Alterations in human ECG due to the MagnetoHydroDynamic effect: A method for accurate R peak detection in the presence of high MHD artifacts

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Abstract— **Blood flow in high static magnetic fields induces elevated voltages that contaminate the ECG signal which is recorded simultaneously during MRI scans for synchronization purposes. This is known as the magnetohydrodynamic (MHD) effect, it increases the amplitude of the T wave, thus hindering correct R peak detection. In this paper, we inspect the MHD induced alterations of human ECG signals recorded in a 1.5 Tesla steady magnetic field and establish a primary characterization of the induced changes using time and frequency domain analysis. We also reexamine our previously developed real time algorithm for MRI cardiac gating [1] and determine that, with a minor modification, this algorithm is capable of achieving perfect detection even in the presence of strong MHD artifacts.**

I. INTRODUCTION

MAGNETIC Resonance Imaging (MRI) has become by far the primary tool for gaining important insights into the functional and metabolic bases of heart disease. However, MRI observations of a moving organ, such as the heart, require synchronization: since an image cannot be wholly acquired in one heart cycle, its successive acquisitions have to be accurately combined with the cardiac phase motion in order to overcome movement related blurring effects. Cardiac gating is usually done by detecting the R peaks on the simultaneously recorded electrocardiogram (ECG), which are then used to trigger the consecutive image acquisition sequences. Hence, achieving good image quality depends greatly on a reliable trigger signal in order to guarantee that accurate data collection always starts at the same point of the cardiac cycle. However, accomplishing an accurate R peak detection, and therefore a correct synchronization, is often obstructed by the high corruption levels of the ECG signal due to electromagnetic effects, especially when high resolution imaging is performed where high static magnetic fields as well as strong and fast switching gradients are needed. Most of the previous studies [2],[3],[4] that developed methods to produce a synchronization signal aimed mainly to reduce gradient switching, radiofrequency pulses and patient movements generated artifacts and have not been proven to be efficient for the magnetohydrodynamic (MHD) artifact removal. To our knowledge the only solution for eliminating this artifact was proposed by Fischer *et.al.* [5]. Their method exploits a vectocardiogram (VCG) signal and necessitates the use of multiple sensors. Nevertheless, positioning a large number of sensors in a NMR environment is not always simple, and might have consequences on the image quality.

The MHD effect is of physiological origins and is due to the blood motion in the magnetic environment. In fact, the blood's charged particles flowing in the static magnetic field get deflected by the Lorentz force and as a result a Hall potential is generated across the vessel walls. The magnitude of these voltages is a function of the blood flow rate and vessel diameter, their amplitude is maximal when the blood flow is perpendicular to the magnetic field. These superimposed voltages, induced by the electrodynamic interactions of the static field with arterial blood flow, especially in the ascending aorta and aortic arch, alter the waveform of the recorded ECG. The largest magnetically induced voltages occur during the blood ejection phase in the aorta which coincides with the ventricle repolarization (T wave). Hence the major MHD-caused change observed on the simultaneously recorded ECG is an increase of the T wave amplitude during in vivo MRI observations.

Magnetic field interactions with blow flow have been demonstrated by multiple authors throughout in vitro experiments [6] as well as in vivo studies [7], [8] where ECG alterations have been observed. For small animals, such as rats, the T wave elevation could be quantitatively measured at field levels above 0.3 Tesla , at a field intensity of 1.5 Tesla Gaffey *et.al.* [7] measured a 216% T wave elevation. However for larger species such as monkeys, who have larger aortas and greater flow rates, the MHD effect could be noted for much lower field intensities starting at 0.1 Tesla, Tenforde *et.al.* [8] measured elevations greater than 300% on macaca monkeys exposed to a 1.5 Tesla magnet. Nowadays, as field intensities augment, in the strive for achieving better image quality, the MHD effect is expected to amplify. Chakeres *et.al.* [9] recently conducted a study with an 8 Tesla magnet to examine the influence of high magnetic fields on human vital signs; they

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noted the same effects on the ECG as Gaffey and Tenforde but did not make any T wave elevation measurements.
In the cardiac MRI gating context, the MHD effect can be particularly hindering for synchronization, as the T wave might reach amplitudes as high as the QRS complex and could be mistaken for an R peak, hence leading to incorrect acquisition triggering.
In this study we examine the MHD effect on several ECG signals recorded on different subjects while exposed to a 1.5 Tesla static magnet and assess the major alterations imposed on the signal. We also review a previously elaborated real time R peak detection algorithm [1] and test its capacity of extracting correct triggers from these MHD contaminated signals.

II. METHODS

A. Signal acquisition

The ECG signals were recorded on 6 healthy subjects aged between 20 and 40 years. MR compatible electrodes (3M Red Dot) were placed on the subjects' chest area according to the Einthoven triangle configuration, and three ECG leads signals were acquired using an optical non-magnetic amplifier (0.5Hz-20Hz). For each subject an ECG signal was first recorded away from the magnet (at 0 Tesla) afterwards the subject was placed inside a 1.5 Tesla Signa GE MRI scanner and their MHD contaminated ECG was recorded and optically transmitted outside the faraday cage, then processed in real time using a previously developed software [1].

B. Temporal and spectral analysis of the MHD contaminated ECG signals

For each subject, the one minute long signals recorded without any magnetic exposure and while exposed to a 1.5 Tesla static magnet were compared in both time and frequency domains.
For temporal characterization we measured the amplitudes of the T waves and the R peaks, whereas in the frequency domain, the spectral density of each signal was estimated, and some characteristic values, were calculated to evaluate the spectral modifications induced by magnetic exposure.

C. Trigger production algorithm

Power spectral analysis of the ECG show that, P and T waves only present a significant spectral density up to 10 Hz, and that most of the QRS power lies in the 3-20 Hz band, beyond which the complex energy decreases gradually [10]. Thus, since gating relies on the R peaks, we can define this frequency band as being our region of interest in which we have all necessary information for trigger production. This concept was exploited in a previous work [11] where we developed a peak detection algorithm based on wavelet sub-band decomposition. It consists in decomposing the ECG signal into multiple scales, then reconstructing the details and keeping only those that contain the maximum of the QRS energy in order to compose a reference signal. For example if the acquired signal had been sampled at 1Khz, we would decompose it into 8 scales and then reconstruct the reference signal by summing details d_6 and d_7 resulting in a [3.91-15.63] Hz sub-band. This reference signal is then subjected to a double threshold comparator to produce a cardiac trigger. The algorithm was tested on simulated as well as small rodents ECGs that had been contaminated by one of three imaging sequences (Gradient Echo, Fast Spin Echo and Inversion Recovery Spin Echo) and some analyzing wavelets revealed having outstanding performances according to the signal and the sequence type. The real time version of this algorithm uses adaptive filtering where a filter is computed to imitate the wavelet method performances with minimum delay. It has proven to be very efficient for insuring good cardiac image quality for small rodents [1].

III. RESULTS AND DISCUSSION

A. Temporal and spectral characteristics

After analysis we found that the MHD artifact was most prominent on the lead I acquired signals; therefore in the following we only show numerical results of these signals.
All recorded ECG signals showed a clear elevation of the T wave when the subject was placed inside the MRI scanner.
Fig. 1 illustrates an example of two ECG signals of the same subject, acquired at 0 Tesla and 1.5 Tesla. For all subjects we calculated the T elevation as being the ratio of the T amplitude at 1.5 Tesla to the one measured at 0 Tesla, and evaluated the T/R amplitude ratios in each case (Fig. 2).

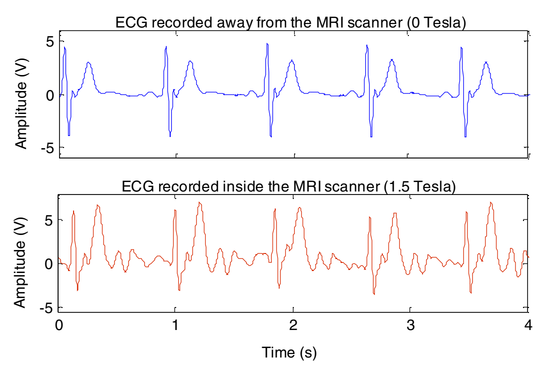
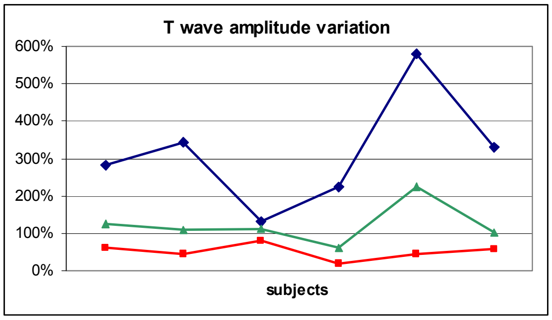


Fig. 1. Two ECG signals recorded on subject n°1, the first without any magnetic field influence and the second while exposed to a 1.5 Tesla magnet. We can clearly depict a prominent elevation (~280%) of the T wave which exceeds the R peak by approximately 20%



	mean	standard deviation
T elevation	315.52%	1.38
T/R 0T	50.90%	0.18
T/R 1.5T	122.23%	0.50

Fig. 2. The *'T elevation'* chart traces the ratios of the T wave amplitudes at 1.5 Tesla to those measured at 0 Tesla. The *'T/R 0T'* and *'T/R 1.5T'* charts show the ratios between the amplitudes of the T waves and those of the R peaks measured in the same signal when recorded at 0 or 1.5 Tesla respectively.

The average T wave increase was found to be greater than 315%, where the T amplitude exceeds that of the R peak reaching over 1.2 times the R amplitude value. Note that, when the ECG is recorded without any magnetic exposure, the T wave amplitude is only around half that of the R peak. For one subject the T wave amplitude even reached over twice that of the R peak, with approximately a 600% elevation.
Fig. 3 shows an example of a spectral density estimate and Table 1 details the computed mean values and standard deviations of some characteristic spectral features. Globally we observed a spectral shift towards low frequencies, and an energy increase: the mean and median frequencies are reduced to almost half their values while the signal power doubles. On the other hand, the frequency where maximum PSD is attained remained relatively unchanged.

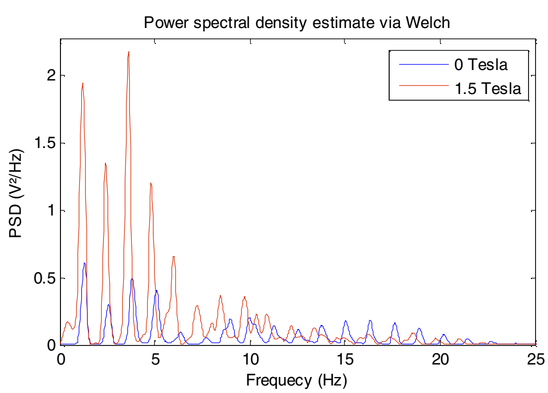


Fig. 3. Power spectral density estimates of the ECG signals of subject n°1 recorded at 0 and 1.5 Tesla. One can observe a spectral shift towards low frequencies and a great increase of signal energy when the subject is exposed to a magnetic field.

TABLE I
SPECTRAL VARIATIONS

	Mean Freq (Hz)		Median Freq (Hz)		Max Freq (Hz)		Signal Power (V²)	
	0 T	1.5T	0 T	1.5T	0 T	1.5T	0 T	1.5T
M	8.40	4.69	7.40	3.39	3.19	2.82	1.23	2.81
SD	0.92	1.28	1.50	1.45	2.42	1.79	0.52	1.32

M : Mean, SD: Standard deviation

Fig. 4 plots the scalograms of the ECGs recorded on subject n°1 at 0 and 1.5 Tesla. It clearly shows a low frequency energy increase at the T waves locations.
It is noteworthy to mention that none of these magnetically induced changes were permanent. As stated by Gaffey [7] Tenforde [8] and Chakeres [9] the ECGs recorded post exposure were similar to those recorded before exposure.

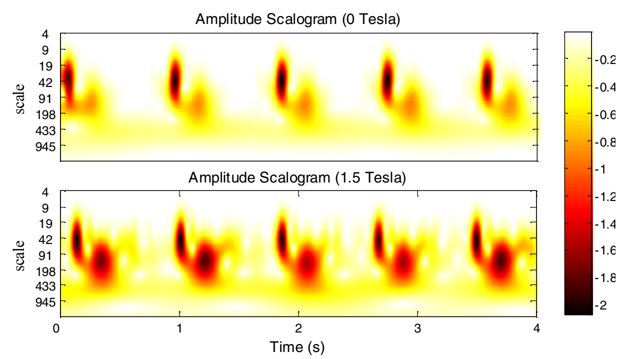


Fig. 4. Amplitude scalogram of the ECGs shown in fig. 1, acquired at 0 and 1.5 Tesla. A great energy increase can be observed at the location of the T waves at low frequencies.

B. Evaluation of the trigger production algorithm

While the subjects were inside the MRI scanner tunnel their recorded ECG was processed using the real time trigger production algorithm described above in order to evaluate its performances in the presence of high MHD artifacts. When the algorithm was first ran while keeping the usual [3.91-15.63] Hz band to extract a reference signal used to produce the trigger, many false detections were made. Nevertheless if the lower band limit was pushed to 6Hz instead of 3Hz perfect detection would be attained. In fact, as can be seen in fig. 3 , beneath 5 or 6Hz the MHD induced spectral content would still be very dominant, thus in the extracted reference signal the T wave amplitude would remain high enough to be mistaken for an R peak, thus leading to false positive triggers.
Fig. 5 illustrates an example of trigger production on a highly MHD contaminated ECG signal using the [6.64-26.56] Hz band to extract the reference signal. After processing with the sym7 wavelet all T waves were eliminated keeping only the R peaks for trigger production.

whether the modification of the reference signal band might affect the elimination of the gradient artifacts.

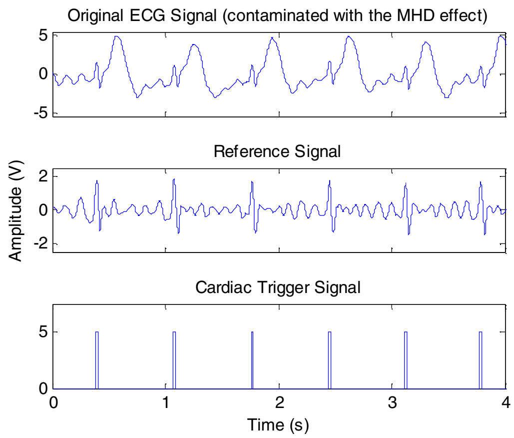


Fig. 5. R peak detection on the contaminated ECG of subject n°5 performed while inside the MRI scanner using the sym7 wavelet. Despite the tremendous T wave elevation which amplitude reaches more than twice the value of the R peak (T/R=225%), the trigger production is 100% accurate when extracting a reference signal in the [6.64-26.56] Hz band.

IV. Conclusion

The perturbation of the ECG signals collected during MR imaging greatly obstructs synchronization tasks. Moreover, the higher the requirements for good space-time or frequency resolution are, the more important the difficulties they induce. Some NMR generated artifacts may overlap the ECG spectrum, and are hard to filter out, such as the MHD induced voltages. These voltages alter the ECG waveform by elevating the amplitude of the T wave and might lead to R peak misdetections.

In this work we examined the MHD induced artifacts on ECG signals recorded in a 1.5 Tesla magnet, and established a primary characterization of the induced changes using time and frequency domain analysis. T wave elevation rates were measured, and were found to agree with the values given by Tenforde. A great energy increase, concentrated in the low frequencies area, was noted.

We also evaluated a previously developed real time algorithm for cardiac synchronization. The algorithm has been tested earlier on highly contaminated ECG signals for small rodents cardiac MRI gating, nevertheless the MHD effect was not very prominent in those signals given the relatively small size of rodents' arteries and low flow rate compared to those of humans. In this paper the method was tested on human ECGs with high MHD artifacts and has proven to be equally efficient by introducing a minor modification to the extraction process to narrow the extracted frequency band.

This study will later be extended to include more subjects and greater magnetic field intensities to further investigate ECG alterations and test the efficiency of the reference extraction algorithm when even higher T wave amplitudes are involved. We will also conduct more experiments to test

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