From Artifact to Merit: Cardiac Gated MRI at 7T and 3T Using Magneto-Hydrodynamic Effects for Synchronization

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Introduction:

In current clinical cardiovascular MR (CMR) practice heart motion is commonly dealt with using ECG based synchronization. ECG is corrupted by magneto-hydrodynamic (MHD) effects [1, 2, 3]. As (ultra)high field CMR becomes more widespread, the propensity of ECG recordings to MHD effects is further pronounced [4, 5]. Artifacts in the ECG trace and a severe T-wave elevation might be mis-interpreted as R-waves resulting in erroneous triggering [6, 7] that render MHD effects detrimental for a robust and reliable ECG gating. MHD being inherently sensitive to blood flow and blood velocity provides an alternative approach for cardiac gating, even in peripheral target areas far away from the commonly used upper torso positions of ECG electrodes. This feature would be very beneficial to address traveling time induced motion artifacts and trigger latency related issues raised by ECG-gated peripheral MR angiographies. For all those reasons, this work proposes the use of MHD for cardiac gated MR. To this end the MHD effect is carefully scrutinized using a pulsatile flow phantom at 7.0 T. The clinical applicability of MHD triggering is examined in an arterial MR angiography (MRA) of the carotids using a subtraction technique, which requires images to be acquired right at the local diastole and systole.

Methods:

The phantom setup comprises an adjustable piston pump positioned outside of the scanner room and connected to a tube system (d = 9 mm, l = 8 m) to provide pulsatile flow. A straight acrylic pipe was incorporated into the tube and positioned in the magnet. Three holes (d=1 mm) were drilled into the acrylic pipe to accommodate ECG electrodes which were used to measure MHD effect induced voltage changes across the electrodes. To assess flow velocities, phase contrast measurements were conducted (gradient echo, voxel size: (1,6 x 1,6 x 6 mm)³, temporal resolution: 48 ms). First, MHD voltage was measured at different orientations (0°, 30°, 60°, 90°) of the pipe with respect to the magnetic field lines in the isocenter of a 7 T MR scanner (Siemens Healthcare, Erlangen, Germany). In another set of experiments MHD voltage was recorded as the function of flow, which was calibrated using a commercial flow meter (B.I.O-TECH e.K., Vilshofen, Germany). MHD signal traces were stored and processed using MATLAB (The Mathworks, Natick, USA). For in-vivo measurements of the MHD signal trace, ECG leads of a Medrad Veris 8600 patient monitor (MEDRAD, Warrendale, USA) were connected to three surface electrodes placed onto skin areas close to the right common carotid artery. To examine the MHD voltage as a function of B_0, MHD recordings were performed at the patient table home position, at the front end of the magnet bore and in the isocenter of a 3T MR scanner (Siemens Verio, Siemens Healthcare, Erlangen, Germany). For MRA a prospectively triggered 3D fast RF-spoiled gradient echo sequence (voxel size: (1 x 1 x 1) mm³; TE=2.6 ms; TR=5.7 ms; GRAPPA=2, total acquisition time≈15 min, five slab segmentation) was applied to obtain MHD-triggered images of the carotids at diastole and at systole using a dedicated head/neck RF coil. For this purpose, the trigger signal provided by the MEDRAD monitor was processed and then transferred into the MR-scanner's standard external trigger signal input. For comparison, MRA acquisitions were repeated using pulse oximetry (POX) triggering. Arterial MR angiography was accomplished by subtracting diastolic from systolic images [8].

Results:

Our results show that MHD effects provide amplitudes of several mV in magnetic fields as illustrated for a field strength of 7 T in Figure 1. The phantom experiments at 7 T demonstrated that MHD voltage depends on the angle between the flow and the magnetic field (Fig. 1). Also, the phantom experiments showed that the MHD effect scales with flow velocity (Fig. 1). Figure 2 illustrates the MHD signal derived from surface electrodes positioned close to the carotids of a human subject for different B_0. At higher field strengths the MHD signal is more pronounced. Here, a distinct MHD signal at the peak blood velocity facilitates the generation of TTL-pulses to be used for triggering / gating. MHD signal diminishes with decreasing magnetic field (Fig. 2). Figure 4 shows an arterial MRA derived from MHD triggered acquisitions. The MHD triggering approach enabled identification of local peak blood flow. Consequently, MHD triggering facilitated an accurate determination of the desired local flow phases at systole and diastole indicated by the arterial MRA in Fig. 4 which was derived from subtraction of images acquired at diastole and systole. In comparison, POX triggered acquisitions (Figure 3) did not correlate with the occurrence of local systolic and diastolic blood flow in the carotids due to the latency between cardiac activity and local flow. Strong MHD signal was also observed in the forearm and the feet. For both anatomic regions synchronization information, which was found to be suitable to trigger/gate peripheral MRA of the hand, the legs or the feet, was successfully generated.

Discussion and Conclusions:

Contrary to the common notion that considers magneto-hydrodynamic effects to be adverse concomitants of traditional ECG acquired in a magnetic field environment this work proposes the use of MHD effects for synchronization of MR acquisitions with the cardiac cycle. Applications demonstrated here include peripheral MRA of target areas/vessels far away from the heart. In the context of latency between cardiac activity and local cardiac phase MHD gating offers the potential to address patient dependent trigger delay constraints of conventional ECG gating. The proposed approach does not require any changes to the MR system's hardware or software since it connects the trigger signal to the MR-scanner's standard external trigger signal input. In conclusion, exploiting the MHD effect provides an alternative approach for cardiac gating/triggering. Because of the linear relationship between the MHD signal and flow velocity, it is useful to exploit the MHD signal for an automatic and real time adjustment of velocity encoding (VENC) in phase contrast MRI applications.

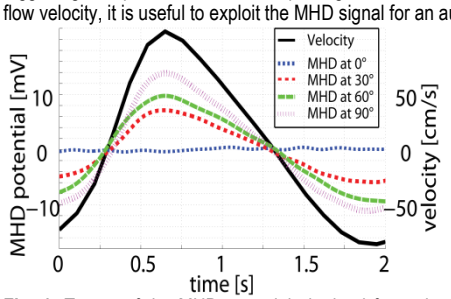


Fig. 1: Traces of the MHD potential obtained for various orientations of a pipe with respect to the magnetic field lines (blue, red, green, purple) and velocity (black). For this purpose a pipe was placed in a 7 T MR scanner and pulsatile flow was generated. Velocity was measured using phase contrast MR sequences.

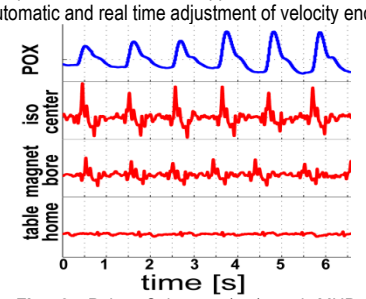
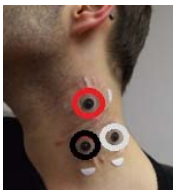


Fig. 2: Pulse Oximetry (top) and MHD traces obtained from carotids a) at the isocenter of a 3 T magnet, b) at the front end of the magnet bore and c) at the patient table home position). The MHD signal diminishes with decreasing magnetic field. Electrodes were placed close to the carotids as shown in the photograph below.



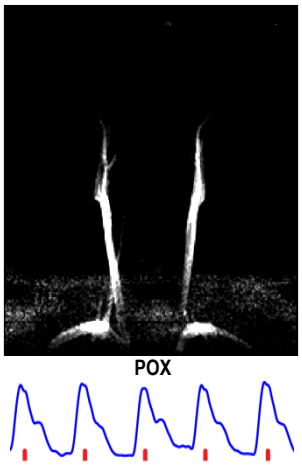


Fig. 3: Arterial MRA derived from pulse oximetry triggered acquisitions at 3 T together with POX signal trace (blue) and trigger detection moments (red).

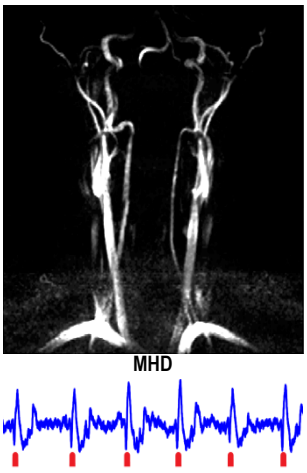


Fig. 4: Arterial MRA derived from MHD triggered acquisitions at 3 T together with MHD signal trace (blue) and trigger detection moments (red).

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