REAL -TIME WAVELET-BASED ALGORITHM FOR CARDIAC AND RESPIRATORY MRI GATING

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Abstract: A real time algorithm for cardiac and respiratory gating, which only requires an ECG sensor, is proposed here. Three ECG electrodes are placed in such a manner that the modulation of the recorded ECG by the respiratory signal would be maximal; hence, given only one signal we can achieve both cardiac and respiratory MRI gating. First, an off-line learning phase based on wavelet decomposition is run to compute an optimal QRS filter. Afterwards, on one hand the QRS filter is used to accomplish R peak detection, and on the other, a low pass filtering process allows the retrieval of the respiration cycle so that the image acquisition sequences would be triggered by the R peaks only during the expiration phase.

Introduction

The constantly evolving MR techniques have resulted in an increasing number of cardiac MRI scans in order to gain important insights into the functional and metabolic bases of heart disease. However, MRI observations of a moving organ, such as the heart, require synchronization so that the image acquisition might be accurately combined with its phase motion, thus eliminating the movement related blurring effects. Efficient synchronization techniques must associate cardiac gating with respiratory blanking, where the heart beat governed acquisitions are only enabled during at-rest periods (between breaths) to overcome the respiratory motion artefacts [1], [2].

Cardiac gating is usually done by detecting the R peaks on the simultaneously recorded electrocardiogram, which are then used to trigger the consecutive image acquisition sequences. 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.

In fact, the signal S(t), recorded in the NMR environment, can be decomposed [3] as follows:

$$S(t) = S_{el}(t) + S_{flow}(t) + S_{move}(t) + S_{rf}(t) + S_{mr}(t)$$

$S_{el}(t)$ represents the signal to be analyzed (ECG). $S_{flow}(t)$ is induced by the magnetohydrodynamic effect that results mainly in an elevation of the T wave, which might reach amplitudes as high as the R wave, thus leading to misgating. $S_{move}(t)$ is due to patient-related sensor motions in the magnetic field such as respiration, heart beat and voluntary motion, which become more pronounced with increasing static magnetic field strength. $S_{rf}(t)$, a high frequency component resulting from the radio frequency pulses, and $S_{mr}(t)$ generated by the temporal variations of the magnetic field gradients, are spurious signals that often resemble the QRS spikes and cause erroneous detection.

In the case of small animal imaging, these artefacts are further aggravated by the exceptionally high heart rate (400-600 beats per minute), the high respiratory rate (30-60 breaths per minute) [2], and the low amplitude of the ECG signal (just a few millivolts).

In order to combine cardiac gating with respiratory blanking, the respiration motion must be detected. This is usually done using motion detectors; however this is not always comfortable for some patients and is cumbersome for very small animals. Nevertheless, the respiration motion information is enclosed within the electrocardiogram as a modulating signal [4]: In fact, the respiratory motion of the thorax, heart and diaphragm changes the vectorial orientation of the electric heart axis, resulting in an amplitude modulation of the ECG which is itself a vectorial projection of the electrical activity of the heart.

In a previous work [5] we developed an off-line algorithm for cardiac triggering based on wavelet sub-band decomposition. A reference signal was extracted from the ECG, considering the sub-bands where the QRS energy was maximal, and was then subjected to thresholding to produce a trigger signal. The algorithm has proven its efficiency even for very low SNR signals.

In the present work we exploit the previously elaborated algorithm to produce an adapted filter, for real time use, that yields maximum QRS energy using the most appropriate wavelet. Furthermore, by applying an adequate positioning of the ECG electrodes that maximizes the respiratory dependent modulation, we make use of the respiration information contained in the ECG signal in order to generate, in real time, a

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synchronization signal that takes into account the respiratory movements as well.

The Algorithm

ECG signals are characterized by a cyclic occurrence of patterns (QRS complexes, P and T waves) with different frequency contents. Power spectral analysis of the ECG show that, P and T waves present a significant spectral density up to 10 Hz only, and that most of the QRS power lies in the 3-20 Hz band, beyond which the complex energy decreases gradually [6]. Thus, a strategical approach for detecting heartbeats would be to analyze different sub-bands of the ECG [7] using wavelet based filter banks.

Figure 1 shows an illustration of a previously developed algorithm [5] that consists in decomposing the ECG signal into multiple scales (8 for a signal sampled at f=1Khz), reconstructing the details and keeping only those that contain the maximum of the QRS energy in order to compose a reference signal.

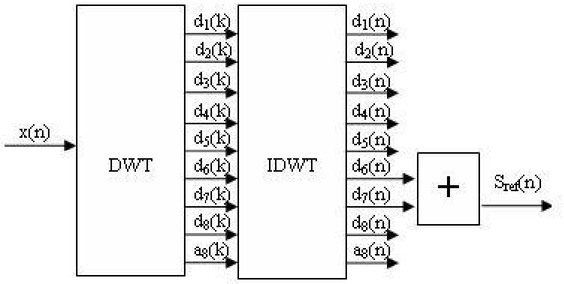

Figure 1: Reference signal extraction: *The contaminated ECG is decomposed into 8 scales using the discrete wavelet transform. The details are then reconstructed and a reference signal is formed by summing details 6 and 7, hence covering the 4-16 Hz sub-band.*

The algorithm was tested with 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.

Even though the wavelet decomposition algorithm gave proof of an almost infallible QRS detection, it could not be applied in real time for image synchronization, because the decomposition into 8 levels followed by the reconstruction of the 6th and 7th details induces a significant delay. Equation (1) gives the time delay necessary for the reconstruction of the n^{th} detail using a wavelet with order M

$$\frac{1}{f}\left(2^{n}+1\right)\left(M-1\right) \tag{1}$$

For instance if we use the Db6 wavelet, to reconstruct the 7th detail of a signal sampled at 1000Hz we get a 0,65 seconds delay, which is almost equal to one heart cycle.

In order to achieve real time synchronization, we elaborated a two phased algorithm that consists firstly of a training stage where an optimal QRS filter is computed based on wavelet decomposition, followed by a real time trigger generation phase.

In the learning phase, we record a portion (~5sec) of signal $S_{ori}(t)$ while the imaging sequence gradients are on, and then process it to produce a reference signal $S_{ref}(t)$ based on the previous method using the most appropriate wavelet.

Afterwards, with a Recursive Least Square (RLS) algorithm we compute the coefficients of the filter that would yield the same reference signal if applied to $S_{ori}(t)$ (minimizing the mean squared error, see [8] for details). Thus we obtain a filter F(n) that is adapted to both the ECG signal and the applied imaging sequence.

The second phase, illustrated in figure 2, consists of real time acquisition and processing of the ECG signal: on one hand, the recorded signal is filtered by the calculated F(n) then subjected to thresholding to produce the cardiac trigger; on the other hand a low pass filter 1,2Hz is applied to that same recorded signal to produce the respiratory modulation signal, which then provides the respiration trigger by a simple threshold at the mean value . The final synchronization signal is a combination of both triggers (logical AND) where the cardiac trigger is only taken into account during the low respiratory phase.

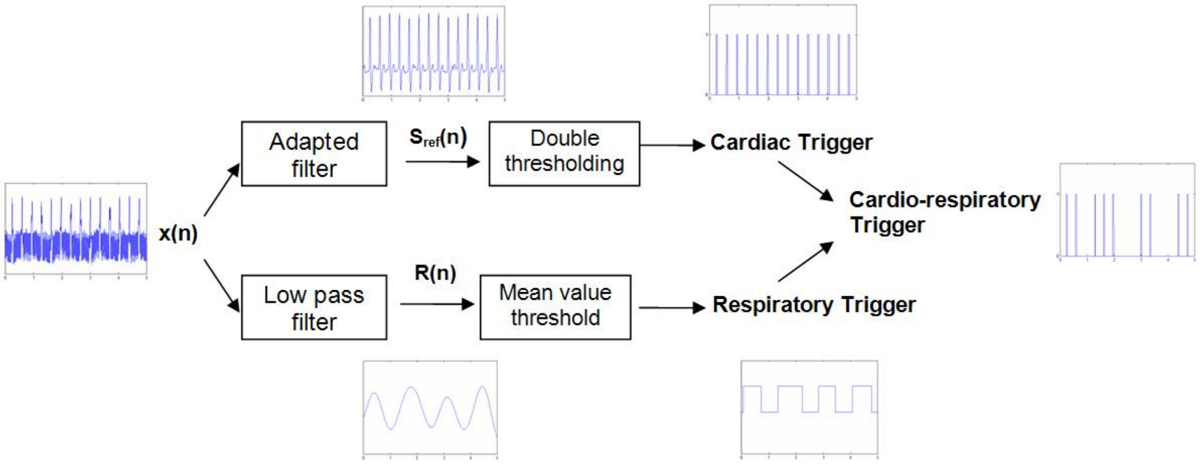

Figure 2: Real time cardiac and respiratory trigger extraction: *The signal is subjected to an adapted filtering to enable QRS detection, as well as a low pass filtering to extract the respiration signal. The cardiac and respiratory triggers are then combined to produce a synchronization signal that controls the image sequence triggering*

Results and Discussion

The method has been applied on anaesthetized mice and rats. The experimental setup incorporates a 2 Tesla OXFORD 85/310 horizontal cryomagnet equipped with a 50 mT/m gradient system, a MR compatible ECG sensor which technical details are provided in [9], and a digital-signal-processing system.

The ECG active electrodes were placed along the heart axis (45°) in order to obtain maximum modulation. The respiration modulated ECG signals were thus detected during MR scanning according to the three sequences mentioned above. The algorithm was able to generate effective online cardiac and respiratory triggering for all 3 sequences. An illustration is given in figure 3.

The images acquired with synchronization revealed a very clear enhancement compared to cardiac MRIs taken without cardiac or respiratory triggering (figure 4 and 5)

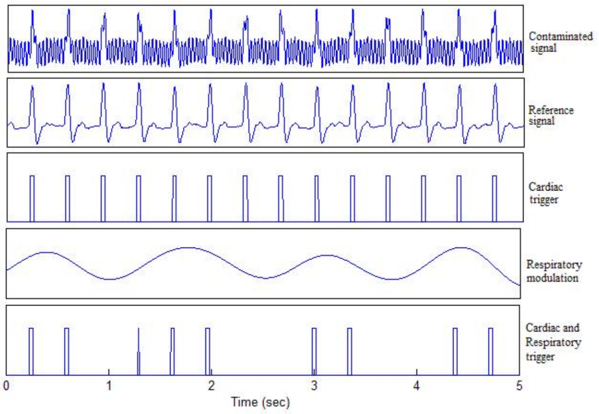

Figure 3: Synchronization signal extraction: *Cardiac and respiratory trigger from a mouse ECG recorded during the FSE sequence.*

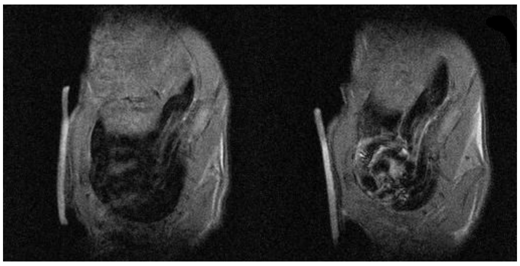
(a) (b)

Figure 4: Mouse cardiac MRIs acquired with an IRSE sequence: (a) with no synchronization, (b) with cardiac and respiratory gating

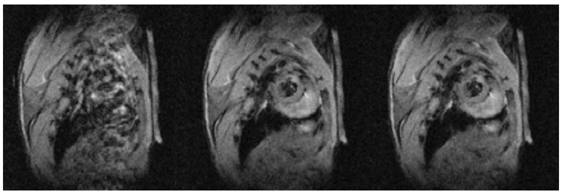
(a) (b) (c)

Figure 5: Mouse cardiac MRIs acquired with a GE sequence: (a) with no synchronization, (b) with cardiac gating, (c) with cardio-respiratory gating.

Respiration signal prediction to avoid setbacks: Due to the narrow bandwidth of the low pass filter, the respiratory signal is greatly delayed. However, given that the respiration is somewhat periodic, the delay was compensated by a prediction of the upcoming signal along a period which value is continuously updated.

Adaptive improvement: For images which acquisition takes a relatively long time to complete, better results would be obtained when the filter coefficients are recalculated during the synchronization operation and updated every few minutes, in order to adapt the processing to the signal changes.

Conclusions

Cardiac and respiratory synchronization is essential for achieving good quality cardiac MR images. However the perturbation of the ECG signal acquired in the NMR environment, especially during small animal imaging, greatly obstructs gating tasks.

In this work, a method for triggering MR imaging sequences on cardiac and respiration rate is presented. An adapted filtering, based on wavelet sub-band decomposition, is applied to the contaminated simultaneously recorded ECG to rid it of the NMR environment artefacts while emphasizing the QRS peaks. This allows the extraction of a cardiac trigger that is completely synchronized with the heart beats.

In addition, based on the fact that the amplitude of the ECG varies according to respiration motions, a demodulation of this "cardiac respiratory" signal yields a respiration curve which is used to build the respiratory triggering signal. A final trigger is then obtained by combining both cardiac and respiratory triggers and used for MRI gating. The algorithm has proven great efficiency for small rodents' cardiac imaging. The trigger extraction was almost flawless and the image quality was greatly enhanced.

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