Combined Real-Time Prospective Motion Correction and Concurrent Field Monitoring

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Introduction

Rigid body motion is a major problem in MRI. It gives rise to artifacts due to data inconsistencies and local violation of the Nyquist distance in k-space. In order to achieve data consistency, it is necessary to track the bulk motion of the object in real-time during the entire readout. This has been achieved with optical markers attached to the object (**Refs. 1,2)**. Krueger et al **(Ref. 3)** proposed to mount NMR probes to the object to track rigid body motion in a phantom. Ooi et al. **(Ref. 4)** further developed that idea for vivo imaging. Their approach, however, exhibits two main drawbacks: **1)** It requires extra scan time (~25ms) for the position determination, limiting the method's temporal resolution. **2)** It is insensitive to motion during a single readout due to their probes' inability to continuously acquire data during the readout.

The present work solves these two problems by **a)** employing advanced ^{19}F NMR field probes **(Ref. 5)** capable of acquiring the field evolution of a whole MR readout and **b)** utilizing each probe's phase evolution during just the image encoding sequence for position determination. Rigidly mounting ^{19}F NMR probes to the object comes with three side benefits: **1)** It allows to concurrently monitor the phase evolution in the object, rendering the image acquisition sensitive to any kind of gradient encoding imperfections during the imaging scan. **2)** The heteronuclear approach perfectly separates the imaging from the monitoring experiment. **3)** Furthermore, the measurement is inherently done in the object frame of reference, which heavily simplifies co-registration in the post-processing.

Methods

The position can be extracted from the probe signal as follows: The phase is given by $\varphi(t) = k_0(t) + \sum_{i=1}^{3} k_i(t) r + w_0 t$, whereas $k_0(t)$ is the B_0 eddy current, $k_i(t)$ denotes the k-space trajectory, r is the probe's position and w_0 its individual off-resonance frequency. Solving for the position can readily be done with a least-square fit.

Two in-vivo experiments were done in a healthy volunteer who was given the following tasks: **a)** to remain still, and **b)** to perform a smooth rotation around the negative z axis. Four ^{19}F NMR probes were mounted on standard clinical headphones and put on the volunteer **(Fig. 4)**. They were altered slightly to allow more motion freedom. A 10-shot interleaved Cartesian EPI sequence (FOV=(0.25m)^2, resolution=(1.3mm)^2, slice thickness=3mm, T_{Acq}=21.5ms/shot, T_R=300ms, T_E~12ms) was used to both encode the image and measure the probes positions. 100 repetitions were done to study motion behavior over a total scan time of 300s. The re-phasing gradients were included in order to resolve the slice select direction**.** The duration of the re-phasing gradient was 1.12ms, and a 10ms delay was incorporated after the readout for the slice update calculations. For each scan, motion of the center of mass as well as Euler angles of rotations along each spatial axis were considered. Errors were estimated in regions with a flat motion. Also, reconstructions based on the concurrently monitored trajectory and the reference trajectory were compared with respect to artifacts. The images were picked from a dynamic period between 71s and 80s.

Results

a) The motion pattern shows a rotation drift in all directions over the whole scan time in the order of 0.5° and a translational drift in the order of 500µm (not shown). The estimated errors for the translational motion directions are about 30µm (readout), 60µm (phase encode), and 100µm (slice).The errors on the rotations are about 0.08°, respectively. The drifts were below the image resolution and didn't cause artifacts in reconstructions on the reference trajectory. **b)** The rotation shows a back and forth rolling motion to the volunteer's right hand side **(Figs. 2, 3)**. During the 23° rotation around z, the head shifted about 2cm along y. The reconstruction with the concurrently monitored object phase shows no artifacts whereas the reconstruction based on the reference trajectory suffers from motion-induced data inconsistencies **(Fig. 1)**.

Conclusion

We propose to rigidly mount small, long-lifetime NMR probes to the object in order to concurrently monitor field evolutions in the object frame of reference and perform real-time motion correction without extra scan sequences. In particular, a mere 1.12ms rephasing gradient along the slice select axis is enough to accurately resolve that direction. We show that concurrently monitored acquisitions subject to motion can be reconstructed when calibration-based reconstructions fail and that performing the experiment in the object frame of reference can heavily alleviate image co-registration.

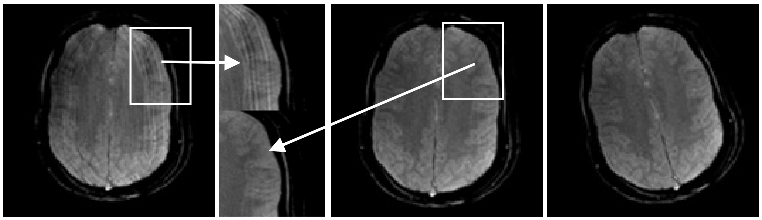

Fig.1 Left: Reconstruction based on a calibrated trajectory with striking motion artifacts. **Center:** Monitoring-based reconstruction in object coordinates **Right:** Monitoring-based reconstruction in laboratory coordinates.

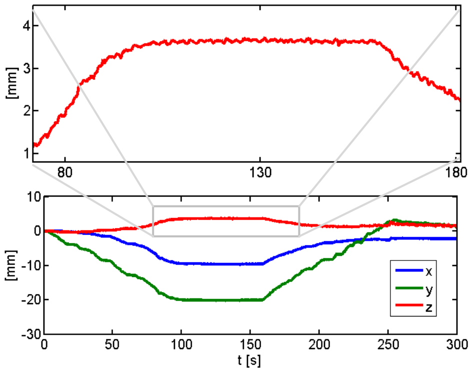

Fig. 2 (bottom) Translations of the head. The y-component indicates a rolling motion around the z-axis. **(top)** Close-up view of the z-coordinate shows the high accuracy achieved with the rephasing gradient.

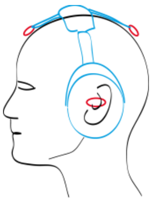

Fig. 4 Schematic of the probe setup with 4 probes (red) and the headphones (blue).

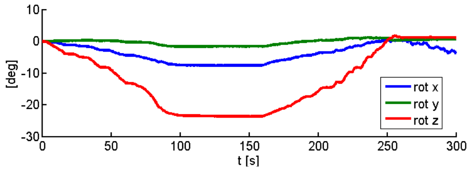

Fig. 3 Measured Euler angles of an intended rotation around the z-axis.

References

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