REMOVING THE MHD ARTIFACTS FROM THE ECG SIGNAL FOR CARDIAC MRI SYNCHRONIZATION

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Abstract: Blood flow in high static magnetic fields induces elevated voltages that disrupt the ECG signal 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 present an algorithm for extracting an efficient reference signal from an ECG contaminated by the Nuclear Magnetic Resonance (NMR) environment, that performs a good separation of the R-wave and the MHD artifacts. The proposed signal processing method is based on sub-band decomposition using the wavelet transform, and has been tested on human and small rodents ECG signals acquired during MRI scans in various magnetic field intensities. The results showed an almost flawless trigger generation in fields up to 4.7 Tesla during the three tested imaging sequences (GE, FSE and IRSE)

Introduction

Magnetic Resonance Imaging (MRI) of a moving organ, such as a beating heart, requires facilities to trigger successive scans and perform synchronization duties. Since an image cannot be wholly obtained during one heart cycle, consecutive acquisitions have to be accurately combined with the heart's phase motion. The easiest way to achieve this purpose consists in simultaneously recording the electrocardiogram (ECG) and detecting its R-waves to trigger the acquisitions. Thus, achieving correct synchronization depends greatly on accurate peak detection in order to guarantee that accurate data collection always starts at the same point of the cardiac cycle.

However the actual technical requirement needed to obtain good image quality (high static magnetic field, intense gradients, short rising time…) constrain the synchronization process, by generating high levels of artifacts that get superimposed on the ECG signal making the R peak detection very difficult. Most of the current synchronization methods fail in a significant number of patients, resulting in poor image quality and low scan efficiency. Artifacts generated by gradient switching, radiofrequency pulses and patient movements can be considerably reduced by the use appropriate acquisition and filtering devices [1], [2]. Nevertheless, previously proposed solutions for NMR artifacts suppression seem to be inefficient for the magnetohydrodynamic (MHD) artifact removal.

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, 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 animal models experiments [5] as well as in vivo studies [3], [4] 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 T [3], 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 0.1 T [4]. At strong intensity fields the T wave might reach amplitudes as high as the QRS complex and may be mistaken for an R peak, hence leading to incorrect acquisition triggering.

In this paper, we present an algorithm, based on wavelet sub-band decomposition that allows correct trigger extraction form an ECG contaminated by the NMR environment.

Materials and Methods

Experimental Setup:
The signals were recorded using a MR compatible ECG sensor which technical details are provided in [6] and a

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digital-signal-processing system placed outside the Faraday screen. Signals were collected during MRI scans in three different MRI platforms: 2T and 4.7T magnets for in vivo small animal exploration, and a 1.5T Signa GE MRI scanner.

The Algorithm:

The frequency distribution of the ECG wave forms is exploited here to extract the necessary information for synchronization. The MHD artifact is superimposed on the T wave and is essentially located in the low frequencies. The main idea is to isolate the frequency band that comprises mostly of QRS energy. This is done by decomposing the contaminated ECG into frequency sub-bands using wavelets than constructing a reference signal by keeping only the details containing the maximum QRS energy.

The algorithm, illustrated in figure 1, includes three main steps:

(i) *Frequency sub-band decomposition:* The corrupted ECG signal is decomposed onto N levels using filter banks, based on the classical orthogonal discrete wavelet transform (DWT). The number of scales was fixed according to ECG spectral analysis, taking into account the frequency components of the contaminating artifacts. For an ECG signal, sampled at 1 kHz, the decomposition would consist of 8 frequency sub-bands resulting in the following filter banks bandwidth: 1.96, 3.91, 7.81, 15.63, 31.25, 62.5, 125, and 250 Hz. For each level, the detail signals are afterwards reconstructed using the inverse discrete wavelet transform (IDWT). As for the choice of the analyzing wavelet, a bibliographical study associated with an analysis of noise samples collected during three imaging sequences (GE, FSE and IRSE) has enabled the selection of 14 wavelets of three families (Daubechies, Symlets and Coiflets) to be tested [7].

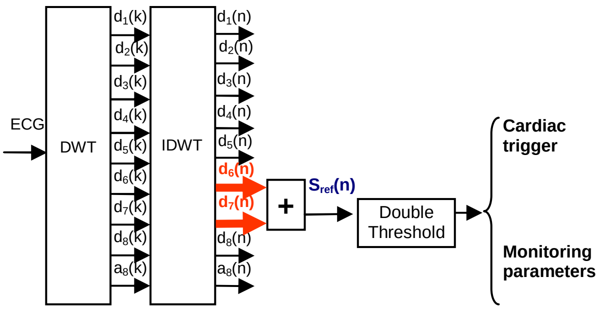

Figure 1: QRS pulse generation with the elaborated extraction algorithm.

(ii) *Reference signal extraction:* an ECG model where the QRS features have the most significant frequency components is then constructed. Given that most of the QRS power lies in the 3-20 Hz band [8], the reference signal is created by summing the sub-bands details that cover that interval. Details 6 and 7 were used when the signal was sampled at 1 kHz, covering the 4-16 Hz band.

(iii) *Trigger production:* A simple double thresholding operation on the reference signal then suffices for QRS pulses extraction, thus producing a synchronization signal that gives the cardiac rhythm and can be used to trigger image acquisitions.

Results and Discussion

The algorithm performances were evaluated on 2 sets of ECG signals collected during MRI observations using three imaging sequences: Gradient Echo (GE), Fast Spin Echo (FSE) and Inversion Recovery with Spin Echo (IRSE). 15 signals were recorded on 5 healthy subjects in 1.5T magnet, and 15 other ECGs were collected on mice and rats in 2T and 4.7T magnets.

Human ECGs recorded in a 1.5 T and mice ECGs recorded in a 4.7 T showed a prominent MHD effect, while the T wave elevation on mice signals recorded in a 2T magnet was less perceptible (figure 2)

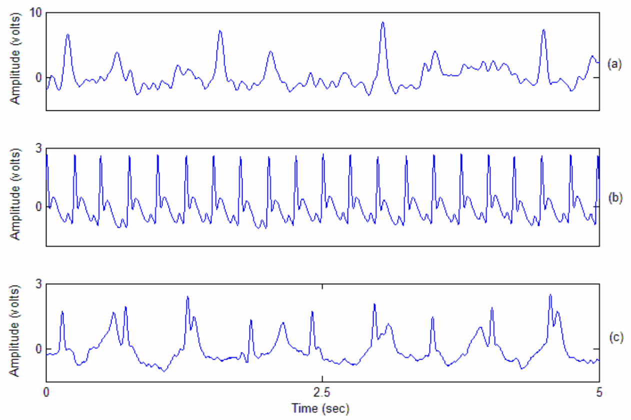

Figure 2: ECG signals recorded in a magnetic field. *(a) Human ECG in a 1.5 T magnet (b) mouse ECG recorded in a 2 T magnet (c) mouse ECG recorded in a 4.7 T magnet*

A total of 30 reference signals were extracted using the 3 wavelet families (Daubechies, Coiflets, and Symlets). Figure 3 illustrates trigger extraction from a human ECG contaminated by the MHD artifact during a FSE sequence. The details d_1 to d_5 contain artefacts due to RF and gradient switching, d_8 contains the MHD artefact, a_8 is mainly composed of the baseline drift and the respiration signal.

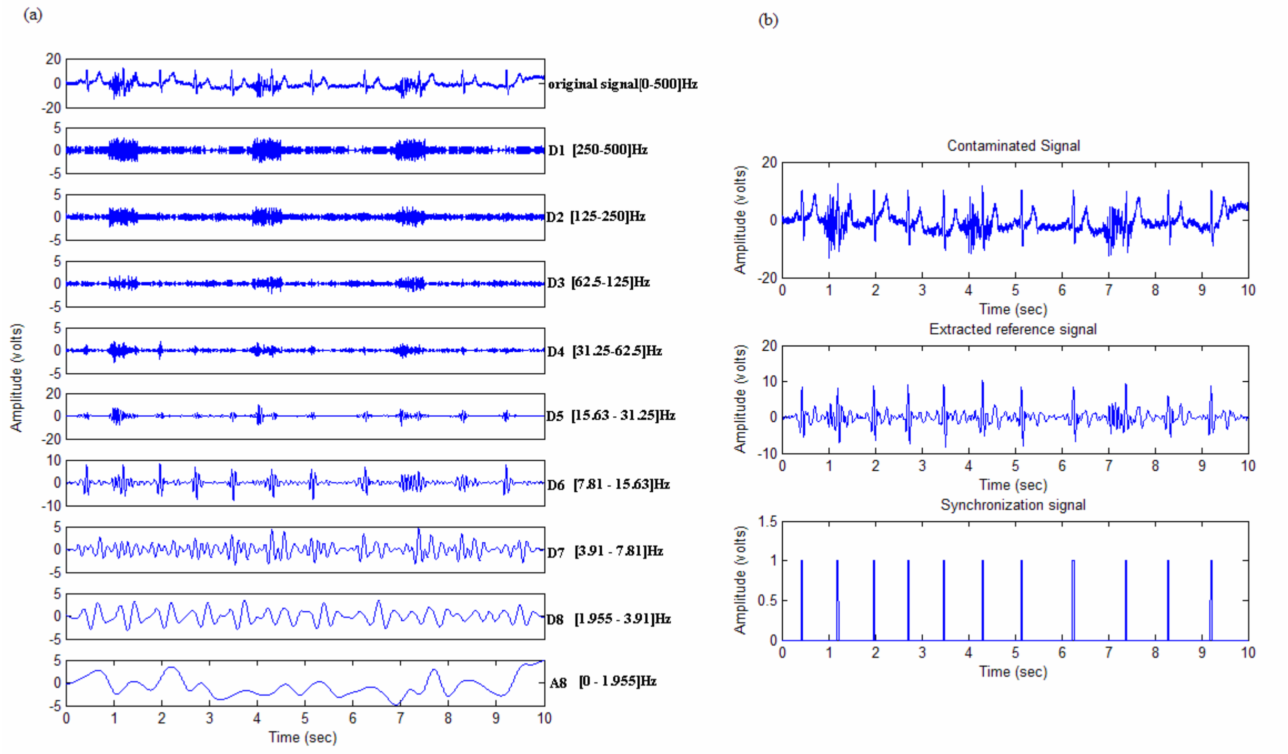

Figure 3: (a) 8 level wavelet based sub-band decomposition of a human ECG subjected to the MHD artifact. (b) The extracted reference signal (sum of details 6 and 7) and the computed trigger

Accurate QRS detection implies that a very high percentage of the R waves are detected with a low number of false R-waves being detected. In order to accomplish a quantitative performance evaluation of the present QRS detection algorithm two parameters were defined: The sensitivity (Se) and the positive predictive value (+P) given by:

$$Se = \frac{TP}{TP+FN} \qquad +P = \frac{TP}{TP+FP}$$

TP is the number of true positives, FN the number of false negatives, and FP the number of false positives. The sensitivity Se is the percentage, among real QRS beats, of those that were correctly detected by the algorithm. However, the positive predictive value +P represents the percentage, among the QRS detections of those corresponding to real beats.

Wavelet performances appeared to be different according to the noise type. For each sequence, some wavelets were more efficient than others in the removal of NMR noise, nevertheless all wavelets were able to greatly reduce the MHD effect. The global algorithm sensitivity is 99.6% and the positive predictive value is 99.9%.

Unlike the method proposed in [9] where multiple derivations are necessary for eliminating the MHD artifact, only one ECG derivation was used in our study, thus it is easier to place the electrodes on obese people, and less cumbersome for use on small animals.

The algorithm performances will further be tested on signals acquired during more complex imaging sequences. With its real-time implementation, and association with respiratory blanking, this method will establish an interesting solution for synchronization of cardiac MRI [10].

Conclusions

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 presented a method that extracts a signal from a contaminated ECG for image acquisition triggering. First the ECG is decomposed into sub-band details using the wavelet transform. A reference signal, containing the necessary information for synchronization i.e. the QRS complexes, is then constructed. Finally a trigger signal is produced by subjecting the reference signal to a double thresholding operation. The simple model proposed in this study has provided a good trigger signal extraction, perfectly synchronized with cardiac events for both human and small rodents. The low error rates have proven its efficiency for eliminating the MHD effect and performing correct R wave detection in the presence of NMR artifacts.

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