Feasibility of Acoustically Triggered CINE Imaging for Global Cardiac Function Assessment Using an MR-Stethoscope

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Introduction:
In clinical MRI cardiac motion is commonly dealt with using ECG based synchronization, but the sensitivity of ECG recordings to interference from electromagnetic fields and magneto-hydrodynamic effects increases at higher magnetic field strengths (1), motivating the search for a practical alternative to gating/triggering (2). This study explores and demonstrates the efficacy and robustness of acoustic cardiac triggering (ACT) for the assessment of global cardiac function using breath-held 2D CINE SSFP imaging in conjunction with retrospective triggering. Acoustic noise of 2D CINE SSFP was measured at 1.5 T and 3.0 T and quantitative analysis of cine images was conducted to compare the performance of ACT with that of conventional ECG. Endocardial border sharpness (EBS) was examined through an objective measurement of acutance followed by quantitative assessment of the LV function.

Methods:
The MR stethoscope is designed to meet the minimum requirements for reliable synchronization of CINE acquisitions with cardiac activity: (i) to use the first heart tone for triggering, (ii) with a latency of maximum 35 ms between the ECG's R-wave and phonocardiogram based trigger output pulse, (iii) to be free of interference with electromagnetic fields and (iv) with immunity to magneto-hydrodynamic effects. 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). For the assessment of the acoustic signal-to-noise ratio (aSNR) at 1.5 T and 3.0 T, acoustic measurements were conducted inside the scanner rooms. Two series of acoustic signals were acquired. The first series consisted of the noise generated by a 2D CINE SSFP sequence (TE=2 ms, TR=4 ms). For the second series both the noise generated by the same CINE sequence and the phonocardiogram derived from a healthy volunteer were collected. Imaging was performed in healthy volunteers (n=6) at 1.5 T and 3.0 T MR systems (Achieva, Philips, Best, The Netherlands) using a 5-element cardiac coil at 1.5 T and a 6 element cardiac coil at 3.0 T. The acoustic sensor was integrated into the coil and positioned at the anterior left side of the torso to obtain phonocardiograms. A retrospectively triggered 2D CINE SSFP technique (TE=1.6 ms, TR=3.2 ms, reconstructed matrix=384x384 pixels, FOV=350 mm^2, 25 cardiac phases) was used to track myocardial contraction/relaxation over entire R-R intervals. Images were acquired with both conventional ECG triggered and ACT in all subjects. For the assessment of EBS the transitional border zone between myocardium and ventricular blood was defined as: $SI_{myo}+1/3*(SI_{blood}-SI_{LV})$ to $SI_{myo}+2/3*(SI_{blood}-SI_{LV})$. LV function assessment including end-systolic volume (ESV), end-diastolic volume (EDV) and ejection fraction (EF) was carried out using a commercial software package. (Philips, Best, The Netherlands).

Results:
Figure 1 illustrates typical sound pressure levels (SPL) and corresponding power spectra obtained in scanner rooms hosting clinical 1.5 T or 3.0 T MR-systems. High levels of acoustic noise were induced by the switching of magnetic field gradients. Numerous noise peaks include several very sharp harmonic components, which are related to SSFP's gradient switching scheme with maximum SPL close to 110 dB were observed. Therefore, filtering was applied to eliminate noise by means of a third order Chebychev filter. For the frequency range between 10 - 50 Hz a minimum aSNR - defined as the ratio between SPL due to cardiac activity and the gradient switching induced SPL – of 20 dB was found at 1.5 T and 3.0 T, which makes the ACT immune to interference with acoustic noise generated by gradient switching. Unlike ECG, the MR-stethoscope provided signal traces at 1.5 T and 3.0 T free of interference from electromagnetic fields or magneto-hydrodynamic effects (Figure 2). Acoustically triggered images (Figure 3) were free of cardiac motion artifacts. In the case of correct R-wave recognition, ECG-gated CINE imaging was found to be immune to cardiac motion effects even at 3.0 T (Figure 3). In the case of faultless ECG-gating, the EBS was found to be 2.0 pixels at 1.5 T and 2.0 pixels at 3.0 T. For comparison, ACT-gated images yielded a mean EBS of 1.9 pixel at 1.5 T and 2.1 pixels at 3.0 T. However, ECG-gated imaging was prone to cardiac motion artifacts if R-wave mis-registration occurred (Figure 4). When ECG-gating was erroneous, the mean EBS derived from ECG-gated CINE was 2.4 pixels at 1.5 T and 2.5 pixels at 3.0 T, whereas ACT-gating yielded a mean EBS of 1.9 pixel at 1.5 T and 2.1 pixels at 3.0 T retrospectively. Global cardiac function parameter obtained with acoustic triggering were in agreement with those derived from ECG triggered acquisitions: (ECG vs. ACT: $\Delta EF = (1.1\pm2.14)$ %, $\Delta EDV = (2.9\pm7.2)$ ml, $\Delta ESV = (-0.5\pm3.0)$ ml).

Discussion and Conclusions:
This work demonstrates the feasibility and efficacy of global cardiac function assessment using acoustically triggered CINE imaging supported by an MR stethoscope that is immune to acoustic fields generated by gradient switching. The MR stethoscope presents no risk of high voltage induction and patient burns and it offers patient comfort and ease of clinical use, which all have practical, patient comfort and safety implications. The MR stethoscope's intrinsic insensitivity to interference with electro-magnetic fields renders it suitable for clinical imaging and results in excellent trigger reliability – even at high magnetic field strengths. Further investigation is anticipated to ensure reliable performance of the MR stethoscope in patients with heart or valvular diseases, although valvular defects need not necessarily be prohibitive for acoustic gating since the murmurs, which might be detected, are at high frequency and hence they could be suppressed by appropriate filtering.

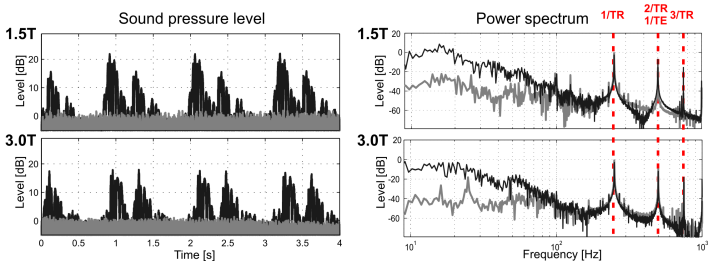

Figure 1: Sound pressure level and power spectrum obtained from the same subject positioned at the magnet's isocenter during 2D CINE SSFP imaging (TE=2.0 ms, TR=4.0 ms) at 1.5 T **(top)** and 3.0 T **(bottom)**. The graphs show signal contributions from gradient switching marked in gray superimposed on the cardiac signals marked in black. The gradient switching manifests itself by very sharp harmonic components at 1/TR, 2/TR, 3/TR and 1/TE.

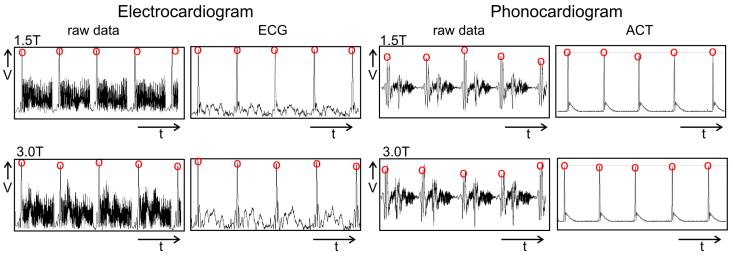

Figure 2: Electrocardiogram raw data (ECG), vectorcardiogram (VCG), raw data of the phonocardiogram and the output of the acoustic gating device (ACT) obtained at 1.5 T **(top)** and 3.0 T **(bottom)**. The MR-stethoscope provided raw data of the phonocardiogram and ACT-traces at 1.5 T and 3.0 T free of interference from electromagnetic fields or magneto-hydrodynamic effects. In comparison, ECG and VCG were susceptible to T-wave elevation and other distortions which were pronounced at 3.0 T.

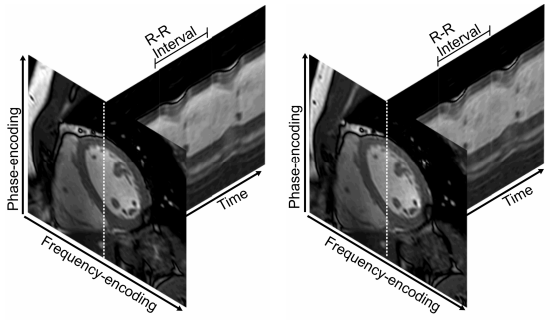

Figure 3: Short axis views of the heart obtained at 3.0 T using CINE with ACT **(right)** and ECG **(left)** triggering. In this example of correct recognition of the onset of cardiac activity both ECG- and ACT triggered CINE imaging were found to be immune to the effects of cardiac motion.

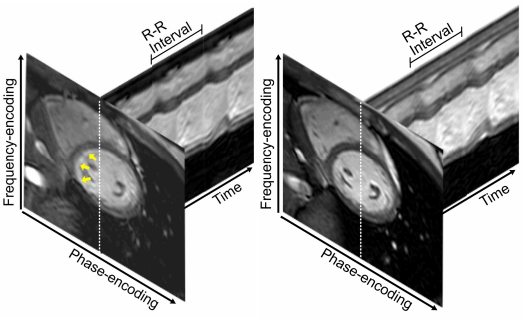

Figure 4: Short axis views of the heart obtained at 3.0 T using CINE with ECG **(left)** and ACT **(right)** triggering. In this example, ECG-gated SSFP was prone to cardiac motion artifacts (arrows) caused when R-wave mis-registration occurred due to T-wave elevation. For comparison, ACT triggered CINE imaging provided faultless trigger recognition.

References: 1) Stuber M. et. al., Magn. Reson. Med. 48: 425 (2002); 2) Frauenrath T. et. al., Acta Acustica united with Acustica 94: 148-155 (2008)