Cardiac imaging at 7.0T: Comparison of pulse oximetry, electrocardiogram and phonocardiogram triggered 2D CINE for left ventricular function assessment

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Introduction:

One important development which is looming on the (pre)clinical research horizon is the move towards cardiovascular MRI (CVMR) at 7.0 T[1]. At (ultra)high magnetic field, the sensitivity of ECG recordings to interference from electromagnetic fields (EMF) and to magneto-hydrodynamic (MHD) effects increases and with it the ECG triggering failure rate rises up. There is a motivation for a robust, practical gating/triggering alternative. Realizing the constraints of conventional ECG, a MR-stethoscope, which uses the first heart tone of the phonocardiogram for triggering purpose has been proposed to meet the demands of cardiac triggered CVMR[2]. Motivated by the challenges and limitations of conventional ECG together with the advantages of acoustic cardiac triggering (ACT) which is immune from interference with EMF and MHD, this study compares phonocardiogram triggered (ACT), vector electrocardiogram triggered (VCG) and traditional pulse oximetry (pO2) triggered MRI for LV-function assessment at 7.0 T. For this purpose, breath-held 2D-CINE imaging in conjunction with a retrospective triggering regime was conducted paralleled by real time logging of the physiological waveforms to track (mis)synchronization between the cardiac cycle and data acquisition.

Methods:

The acoustic cardiac triggering device is designed to meet the requirements of reliable image acquisition synchronization in CVMR: (i) use of the phonocardiogram's first heart tone for triggering, (ii) maximum latency of 35 ms between the ECG's R-wave and phonocardiogram based trigger output pulse, (iii) free of interference with electromagnetic fields and (iv) immunity to MHD. The acoustic gating device comprises three main components: (i) an acoustic sensor, (ii) a signal processing unit and (iii) a coupler unit to the MRI system [2]. The ACT setup does not require any hardware or software changes on the scanner side. For the assessment of the acoustic signal performance at the 7.0 T whole body MR system (Siemens, Erlangen, Germany), two series of acoustic measurements were conducted inside the scanner room. The first series consisted of the noise generated by the MR environment using a 2D CINE FLASH sequence (TE=2 ms, TR=4 ms). For the second series both the scanner noise and the phonocardiogram derived from a healthy volunteer were collected and an acoustic signal to noise ratio was calculated. Cardiac images were acquired from 9 healthy volunteers using a retrospectively triggered 2D CINE FLASH sequence (TE=2 ms, TR=4 ms, matrix=256x192, FOV=(36 x36) cm^2, 25 cardiac phases, slice thickness 4 mm) together with a dedicated 4-element TX/RX cardiac coil array [3]. Vector ECG, pO_2 and ACT were connected to the subjects at the same time in order to record traces of physiological waveforms along with the trigger information simultaneously. The recorded data were processed to analyze the trigger information and to assess triggering efficiency and temporal fidelity of synchronization with the cardiac cycle for each trigger technique. Endocardial border sharpness (EBS) was assessed to examine cardiac motion artifacts induce by mis-synchronization. For this purpose, the transitional border zone between myocardium and ventricular blood was defined as: $SI_{myo}+1/3*(SI_{blood}-SI_{myo})$. Quantitative assessment of the LV function including end-systolic volume (ESV), end-diastolic volume (EDV) and ejection fraction (EF) was carried out using a commercial software package (CMR42, Calgary, Canada).

Results:

ECG waveforms were susceptible to severe T-wave elevation, which was pronounced at the isocenter of the magnet. R-wave mis-registration occurred in ECG-triggered acquisitions with a failure rate of appr. 50%, which manifests itself in a severe jitter of the R-wave recognition tickmarks (Fig.1 bottom). ECG triggered images were prone to severe cardiac motion artifacts, when R-wave misregistration occurred (Fig.1 right). The failure to detect the onset of the cardiac cycle was reduced for pulse oximetry, nevertheless a temporal inaccuracy of the triggering was observed (Fig.1 mid). The MR-stethoscope provided phonocardiograms free of interferences with electromagnetic fields or from magneto-hydraulic effects even in the isocenter of the 7 T system. ACT produced images free of motion artifacts (Fig.1+2 left). This renders ACT suitable for reliable synchronization at ultrahigh fields as demonstrated in signal traces. When ECG-gating was erroneous, EBS derived from ECG-gated 2D CINE FLASH was increased to 1.55 pixel. For comparison, ACT-gated 2D CINE FLASH yielded an EBS of 1.13 pixel while pO2 showed a EBS of 1.05 pixel. In the case of faultless ECG-gating, the mean EBS derived from ECG-gated 2D CINE FLASH was found to be 1.02 pixel. For comparison, ACT-gated 2D CINE FLASH yielded a mean EBS of 0.86 pixel while pO2 yielded an EBS of 1.05 pixel. For ACT triggered 2D CINE FLASH global cardiac function parameter were found to agree with those obtained for faultless ECG (fig.2 right) and pO_2 triggered 2D CINE FLASH: (EDV: 166,3 ml vs. 169,3 ml, ESV: 66,6 ml vs. 71,1 ml, EF: 59,9 % vs. 58,9 %)

Conclusions:

This work demonstrated the feasibility and efficacy of LV-function assessment at 7.0 T using acoustically triggered 2D-CINE FLASH imaging. ACT's superior robustness has been demonstrated by eliminating the frequently-encountered clinical challenge of mis-triggering due to ECG-waveform distortions or temporal jittering in the pulse-oximetry synchronization. ACT presents no risk of high voltage induction and patient burns, patient comfort and ease of clinical use, which all have practical, patient comfort and safety implications. ACT's intrinsic insensitivity to interference with EMF and MHD renders it suitable for clinical imaging at ultrahigh fields due to its excellent trigger reliability. Due to the short latency ACT can also be used for prospective triggered acquisitions.

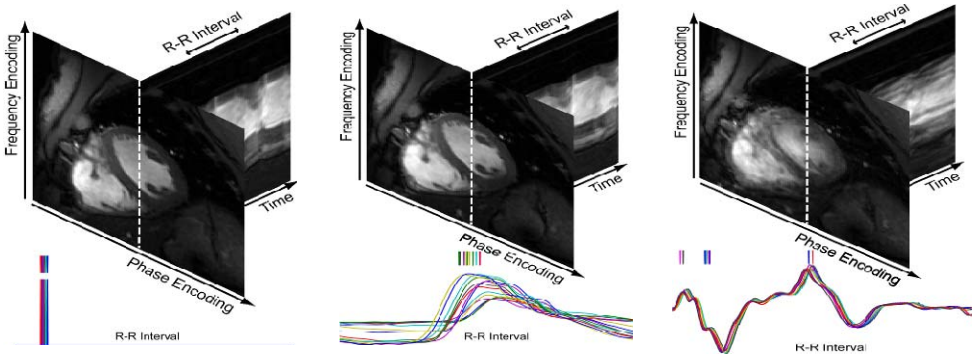

Fig.1 (top): Short axis views of the heart together with whole R-R interval time series of one-dimensional projections over time (dotted line) marked in the short axis view. Data were obtained at 7.0 T using ECG **(left)**, pulse oximetry **(center)** and acoustic trigger **(right)** 2D CINE FLASH acquisitions. In this example ECG triggered CINE imaging was prone to severe cardiac motion artifacts due to R-wave mis-registration which induced reduction in myocardium/blood contrast and image sharpness. ACT triggered 2D CINE FLASH imaging provided faultless trigger recognition and hence produced images free of motion artifacts.

Fig.1 (bottom): Traces of the cardiac activity obtained from a single subject over 15 cardiac cycles using ECG **(left)**, pulse-oximetry **(center)** and acoustic **(right)** measurements at 7.0 T. Severe T-wave elevation and signal distortion occurred in ECG due to magneto-hydrodynamic effects, which resulted in a severe jitter of the R-wave recognition tickmarks. The jitter in the pulse-oximetry trigger recognition also constituted a synchronization problem.

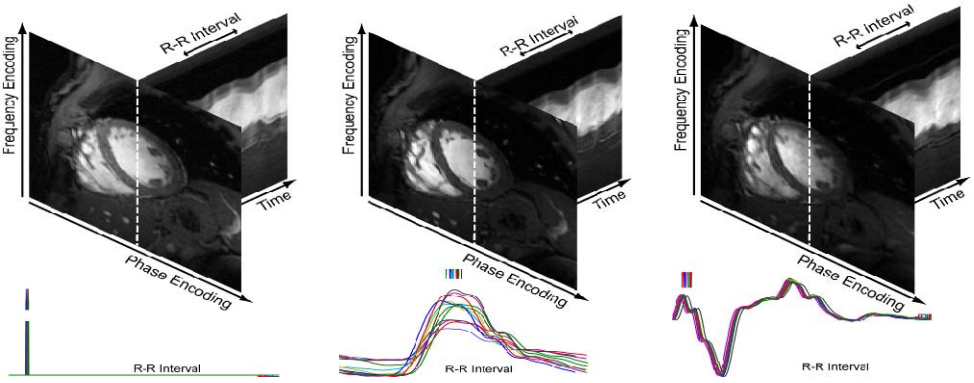

Fig.2 (top): Short axis views of the heart together with whole R-R interval time series of one-dimensional projections along the profile (dotted line) marked in the short axis view. Data were obtained at 7.0 T using ECG **(left)**, pulse oximetry **(center)** and acoustically triggered **(right)** 2D CINE FLASH acquisitions. In this example of correct recognition of the onset of cardiac activity, ECG, pO_2 and ACT triggered 2D CINE FLASH imaging were found to be immune to the effects of cardiac motion.

Fig.2 (bottom): Traces of the cardiac activity obtained from a single subject over 18 cardiac cycles using ECG **(left)**, pulse-oximetry **(middle)** and acoustic **(right)** measurements at 7.0 T. Inspite of ECG's T-wave elevation and signal distortion faultless ECG triggering was observed for this example.

References:

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