MRI-compatible 12-lead ECGs with MHD separation: Application to Cardiac MRI gating, Physiological Monitoring and Non-invasive Cardiac-output Estimation

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Introduction: The Magneto-Hydro-Dynamic (MHD) effect during cardiac MRI creates voltages which arise from conductive blood flow within a strong magnetic field (B_0). These voltages contribute to large distortions in the Electro-Cardio-Gram (ECG_{real}) signals, and adversely affect the accuracy of MRI gating and of physiological monitoring. The MHD voltages are frequently higher than the QRS complex of the real ECG (ECG_{real}) in high-field scanners, primarily during the S-wave to T-wave (S-T) cardiac segment, when blood is rapidly ejected from the left ventricle (LV) into the aorta, and contributes to large MHD voltages. The MHD voltages have a similar frequency spectrum as ECG_{real} [1], making elimination of the MHD signals with conventional, frequency-based, filtering technique difficult. An undistorted S-T segment is important for ischemia monitoring during cardiac imaging/interventions, whilst precise MRI gating relies on clear visualization of the QRS complex [2]. We hypothesized that real-time adaptive filtering could separate the MHD signals from ECG_{real} and that the MHD voltages could be used to estimate the subject's cardiac output.

Material and Methods: A Cardiolab-IT digital ECG-recording system [3] was made MRI compatible and used in a 1.5T scanner to acquire 12-lead ECGs from five healthy human subjects, including an athlete subject exercising in the magnet, and a patient with idiopathic outflow tract Premature Ventricle Contractions (PVCs) (Ejection Fraction 20-25%, LV wall thickening, mitral regurgitation). Three sets of ECGs were measured during 20-sec breath-holds, with subjects placed (i) outside the scanner with their feet-in ($ECG=ECG_{real}$), (ii) at iso-centre with their feet-in ($ECG=ECG_{real}+MHD_{feet\text{-}in}$), and (iii) at iso-centre with their head-in ($ECG=ECG_{real}+MHD_{head\text{-}in}$), which reverses B_0 polarity ($MHD_{feet\text{-}in} \sim -1 \times MHD_{head\text{-}in}$). Fig.2(a) shows the data processing block diagram, which includes training of adaptive Lease-Mean-Square filters with ECG_{real} (i), as well as application of the trained filters to (ii) and (iii) to separate the MHD signals from ECG_{real}.

Results: Processing of the patient's V6 electrode in position (ii) is shown in Fig.1. ECG_{real} is extracted from the MHD signal in Fig. 1(b) with the S-T segment preserved. In Fig.1(c), the MHD voltage exhibits maximal amplitude during the S-T segment. Oscillating positive and negative MHD voltages during systole can be explained by flow vortices during the cardiac cycle. In Fig.1(d), estimation of cardiac output using the systolic, time-integrated, MHD voltage suggests that PVC beats produce much lower cardiac output than during normal sinus rhythm. In Fig.2(b) The PVC patient provided 51% less cardiac output than the four normal healthy subjects on average, a result of the less effective PVC beats, whilst the athlete subject generated 30.4% greater cardiac output than the other normal subjects. The filtering procedure was able to adapt to heart rate changes from 44bpm to 87bpm in an experiment where exercise was performed by the athlete subject inside the scanner, with cardiac output monitored by the integrated MHD. The amplitude of the MHD signal increased with heart rate in Fig.3(b), suggesting that a high cardiac output, along with a faster heart beat, was required to provide enough oxygen to the body during exercise ((Fig.3(c)). Also, the extracted MHD signals exhibited more high frequency components at the higher heart rates. This can be explained by the turbulent flow in the bloodstream at higher blood flow rate.

Conclusions: The filtering scheme extracts ECG_{real} from MHD signals, preserves the S-T segment for ischemia monitoring, and keeps the QRS complex dominant for MR gating during cardiac imaging/interventions. The MHD signals provide a non-invasive means for beat-to-beat cardiac output monitoring.

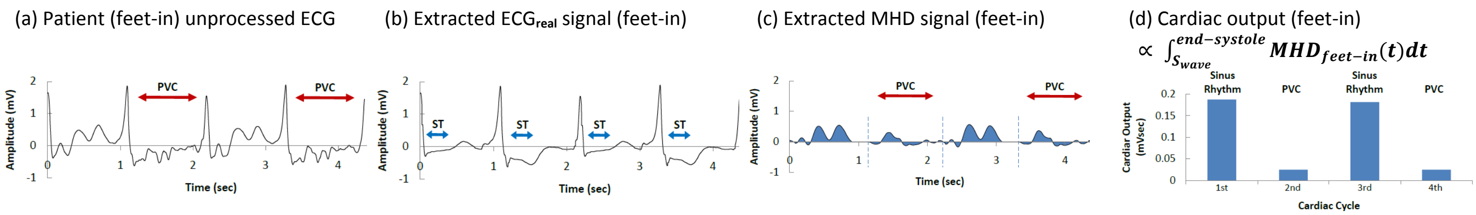
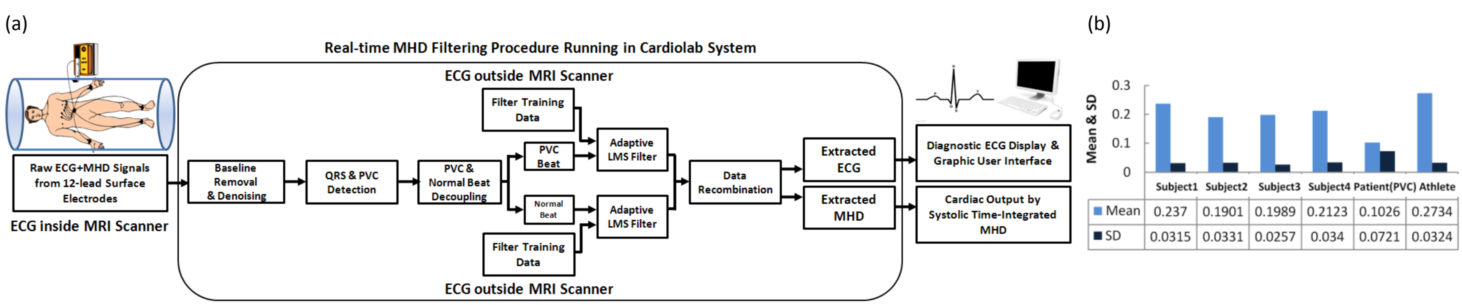
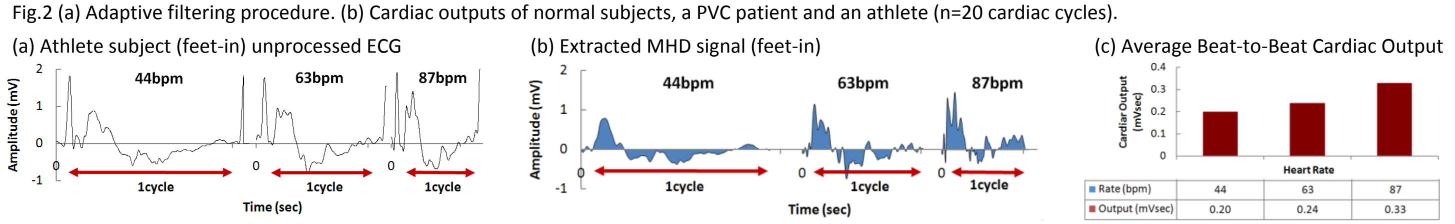


Fig.1 Patient results: (a) Acquired ECG at iso-centre, (b) extracted real ECG and (c) extracted MHD signal, (d) beat-to-beat cardiac output from integrated MHD.



	Subject1	Subject2	Subject3	Subject4	Patient(PVC)	Athlete
Mean	0.237	0.1901	0.1989	0.2123	0.1026	0.2734
SD	0.0315	0.0331	0.0257	0.034	0.0721	0.0324

Fig.2 (a) Adaptive filtering procedure. (b) Cardiac outputs of normal subjects, a PVC patient and an athlete (n=20 cardiac cycles).



Rate (bpm)	44	63	87
Output (mVsec)	0.20	0.24	0.33

Fig.3 Results from athlete subject: (a) Acquired ECG during exercise at iso-centre , (b) extracted MHD signal, and (c) average cardiac output versus heart rate (n=20).

Reference: [1] Gupta, IEEE Trans. BioMed. Eng., 2008. [2] Haberl, ECG pocket, Borm Bruckmeier Publishing, 2006. [3] Dukkipati, Circulation, 2008.