Magnetohydrodynamic Distortions of the ECG in Different MR Scanner Configurations

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Abstract

Diagnostic electrocardiograms (ECG) are required to ensure patient safety during minimal invasive interventions and cardiac stress testings. The ECG is corrupted by several other signals when performing these interventions under magnetic resonance (MR) guidance which makes it impossible to use the ECG as a diagnostic tool in MR guided interventions. The interfering signal that is caused by the static magnetic field of the MR scanner - namely due the magnetohydrodynamic (MHD) effect - is investigated within this work. The MHD effect is measured regarding different aspects like the strength and orientation of the static magnetic field as well as the patient's position and heart rate.

1. Introduction

The primary usage of Magnetic Resonance Imaging (MRI) is in diagnostic applications. Here, MRI has several advantages compared to other imaging modalities as computer tomography, e.g. a high soft-tissue or the lack of ionizing radiation. The present trend is to use MRI as modality for guiding and monitoring minimal invasive interventions like biopsies, brachytherapies, radio-frequency ablations of malignant tissue, catheter ablation of the heart or in cardiac stress testings. To supervise the patient's health status, a diagnostic ECG is necessary in some of these therapeutic applications, e.g. to detect acute ischemia.

The presence of different types of magnetic fields in an MR scanner leads to several challenges while recording a diagnostic ECG. Gradient magnetic fields and high frequency fields can lead to induction effects in the ECG cables resulting in high voltages or heating of the ECG electrodes [1]. Besides these safety related issues, different algorithms have been developed to filter the gradient induced artifact signals from the recorded ECG signal [2].

In addition the above mentioned effects, the MR scanner's static magnetic B_0 field, which ranges from 1 T to 3 T in clinical applications, has an significant influence on the recorded ECG signals. The influence of the B_0 field on the blood flow inside the human vessel system leads to the so called MHD effect resulting in a measureable voltage that superimposes the ECG signal. This superposition makes it impossible to perform a diagnostic analysis of the ECG signal.

This work focuses on the measurement of the ECG signal in the presence of the B_0 field under various aspects as explained in the following section.

2. Materials and methods

2.1. Theory of the MHD effect

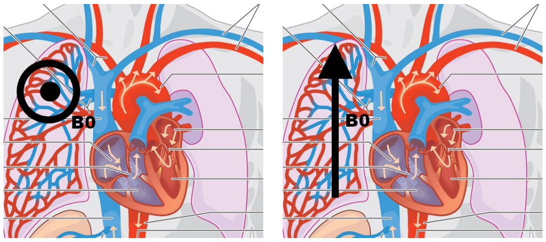
Blood plasma, which makes up about 60 % of the total blood volume contains approximately 10 % solutes such as Na^+, Cl^- or HCO_3^- ions. These ions are moving inside the vessels where they experience a force due to the presence of the external magnetic field - namely the MR scanner's B_0 field. This force is known as Lorentz force $\vec{F}$:

$$\vec{F} \propto (\vec{v} \times \vec{B}_0) \qquad (1)$$

and depends on the magnitude and orientation of the blood flow velocity $\vec{v}$ with respect to the $\vec{B}_0$ field. This force causes the ions to move perpendicular to the direction of the blood flow and perpendicular to the magnetic B_0 field. The ions accumulate near the vessel's wall leading to an potential difference across the vessel that may be expressed as:

$$V \propto \int_0^l \vec{v} \times \vec{B}_0 \, d\vec{l} \qquad (2)$$

where l is the diameter of the vessel. This is the so called MHD effect. Besides these basic assumptions, additional parameters as the density, conductivity, and viscosity of blood, the Hartmann number or the aortic blood pressure have to be considered to estimate the induced voltage across the vessel [3] whereas additional transfer functions are used to estimate the body surface potentials [4].



(a)Vertical B_0 field (from anterior to posterior) (b)Horizontal B_0 field (from feet to head)

Figure 1. Alignement of the magnetic fields for a) the 1 T scanner and b) the 1.5 T and 3 T scanner.

The MHD effect leads to a disturbance of the ECG signal when measuring it in the MR scanner. This makes it impossible to use the measured ECG for cardiac diagnostics. However, the MHD signal can be used as an alternative approach in cardiac gating of peripheral target areas in MR angiography [5] or in the estimation of blood flow volume [6].

2.2. ECG recording hardware

To obtain maximum information from the ECG measurements under the presence of the B_0 field, a 12-lead ECG recorder was used. Since there is no MR safe 12-lead ECG recorder available, a standard 12-lead Holter ECG (*CardioMem CM3000-12, GETEMED, Germany*) was modified. Standard, non-magnetic ECG Electrodes were used during the experiments. All ECGs were recorded using 12-leads with a sampling rate of 1024 Hz, a resolution of 12 Bit, an input voltage range of ±6 mV and an analog bandwidth ranging from 0.05 Hz to 100 Hz.

2.3. MR scanners

To evaluate the influence of the magnetic field strength and the orientation of the field, the ECGs were recorded in three MR scanners:

- 1 T Philips Panorama High Field Open MRI
- 1.5 T Siemens Magnetom Vision
- 3 T Philips Achieva TX MRI

Fig. 1 shows the direction of the B_0 field and the blood flow inside the primary blood vessels[1]. The magnetic B_0 field of the 1 T scanner is aligned along the vertical axis whereas the patient lies along the horizontal axis (Fig. 1a). This means that most parts of the aorta - the *aorta ascendens*, *arcus aortae* and *aorta descendens* - have a perpendicular component with respect to the B_0 field. This fact might increase the MHD effect. The horizontally aligned B_0 fields of the more commonly used 1.5 T and 3 T scanners have fewer perpendicular components with respect to the aorta, mainly with the *arcus aortae* (Fig. 1b).

MR imaging was switched off during the recording of the ECGs. Hence, MR-unsafe hardware as mentioned in section 2.2 can be used. Regarding the measured ECG signals, the deactivation of MR imaging restricts the artifacts to the MHD effect.

2.4. Patients and measurement protocol

Measurements were made on two healthy, male volunteers at the age of 24 (Patient *P1*) and 28 (Patient *P2*).

To investigate different effects for the different scanner types and field strengths, the ECGs were recorded for at least 40 s in prone/supine position (for the 1 T scanner), in head-first/feet-first position (1.5 T and 3 T scanner) with normal breathing/breath hold for the following situations:

- Patient outside the MR scanner as reference
- Patient's chest in the center of the MR scanner's bore
- Different heart rates during stress testing

2.5. ECG signal filtering

To remove baseline wandering, an elliptical high-pass filter of fifth order with cutoff frequency 0.8 Hz and 60 dB stop band attenuation has been applied to the recorded ECG signals. To improve QRS detection[2], the MHD artifacts were filtered using a high-pass filter with cutoff frequency 10 Hz. 50 Hz power line interferences were not observed within the MR scanner room.

2.6. MHD signal extraction

To estimate the MHD signal's shape, the differential signal between the ECGs outside and inside the scanner is calculated. Episodes of constant heart rate are used. A mean value over ten consecutive heart beats is calculated for the 12 leads of the ECGs measured outside ($\overline{ECG_{OUT}}$) and inside the scanner ($\overline{ECG_{IN}}$). The mean MHD voltage signal $\overline{MHD}$ is then defined as $\overline{MHD} = \overline{ECG_{IN}} - \overline{ECG_{OUT}}$.

3. Results

ECG signal properties: Resting heart rates measured outside and inside the scanner ranged from 51 bpm to 72 bpm. An example for an ECG signal measured outside the scanner as reference is shown in Fig. 3a). The R-wave of all mesurements shown in Figs. 2-5 is positioned at 150 ms. The results presented in Figs. 2-5 show the mean value of ten consecutive heart beats.

Dependency of MR scanner and patient position: Fig. 2 summarizes the ECG measurements inside the three

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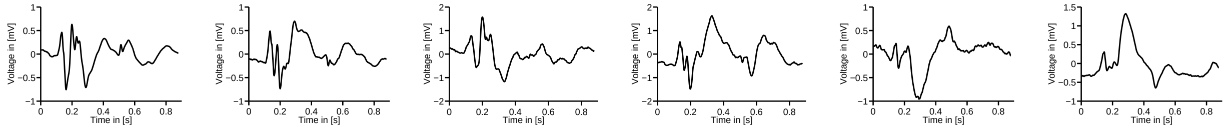
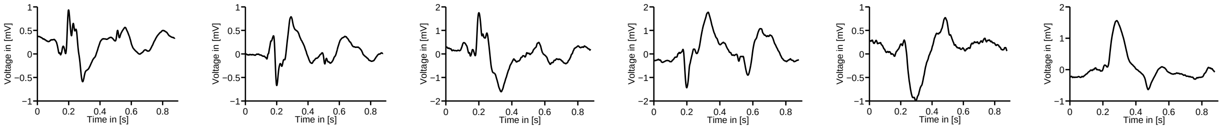
[1] Image modified according to: www.genetherapyreview.com

[2] QRS detector taken from *BioSig* library: biosig.sourceforge.net

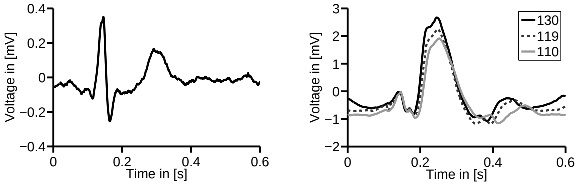


(a)Head first, ECG signal at 1.5 T (b)Feet first, ECG signal at 1.5 T (c)Head first, ECG signal at 3 T (d)Feet first, ECG signal at 3 T (e)Prone, ECG signal at 1 T (vertical field) (f)Supine, ECG signal at 1 T (vertical field)



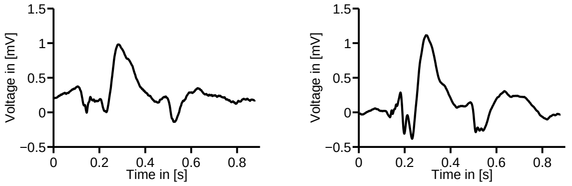
(g)Head first, MHD signal at 1.5 T (h)Feet first, MHD signal at 1.5 T (i)Head first, MHD signal at 3 T (j)Feet first, MHD signal at 3 T (k)Prone, MHD signal at 1 T (l)Supine, MHD signal at 1 T

Figure 2. Measurement of ECG lead I and extracted MHD signals for different positions and for 1.5 T, 3 T (horizontal aligned B_0 field) and 1 T (vertical aligned B_0 field) scanner.



(a)ECG outside scanner (b)ECGs inside scanner

Figure 3. ECG lead I of Patient P2 measured outside and inside the 1 T scanner for different heart rates ranging from 110 bpm to 130 bpm.



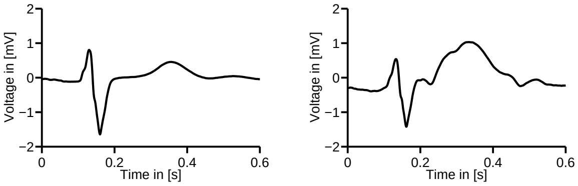
(a)Patient *P1*, heart rate: 53 bpm (b)Patient *P2*, heart rate: 68 bpm

Figure 4. Comparions of the MHD in two patients in ECG lead aVL in the 1.5 T scanner, feet first.

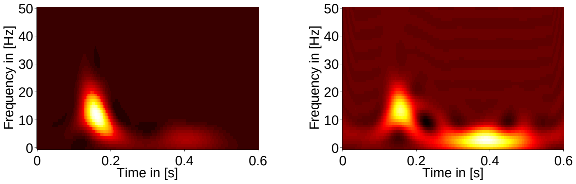
different MR scanners. For the 1.5 T and 3 T scanner, the ECGs were recorded in head first and feet first positions (supine). Results are shown in Figs. 2a)-d). For the 1 T scanner, ECGs were recorded in supine and prone position due to the different orientations of the B_0 field (head first). Results are shown in Figs. 2e)-f). Figs. 2g)-l) show the extracted MHD signals.

MHD signal at different heart rates: The ECG measurements at different heart rates were performed within the 1 T scanner system in supine position after exercising. ECG recordings for heart rates ranging from 110 bpm to 130 bpm are shown in Fig. 3b).

Interpatient MHD signal comparison: Fig. 4 shows the extracted MHD signals of patient *P1* and *P2*.



(a)ECG outside scanner (b)ECG inside scanner



(c)TFD outside scanner (d)TFD inside scanner

Figure 5. Time-Frequency-Distributions for ECG lead V2 measured outside and inside the 1.5 T scanner.

MHD signal frequency distribution: The spectrograms from ECG lead V2 taken outside and inside the 1.5 T MR scanner are calculated using the Smoothed-Pseudo-Wigner-Ville-Distribution (window lengths: $h = 138\,\mathrm{ms}$ and $g = 70\,\mathrm{ms}$ [7]) and are shown in Fig. 5.

4. Discussion

Dependency of MR scanner: As expected from Eq. 2, the measured MHD voltage is directly related to the absolute magnitude of the B_0 field. This effect can be observed in the measurement for the 1.5 T and 3 T scanner as shown in Fig. 2g) vs. Fig. 2i) and Fig. 2h) vs. Fig. 2j), respectively.

The 1 T scanner has to be dissociated from the 1.5 T and 3 T scanner due to its deviating field orientation as described in section 2.3. Despite its relatively low field strength, the amplitude of the MHD signal observed in the 1 T is in the order of those measured in the 1.5 T and 3 T scanners. This agrees with the theory given in section 2.3.

For the 1.5 T and 3 T scanners, the MHD voltage is minimal in leads V2 and V3 which agrees with previous measurements [8]. For the 1 T scanner, it is minimal in lead III.

Patient position dependence: For the MR scanners with an horizontal alignment of the B_0 field (1.5 T and 3 T system), the induced MHD voltage depends on whether the patient is placed head first or feet first inside the MR scanner. Results are shown in Fig. 2g) vs. Fig. 2h) and Fig. 2i) vs. Fig. 2j), respectively.

For the 1 T scanner system which has an vertically aligned B_0 field as shown in Fig. 1a), the change of the patient's position from supine to prone position leads to changes in the measured MHD signal. This is shown in Fig. 2k) and Fig. 2l).

MHD signal at different heart rates: The MHD signal changes with varying heart rate. An increasing heart rate leads to an increased amplitude of the MHD signal as well as a temporal compression. This relation can be explained by the effect that the QT interval is shortened with increasing heart rates. Assuming a constant stroke volume, this would lead to an increased blood flow velocity. However, one has to consider that the relation between the heart rate and the QT interval in healthy patients is different compared to patients suffering from coronary artery disease [9].

Interpatient MHD signals: There is an obvious visual similarity between the shape of the MHD signal of the two patients. However, due to the different anatomy and electrode placement in different patients and measurements, significant variations of the MHD signal have to be expected. Hence, a patient specific filtering of the corrupted ECG seems to be the most promising way.

Spectrogram: The frequencies of the ECGs taken outside and inside the MR scanner have overlapping frequency ranges in the T-wave segment. As shown in Figs. 5c)-d), both signals are in the frequency range between 0 Hz and 10 Hz within this segment. This precludes the usage of frequency based filters since those methods would eliminate the diagnostic information contained in the T-wave and ST-segment.

5. Conclusion

The MHD effect mainly depends on the orientation of the B_0 field with respect to the patient whereas the amplitude of the B_0 field is of secondary importance. The elimination of the MHD artifact using frequency based filtering is not possible due to the overlapping frequency ranges of the ECG and the MHD signal. One interesting aspect is the similarity of the MHD signal at varying heart rates in intrapatient measurements. Future work will investigate this relation more in detail. Additional measurements, e.g. blood pressure, might be necessary to cope with the MHD induced signals.

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