MRI-Compatible 12-lead ECG: Improved MHD suppression, ischemia monitoring, and non-invasive cardiac output

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PURPOSE

Reliable QRS-complex visualization is a necessity for gated cardiovascular acquisitions. In therapeutic interventions in the MRI, there is also a need to accurately visualize the cardiac cycle's ST segment , since changes in the ST segment are a strong indication of acute ischemia of the heart. The strong (*intra*-MRI) Magneto-Hydrodynamic (MHD) voltage additions to the real (*extra*-MRI) ECG present difficulties in observing both ECG characteristics reliably. The MHD effect has been shown [1, 2] to be primarily caused by flow in the aortic arch. We surmised that use of a 12-lead MRI compatible ECG, as opposed to the standard 4-lead ECG, in a combined protocol requiring three preliminary calibration measurements, would allow improved gating and monitoring, during both diagnostic and therapeutic MRI. In addition, a clearly separated MHD signal may permit non-invasive qualitative flow monitoring, which can be used to separate between beats followed by differing mechanical motion of the heart, such as differentiating sinus-rhythm and premature beats in atrial fibrillation patients.

METHODS

The MHD Voltage $\vec{V}_{MHD} \sim \vec{v} \times \vec{B0}$ is caused by interaction of the static magnetic field $\vec{B0}$ with charged electrolytes flowing at a velocity $\vec{v}$, causing a build-up of a potential on opposing sides of a blood vessel, and also creating a voltage at the surface electrodes [1]. Assume a right-hand co-ordinate system X, Y, and Z, where X is Left-Right, Y is Anterior-Posterior and Z is Inferior-Superior (e.g., parallel to $B0$). Since $\vec{B0} = |B0|\,\hat{z}$, $\vec{V}_{MHD}$ must be only in the X-Y plane, and since $\vec{v}_{Aorta} \sim |v|\ -\hat{Y}$ (e.g. flow in the –AP direction), $\vec{V}_{MHD}$ is primarily in the -X (Left) direction, and is greatest during the systolic phase [2]. As a result, both the true ECG voltage (ECG_{Real}) and the MHD voltage are expected to appear with a differing intensity and phase at the 12 surface electrodes [1]. A Cardiolab-IT digital ECG-monitoring system (GE Healthcare, Waukesha, WI), made MRI-compatible using in-room RFI filters [3], was used for the volunteer experiments. ECG protocol: 14-bit digital sampling with 10 mV PTP voltage, 1 KHz sampling frequency, acceptance pass-band of 0.05-100 Hz, 60 Hz notch filter. After fixing electrodes to the subject at 12-lead positions [Figure 1], with maximum S/I distance 40 cm, and lead connection to the Cardiolab amplifier, 20 sec breath-held ECG measurements were conducted at three spatial positions; A. Supine on the MRI table, but outside the magnet ($\hat{V} = \hat{ECG}_{Real}$ only) B. Supine at magnet iso-center, with *head-in* ($\hat{V} = \hat{ECG}_{Real} + \hat{V}_{MHD}$) C. Supine at magnet iso-center, with *feet-in* ($\hat{V} = \hat{ECG}_{Real} - \hat{V}_{MHD}$). Between B and C, the sign of $\vec{V}_{MHD}$ changes due to effective reversal of B0. In post-processing, the QRS complexes were temporally synchronized by time-shifting the 3 waveforms in each channel using a 50msec kernel cross-correlation, and the cycle-lengths at the 3 positions were stretched/compressed to account for *inter*-position heart-rate changes. A 30 Hz 4th order Butterworth low-pass filter was applied prior to performance of vectorial mathematics.

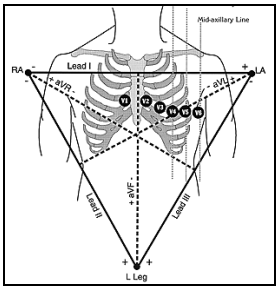

Figure 1: 12-lead ECG (v1-v6, RA, LA, LL) electrode positions. RL (not shown) serves as ground.

RESULTS & CONCLUSION

Figure 2 shows 12-lead measurements in a volunteer. The variation of ECG channels v1-v6 between outside the magnet (A), inside the magnet with head first (B) and inside legs first (C) is shown. The QRS complex is still identified inside the magnet, but it is followed by signals in the systolic phase, with strong peaks in the ST segment. The MHD effect has a strong 5-10 Hz oscillatory nature, which is not present in the original ECG. MHD amplitude is weakest in v2-v4. It is clearly seen that many of the main MHD-created peaks, with emphasis on the lower frequency ones during the ST segment, reverse polarity between positions B and C. Figure 3 shows averaging of the v4 electrode signal taken at positions B and C, after temporal shifting and stretching has been performed. It is evident that the MHD effect is greatly reduced (Fig. 3, Lower), leaving the QRS complex dominant, and the ST segment approaching its true value outside the magnet. There is still a need to remove high-frequency oscillations without damaging the QRS complex, or T and P wave fidelity, which is the subject of our present work. **In conclusion**, 12-lead MRI-compatible ECG with initial calibration at three MRI-table positions may provide a means to obtain improved gating and patient monitoring.

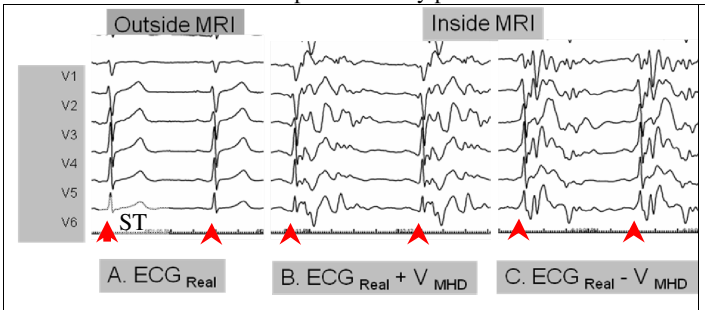

Figure 2: 12-lead ECG leads outside the MRI (position A), inside the MRI head first (position B) and inside the MRI feet-first (position C). ECG channels v1-v6 are shown. The QRS complexes are denoted (red arrows) The ST segment in the cardiac cycle is denoted in the left figure.

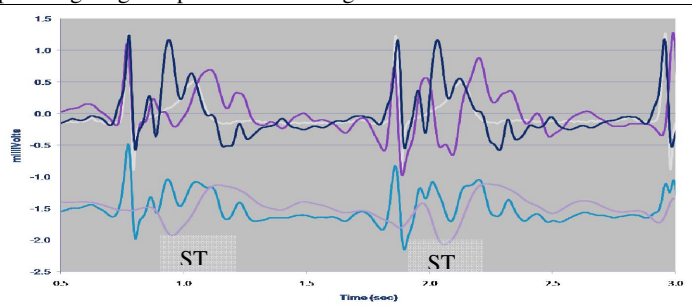

Figure 3: Electrode v4 signals prior to (Upper) and post (Lower) processing; ECG_{Real} (white, from position A), $ECG_{Real} + V_{MHD}$ (dark purple, from position B), $ECG_{Real} - V_{MHD}$ (black, from position C). Lower: Averaging signal from positions B and C (light blue) removes much of the MHD, which is also shown alone (light purple). High-frequency oscillations must still be removed.

REFERENCES:[1] R.N. Dimick, *Invest. Rad.* 1987 22:17-22, [2] A. Gupta, *IEEE Trans. BioMed. Eng.* 2008 55:1890-1896 [3] S. Dukipapti, *Circulation* 2008 118;853-862.