Real-time Navigation of a Catheter with Ferromagnetic Tip in Interventional MRI

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Introduction

Cardiovascular interventions can be difficult to perform, because the devices (catheters or guidewires) are often very flexible, so that manoeuvring over complicated vessel branches is challenging. In the MRI environment recently use has been made of the available magnetic forces, in particular the gradient-induced forces that act on ferromagnetic objects [1]. Unfortunately, ferromagnetic components introduce artifacts such as image distortion and signal voids in the real-time MR images acquired during navigation.

In this study we present a catheter with a deflectable, ferromagnetic tip and a real-time sequence for tip navigation, localization and imaging. The directions of the magnetic forces for navigation of the catheter's tip are controlled via an iterative input device. The pulse sequence combines the acquisition of imaging and interleaved projection data for automatic alignment of imaging slice according to the tip position. Projection data for tip tracking are acquired by a novel strategy that uses an off-resonance excitation [2] and an additional rephasing gradient [3] to enhance the SNR of the projections.

Materials and Methods

Gradient-induced Forces

The force F exerted on a ferromagnet with magnetic moment m is given by $F = m{\cdot}G$, where G is the strength of the magnetic gradient. In our clinical 1.5 T MR system (Siemens Symphony) the imaging gradients have a strength of up to 30 mT/m in each direction. To maximize the force, ferromagnetic components with a high magnetic moment should be used. Here we used a steel sphere (Fig. 1a) with 2 mm diameter that had a saturated magnetic moment of 18 emu. In a 10 mT/m gradient field applied for 1.6 s this sphere can reach velocities of up to 6.6 cm/s. For the interventional experiments, the sphere was glued to the tip of a 8 F catheter (Fig. 1c) with the help of a small 2 mm-thick silicon tube (Fig. 1d).

Off-resonance Localization

Since the ferromagnetic tip causes strong local inhomogeneities of the magnetic field, one can use non-selective off-resonant RF pulses for device localization. The pulses selectively excite only spins in a volume close to the sphere, and the off-resonant signal is read out with in a rapid projection measurement. In addition, a rephrasing gradient is introduced which dephases signal from on-resonant spins in the projection direction, whereas the off-resonant signal in the vicinity of the sphere is selectively rephased [3]. For device localization, three one-dimensional projection data sets with orthogonal readout gradients are acquired, a one-dimensional Fast Fourier transform is performed, and the tip position is detected using a threshold algorithm.

Pulse Sequence

To realize endovascular navigation, imaging, application of the force gradient pulse, and tracking blocks were interleaved within one real-time pulse sequence as presented in Fig. 2. The force gradient was inserted into each TR interval of a FLASH pulse sequence for real-time imaging. The following parameters were used: TE = 1.8 ms, FOV = 205×300 mm², matrix = 88×128, $\alpha = 15°$, partial Fourier = 6/8, slice thickness = 10 mm, force gradient = 28 mT/m, TR = 3.5 ms + force duration = 14 ms. To change the direction of the force, the orientation of the force gradient was controlled in real-time via a graphical input device (Magellan Space Mouse, Fig. 1b). After acquisition of one complete image (88 k-space lines), three projection data sets were collected. A rectangular RF pulse with an offset frequency of 2000 Hz, a flip angle of 30^{o} and duration of 1 ms was followed by a 14 mT/m and 1 ms-long rephasing gradient. Real-time information from the projections was sent back to the sequence to initiate an automatic re-positioning of the imaging slice. The technique was tested in phantom experiments and in an anaesthetized animal (pig).

Results and Discussion

After combination of the signals from three spine array coils and a flexible surface coil, an SNR of about 6 was measured in the projection as shown in Fig. 3, and the sphere could safely be detected. Two time frames of the animal experiment are shown in Fig.4. Starting from the aorta the catheter was pushed forward manually, and a gradient force was applied to the left or to the right. With this lateral force the catheter could be advanced into the left and right renal artery indicating that catheter motion can indeed be controlled by gradient forces in real time with frame rates of 1 image/s at reasonable artifact sizes.

References

[1] Chanu A et al, MRM 2008; 59(6): 1287-97, [2] Zurkiya O et al, MRM 2006; 56(4):726-732, [3] Seppenwoolde JH et al, MRM 2003; 50(4):784-790.

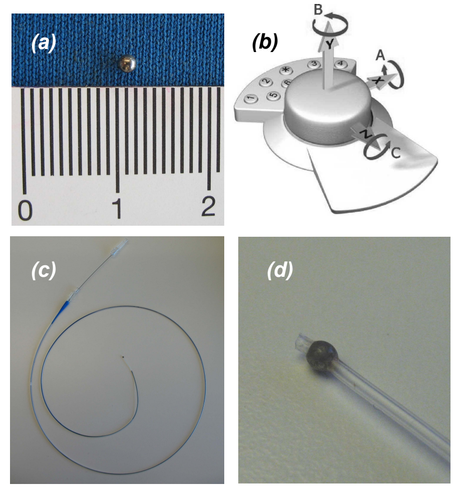

Fig 1. Ferromagnetic sphere (a) combined catheter (c) with a 3cm long 2mm thick silicon tube (d) and interactive control tool "space mouse" (b).

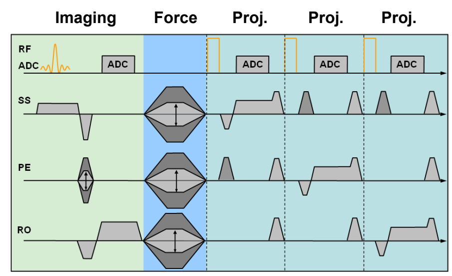

Fig 2. Schematic of the 2D FLASH navigation pulse sequence with force gradient and projections in all three spatial directions.

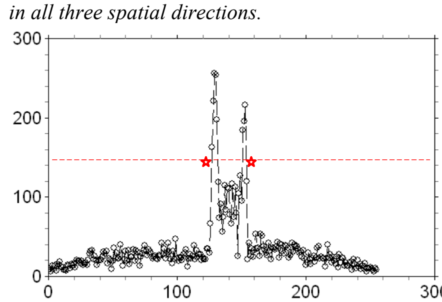

Fig 3. The center positions of the region (which was three times higher than the mean signal value) of the projection signal were calculated and supposed as positions of the tip.

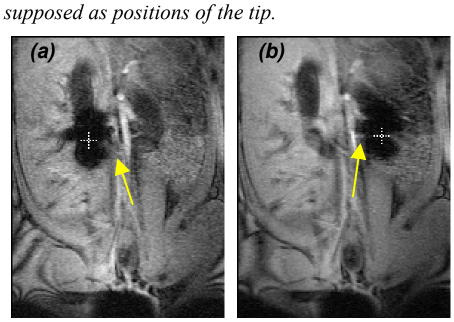

Fig 4. Real-time navigation of the ferromagnetic tip into the right (a) and left (b) renal artery.