System for real-time cardiac MRI gating, 12-lead ECG monitoring, and non-invasive stroke volume estimation

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Introduction: Motion-synchronized images accurately reflect heart dynamics, and a dominant QRS complex in ECG signals, which signals the cardiac-cycle beginning, is therefore essential for cardiac MRI. Obtaining proper ECG gating inside the MRI is a difficult problem, due to the Magneto-Hydro-Dynamic (MHD) effect, resulting in frequent intermittent gating and blurred cardiac MRI images. MHD voltage (V_{MHD}) primarily originates from the aortic arch, where V_{MHD} is induced when conductive blood flows perpendicular to the magnet B_0 direction, and is superimposed on the real ECG (ECG_{real}) [1]. V_{MHD} is dominant during the systolic S-T segment, when ejection of blood from the left ventricle occurs, while S-T segment visualization is essential for ischemia monitoring [2]. We hypothesized that an unique adaptive filtering procedure, integrated into a 64-bit real-time processing workstation, could provide (1) an MHD-free 12-lead ECG_{real}, and (2) a beat-to-beat stroke volume (SV) estimation, for cardiac monitoring during imaging/interventions, and (3) real-time QRS complex detection and scan triggering could be achieved with a novel 3-D ECG multichannel analysis. This work presents improved gating, and a progression to real-time, relative to our prior work [1, 3].

Materials and Methods: The real-time system (Fig. 1) consisted of 10 carbon-tipped ECG leads inside the MRI room, whose signals were conducted on 2mm-diameter coaxial cables, which then passed through 20MHz RF low-pass filters at the penetration panel, reaching a digital ECG-recording system (Cardiolab-IT, GE) sampling at 2kHz and 16-bit resolution, which was modified to stream out raw ECGs. The filtering procedure and QRS complex detection were implemented in the processing station, which displayed ECG_{real} and SV estimation, and also output TTLs to a gating circuitry to trigger the MRI scanner. 20-sec breath-held ECGs were taken at 3 positions (Fig. 3) for adaptive filter training. The system was tested on two patients with Atrial Fibrillation (AF), one patient with Premature Ventricular Contractions (PVCs), and five healthy subjects, including an athlete under a stress test. Filter-derived ECG_{real}s were compared to the ECGs measured periodically outside the MRI for validation. To improve R-wave detection, a 3-D ECG representation (Fig. 4) was developed, which consisted of a time, a voltage axes, and *a channels* axis, which combined ECG channels V1-V6. Experiments were conducted at 1.5T and 3T MRIs. MRI imaging was performed on a volunteer in the 1.5T, using the system, with no heating observed.

Results: Fig. 2 shows an AF patient's (a) unprocessed surface-lead V6, (b) filter-derived ECG_{real}, and (c) V_{MHD}. The S-T segment in (b) is preserved, keeping the QRS complex dominant. As V_{MHD} is related to the ejected blood volume [4], (d) beat-to-beat SV estimation was derived from time-integrated systolic $|V_{MHD}|$. Irregular (c) MHD patterns and irregular (d) SV are explained by the ventricular-filling changes, consistent with the AF patient's pathology. The patients' varying heat rates (100-150bpm) were tracked successfully during the experiment. SV comparison, based on MHD estimation, among all subjects was previously presented [3]. The 3-D QRS complex (Fig. 4) formed a 3-D geometry (a) which was more distinguishable from the MHD signal (b), than in previous work, which used only a single channel, because the channels axis carried information on electrical-signal propagation from the sources to the surface leads. Because sinus rhythm originates from the sinus node, and V_{MHD} from the aortic arch, their source locations and electrical-signal propagations to the surface electrodes both differ, which makes the QRS complex identifiable, even in ECGs with a large MHD effect (Fig. 5). Using a Fast Fourier Transform 2D-cross-correlation, all QRS complexes were correctly detected in ECGs acquired at both 1.5T and 3T in all 7 subjects (Fig. 6), at a computational speed of < 5msec, which enabled real-time MRI triggering. **In conclusion:** The real-time system extracted ECG_{real}, preserved the S-T segment and delivered ECG traces for cardiac physiological monitoring. Beat-to-beat SV was non-invasively derived from the time-integrated systolic V_{MHD}. Using 3-D ECG analysis, real-time QRS complex detection and scanner triggering were achieved even with the strong 3T MHD.

References: [1] Tse, SCMR 2010, [2] Haberl, ECG pocket, Borm Bruckmeier Publishing 2006, [3] Tse, ISMRM 2010, [4] Larson, Med Biol Eng Comput. 2008.

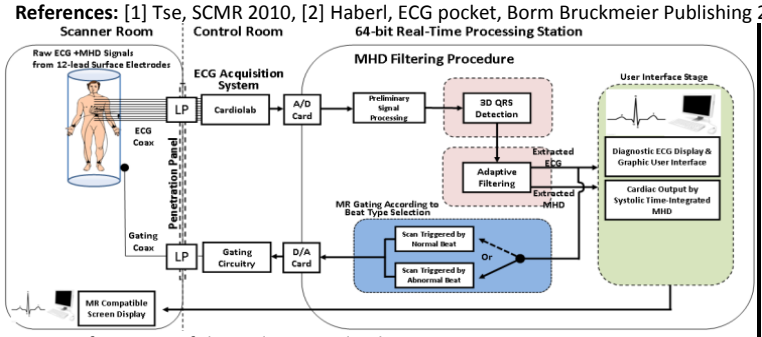


Fig.1. Configuration of the real-time 12-lead ECG system

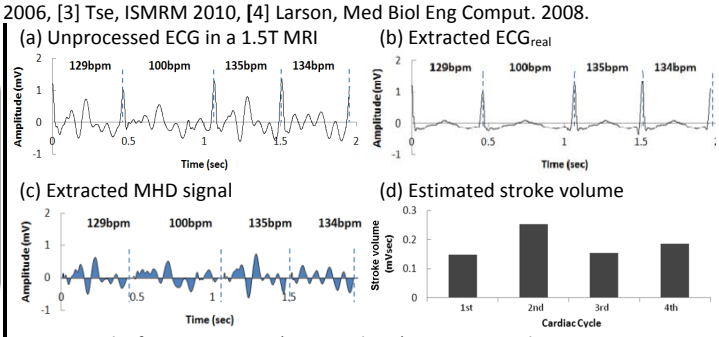


Fig. 2 Results from AF patient (100-150 bpm). ECG acquired in a 1.5T MRI

Fig. 3. ECGs measured at 3 positions; outside the magnetic field (i), at magnet isocenter with head-in (ii) and with feet-in (iii).

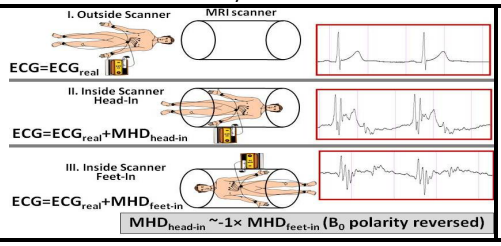


Fig. 4: 3-D ECG representation of an AF patient's ECG taken in a 3T MRI

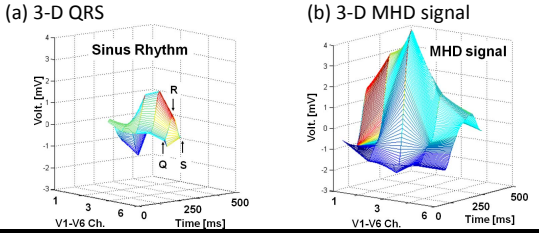
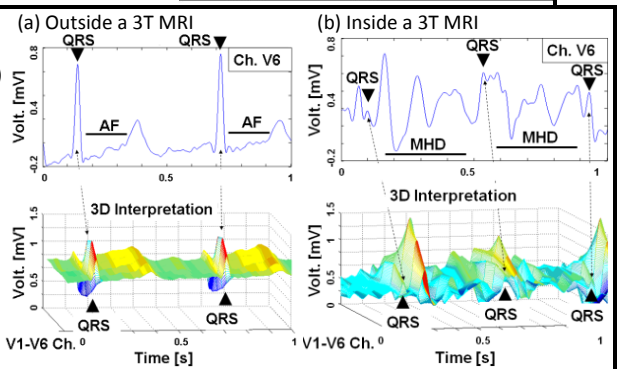


Fig. 5: AF patient's ECG: channel V6 (top) and 3D representation (bottom). 3D-QRS is identified even with stronger MHD peaks (b, bottom).



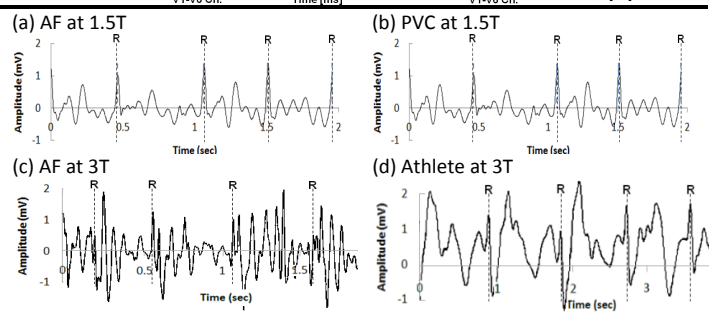


Fig 6. Gating results. R designates detected R-wave peaks using 3D-QRS. All R peaks (dotted lines) are correctly identified.