Body fluids are typically considered as the transport medium for such microdevices for obvious reasons. In particular, the human blood circulatory system with its overall length of approximately 96,000 kilometers is of great interest as a medium to reach the various remote locations within the human body. Because the human blood circulatory system is made of arteries, veins and capillaries where the respective diameters of the pathways to pass a microdevice may range from a maximum of approximately 25 mm (Aorta), 1.0 to 4.0 mm in large arteries, and down to 0.006 to 0.010 mm for the capillaries, it becomes obvious that being able to reduce the size of such microdevices would allow a larger percentage of locations in the human body to be of reach.

In order to propel such microdevices into the human blood circulatory system and prior to envision any applications, some fundamental requirements need to be resolved within such space constraints. These fundamental requirements are the means of propulsion, the positioning system, and the control of such microdevices to reach the target locations.

II. Methods of Propulsion

The simplest propulsion method for such a microdevice is passive navigation using the normal blood flow itself. Although simple, it is very restrictive as the flow rate reduces significantly in a vessel with a smaller diameter. This approach also lacks the control level needed to navigate and to position such a microdevice at a specific location. Although this approach is valuable in many cases, it should be considered as a supplementary means of locomotion.

Several means of propulsion to be embedded onto such a microdevice have been proposed [1]. They include propellers, electromagnetic pump, jet pump, membrane propulsion, and active mechanisms to crawl along the surface of the blood vessels. Practically, embedded means of propulsion add complexity in the design, the implementation, and the level of miniaturization that can be achieved for such a microdevice. Furthermore, if the required energy to produce sufficient torque is not induced from an external source but must be embedded, its implementation becomes extremely challenging yet adding restrictions on the level of functionality that can be integrated. A tethered implementation to deliver the power and possibly for communication could be envisioned. Unfortunately, it is not clear if such tethered microdevices would have significant advantages compared to modern tools such as the catheters for instance since they would share the same constraints in term of encumbrance of the pathways, risks for tissue damages caused by friction of the wires especially in tight corners, and limits in accessing some remote locations due to an increase of the friction forces through complex pathways geometries, just to name a few.

III. Magnetic Resonance Propulsion

Magnetic resonance propulsion (MRP) consists of applying magnetic gradients to exert a displacement force on a ferromagnetic core. The major advantage of this approach is that no complex mechanisms of propulsion need to be integrated onto the microdevice, making its implementation and miniaturization much easier while offering more volume to implement added functionality onto the microdevices.

Although a special platform could be built to generate such gradients, adapting existing MRI systems as MRP systems[*] to expand the range of applications, would offer significant advantages. First, MRI systems already provide magnetic gradients in all three axes while providing the image modality, interfaces, and controls. Second, the implementation costs related to such MRP systems can be substantial and the use of existing MRI facilities may provide a lower cost alternative. This is particularly true if no or minimum additional hardware would be necessary to transform MRI systems to MRP systems while maintaining MRI functionalities. This is one of the fundamental goals of the MR-Sub (Magnetic Resonance Submarine) research project [2-3]. Although using existing MRI systems has many advantages, the techniques must be developed within the constraints imposed by MRI systems used for clinical applications on humans, adding a level of complexity that may not exist for a custom made system.

A. Fundamental Principle

The torque and the force on a ferromagnetic object that can be induced by an MRI system can be estimated [4] as

$$\vec{\tau}=\vec{m}\times\vec{B}=V_{ferro}\vec{M}\times\vec{B}, \quad (1)$$

$$\vec{F}_{magnetic} = \vec{m}\cdot\nabla\vec{B}=V_{ferro}\cdot\vec{M}\cdot\nabla\vec{B}. \quad (2)$$

In Eqs. 1 and 2, τ is the magnetic torque (N·m), $\vec{F}_{\text{magnetic}}$ is the magnetic force (N), $\vec{m}$ is the magnetic moment of the ferromagnetic body (A·m^2), $\vec{M}$ is the magnetization of the material (A/m), V_{ferro} is the volume of the ferromagnetic body (m^3), $\vec{B}$ is the magnetic induction (T), and $\nabla\vec{B}$ is the gradient (spatial variation) of the magnetic induction (T/m).

It can be seen from Eq. 2 that as the volume or the overall dimension of a ferromagnetic core in a microdevice or the volume of the ferromagnetic microdevice itself decreases, the force induced by the MRI system will decrease as well. Fortunately, as the size of the ferromagnetic body decreases for applications in smaller blood vessels, the rate of blood flow is much lower compared to within larger diameter blood vessels.

This suggests that for a given magnitude of magnetic gradients generated by the MRI system, the size of the ferromagnetic body must be selected according to the diameters of the blood vessels (typically the diameter of the microdevice is selected to be not much greater than 1/3 the inner diameter of the blood vessel) to be used for the pre-planned path to the final target location. In other words, the ferromagnetic body must be larger in arteries for instance than in smaller blood vessels such as capillaries.

To provide a feel for this approach, let us consider a ferromagnetic core in the form of a sphere with a volume of 1 mm^3 made of permendur with a saturated magnetization level of $M_0 = 1.95 \times 10^6$ A/m and a corresponding intensity of saturated magnetization $I_0 = 2.45$ T placed into the bore of an MRI system generating magnetic gradients of 10 mT/m as typically used in MRI imaging sequences. From Eq. 2, the induced magnetic force is estimated at 1.95×10^{-5} N. Since the density of permendur is 8.15 g/cm^3, the mass of this ferromagnetic core is estimated at 8.15 mg (a weight of 7.995×10^{-5} N). Hence, the ratio magnetic force versus weight is 0.244.

Since both the gravitational force and the induced magnetic force are proportional to the overall volume of the ferromagnetic core, the magnetic force can therefore be expressed in term of acceleration only and independently of the volume. In this particular example, with a 10 mT/m magnetic gradient, the acceleration of this ferromagnetic core is estimated at 0.244 *g*. Therefore, to achieve levitation ($g \geq 1.0$) such that the microdevice can avoid additional friction forces due to contacts with the walls of the blood vessels, a magnetic gradient of approximately 41 mT/m is necessary. This value is possible on many MRI systems used in clinics but not on all models. Some models can also provide magnetic gradients in the order of 80 mT/m (equivalent to 1.95 *g* on a permendur core).

Although a 1-*g* acceleration may be sufficient for horizontal displacements of the microdevice within the human body considering the effects of drag forces on a properly designed device, vertical displacements against gravitation and drag forces are still feasible with present MRI systems. Furthermore, the addition of less dense materials to increase flotation could be considered and potentially be integrated onto such microdevices to decrease the magnetic force required for propulsion against

[*] Patent pending

gravitation. Tilting the patient at a specific angle depending on the displacement paths of the microdevices may also be an alternative and/or complementary solution. A technical issue especially to achieve levitation is the Joule effect that causes excessive heat on the gradient coils of many MRI systems, preventing continuous operation. To allow sufficient time for heat dissipation, the coils must be operated in a pulsating mode by varying the duty cycle. During the MRP process, the power dissipation of the coils must not exceed the maximum power dissipation that can be handled by the cooling system. The duty cycle can be increased closer to continuous operation provided that the amplitude of the magnetic gradients is adjusted accordingly. From the previous example, with a duty cycle of 83.3% (i.e. 10 ms of magnetic gradients within a 12 ms cycle for instance), a pulsed magnetic gradient of 49.2 mT/m would be necessary for levitation (equivalent to 41 mT/m with 100% duty cycle or continuous operation mode). Unfortunately, a pulsating gradient mode typically increases the complexity of the feedback control for proper motion of the microdevice since the force is not constant. Furthermore, rapid changes in the gradient coils can induce stimulations on the nervous system of the patient and must be considered carefully during the MRP process.

IV. TRACKING AND POSITIONING

A critical aspect of the MRP system and in particular to be able to control the displacement of the ferromagnetic microdevice is to determine its positioning accurately. Ideally, tracking and positioning of the microdevice should be performed by the MRI system and not by additional magnetic sensors, search coils, SQUID, Hall sensors or nuclear magnetic resonance (NMR) magnetometers. Unfortunately, ferromagnetic materials cause image distortions in an MRI system as depicted in Fig. 1.

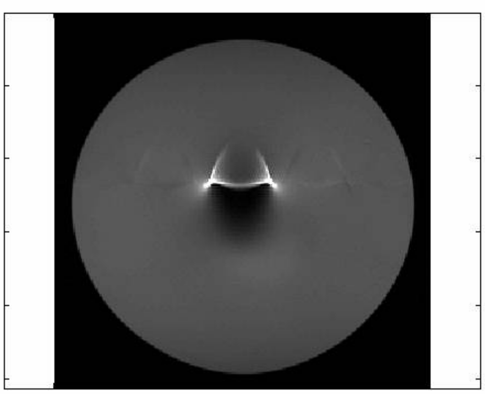

Fig. 1. MRI image artifact of a 1010/1020 carbon steel sphere.

Hence, to use the MRI system to position such microdevices, image processing techniques must be developed and integrated as part of the MRI system. Although much work needs to be done on positioning using the MRI system, a positioning method [5] using signal processing techniques is being developed. The method considers the phase image and spatial gradient representation of the induced field providing information on the position of a dipole. Although these representations are dependent on the magnetic field, they are typically well defined as shown in Fig 2 for common geometries such as a sphere which is the geometry considered so far for the first microdevices.

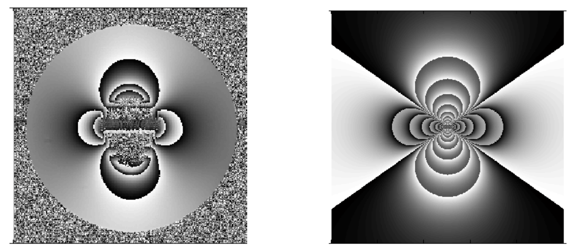

Fig. 2. Magnetic dipole MRI phase image (left) and simulated field mapping (right) of a 1010/1020 carbon steel sphere (from [5]).

Depending on the required resolution for positioning, MRI systems can be relatively slow for real-time control purpose, especially when targeting smaller diameter vessels. As such, external sensors such as SQUID to complement the proposed positioning method may be required for the more demanding applications.

V. CONTROL

One of the major constraints for the real-time control for the displacement of a microdevice beside the spatial resolution of the positioning method being used is the latency or delays within the closed-loop system. The major delays are caused mainly by the positioning process and the overheads during the transfer of data between the different modules including the software modules within the computational platform of the MRI system. Presently, efforts are done to determine the best approaches to decrease such overheads and to determine appropriate methods to compensate for such overheads. Nonetheless, preliminary results suggest that efficient control of a microdevice in the blood streams, although challenging, may be feasible.

Although larger blood vessels can tolerate a larger error margin for the control in displacement of the microdevice, changes in the diameter of the vessels coped with pulsating flow rates must be accounted for, unlike in the cases of much smaller blood vessels. Furthermore, because of image artifacts, initially the sites of interests including the target site and the pre-planned path for displacement must be imaged with the MRI system prior to introduce the microdevice. During the MRP process, the position of the microdevice indicated by a symbol on a computer display is superimposed on the image of the site previously acquired. As such, because of possible motion artifacts, real-time registration techniques need to be developed for this particular application until real-time reconstruction of the distorted images becomes possible.

VI. Interventional Procedure

The medical procedure envisioned with this approach is different from actual interventional procedures. With this approach, an interventional radiologist images the region of interest with the MRI system and then injects with a catheter a microdevice (specially designed for a chosen operation and a target location) into the blood vessels (see Fig. 3).

Fig. 3. Vision of the MRP facility.

Fig. 4. Vision of the user interface for the MRP system.

Using a simple computer mouse or a similar pointing device, the interventional radiologist indicates the target location to be reached (see Fig. 4). From the actual location to the target location, the microdevice is controlled automatically by the MRI system by tracking and generating the required magnetic forces to propel and control the microdevice until the target location is reached. Once at the target location, the interventional radiologist begins the medical procedure by interacting with the microdevice through a special computer interface (Fig. 4).

VII. Conclusion

We demonstrated that an MRI system such as the ones used in hospitals and clinics can generate sufficient magnetic force to propel a microdevice in the cardiovascular system. The propulsion force acting on the microdevice is proportional the overall size of its ferromagnetic core with larger force induced on larger ferromagnetic cores. Our preliminary studies have shown that it is feasible within the MRI system specifications and the characteristics of the human cardiovascular system to design microdevices of various sizes with propulsion forces adjusted to blood flows and angles of displacement relative to the gravitational force. Positioning the microdevice through the MRI image artifacts caused by the ferromagnetic material and the delays in the closed-loop control system pose additional technical issues that need to be addressed. The proposed method if successful could provide minimally invasive accesses to remote locations in the human body that are at high risks or impossible to reach with actual methods.

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