Improved Cardiac Triggering by Combining Multiple Physiological Signals: A Cardiac MR Feasibility Study at 7.0 T

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Introduction:

In current clinical cardiovascular MR (CMR) practice cardiac motion is commonly dealt with using ECG based synchronization. However, ECG is corrupted by magneto-hydrodynamic (MHD) effects in magnetic fields [1]. This leads to artifacts in the ECG trace and evokes severe T-wave elevations, which might be misinterpreted as R-waves resulting in erroneous triggering. At (ultra)high field strengths, the propensity of ECG recordings to MHD effects is further pronounced [2, 3]. Pulse oximetry (POX) being inherently sensitive to blood oxygenation provides an alternative approach for cardiac gating. However, due to the travel time of the blood the peak of maximum oxygenation and hence the trigger is delayed by approx. 300 ms with respect to the ECG's R-wave. Also the peak of maximum oxygenation shows a jitter of up to 65 ms [1]. Alternative triggering approaches include acoustic cardiac triggering (ACT) [2]. In current clinical practice cardiac gating / triggering commonly relies on using single physiological signals only. Realizing this limitation this study proposes a combined triggering approach which exploits multiple physiological signals including ECG, POX or ACT to track cardiac activity. The feasibility of the coupled approach is examined for LV function assessment at 7.0 T. For this purpose, breath-held 2D-CINE imaging in conjunction with cardiac synchronization was performed paralleled by real time logging of physiological waveforms to track (mis)synchronization between the cardiac cycle and data acquisition. Combinations of the ECG, POX and ACT signals were evaluated and processed in real time to facilitate reliable trigger information.

Methods:

The proposed combined triggering approach is designed to meet the requirements of reliable synchronization of image acquisition with the cardiac cycle. It uses (i) the ECG´s R-wave or the phonocardiogram's first heart tone for triggering and (ii) a blanking signal derived from POX to suppress the ECG´s T-wave or the phonocardiogram´s second heart tone. The suggested approach comprises three main components: (i) input stage with two analog to digital converters, (ii) a real time signal processing unit which embodies threshold detection algorithms, and (iii) a coupler unit to the MRI system. The setup does not require any hardware or software changes on the scanner, since external hardware is used (ECG&POX: Medrad Veris 8600 patient monitor (MEDRAD, Warrendale, USA); ACT: EasyACT (MRI.TOOLS GmbH, Berlin, Germany)). To assess the performance of combined triggering two series of measurements were conducted: (i) combination of ECG and POX and (ii) combination of ACT and POX. For comparison traditional ECG gated acquisitions were performed. Cardiac images were acquired in healthy volunteers using a 7.0 T whole body MR system (Siemens Healthcare, Erlangen, Germany). A retrospectively triggered 2D CINE FLASH sequence (TE=2.7 ms, TR=5.4 ms, matrix=256x232, receiver bandwidth 445 Hz/pixel, FOV=(326 x 360) mm^2, 25 cardiac phases, slice thickness 4 mm) was applied together with a dedicated 16-element TX/RX cardiac coil array [4]. Traditional vector ECG, POX, and ACT were connected to the subjects at the same time in order to record traces of physiological waveforms along with the trigger information simultaneously and processed for synchronization of the measurement.

Results:

The physiological signals ECG, POX and phonocardiogram (Phono) are displayed in Figure 1. Our results showed that POX can be used to blank and unblank the area around the ECG's T-wave or the phonocardiogram's 2nd heart tone. For example, ECG waveforms were susceptible to severe T-wave elevation (marked with open triangles in fig. 1). ECG mis-registration occurred in ECG-triggered acquisitions, which manifests itself in erroneous TTL trigger signals which occur during repolarization of the ventricle. The combined approach using ECG for tracing and POX for blanking provided TTL trigger generated by the ECG's R-wave only as demonstrated in Fig. 2. The combination of the phonocardiogram for tracing and POX for blanking helped to differentiate the first and second heart tone. With this approach reliable TTL pulses were generated for the first heart tone as illustrated in Figure 3. Figure 4 shows cardiac images derived from triggered 2D CINE FLASH acquisitions at 7.0 T using ECG-POX and ACT-POX combinations for blanking and triggering. The images resulting from the coupled approach were found to be free of cardiac motion artifacts. For comparison, ECG gated 2D CINE FLASH images acquired at 7.0 T were found to be susceptible to motion induced blurring due to mis-synchronization between data acquisition and cardiac activity.

Discussion and Conclusions:

This work proposes combined cardiac triggering using multiple physiological signals. The feasibility and applicability of the combined approach have been demonstrated by eliminating the frequently encountered challenge of mis-triggering due to ECG-waveform distortions. Also, the coupled approach using ACT-POX supports the differentiation between the phonocardiogram's first and second heart tone. This feature does not come at an extra cost of extra delays since it is real time. The short latency of the combined approach facilitates prospectively triggered acquisitions. In general, using the characteristics of multiple physiological signals with the coupled approach helps to reduce erroneous trigger recognition resulting from using a single physiological signal only. The combined approach holds the promise to adapt blanking periods to the cardiac activity and hence to the heart rate while conventional approaches commonly use fixed blanking windows.

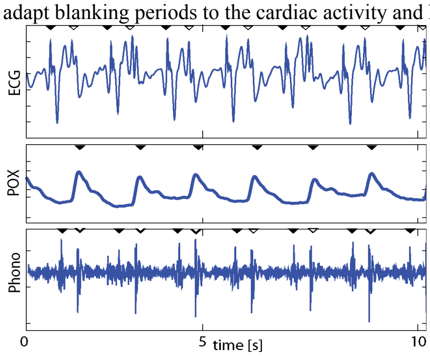

Figure 1: ECG, POX and phonocardiogram signals derived simultaneously from a healthy subject. ECG is corrupted by magneto-hydrodynamic (MHD) effects which lead to so called T-wave triggers (open triangles) in addition to the wanted R-wave triggers (filled triangles). The phonocardiogram contains two heart tones. Here, ACT was tailored to generate a TTL trigger at the first heart tone. POX trigger occur approx. at the same time as the T-wave and the second heart tone and can be used to blank triggering due to T-waves or due to the second heart tone.

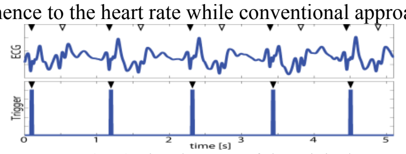

Figure 2: (Top) Signal output of the original ECG wave including valid (filled triangles) and erroneous trigger pulses (open triangles). (Bottom) Trigger output derived from a combination of ECG and POX, whereby POX is used for blanking. The combined approach helps to eliminate the erroneous triggers generated around the ECG's T-wave. Trigger pulses are only generated for the R-wave.

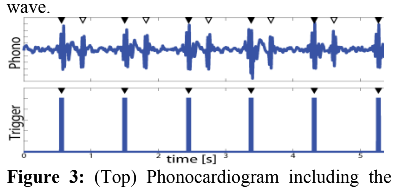

Figure 3: (Top) Phonocardiogram including the first (filled triangle) and the second heart tone (open triangle). (Bottom) With a combination of ACT and POX reliable TTL pulses were generated for the first heart tone.

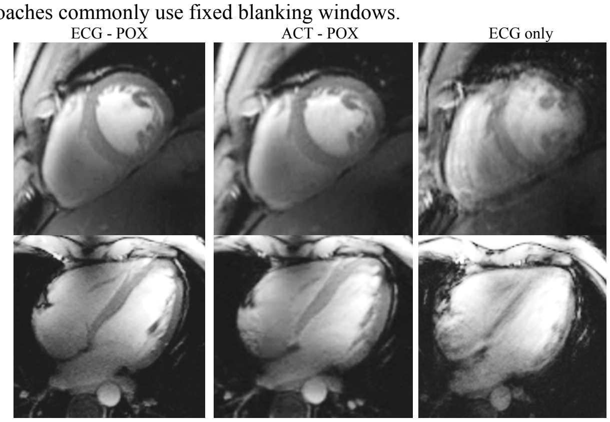

Figure 4: Short axis views and four chamber views of the heart. Data were obtained at 7.0 T using ECG - POX (left), ACT - POX (mid) combinations and ECG only (right) for 2D CINE FLASH acquisitions. ECG – POX and ACT – POX triggered CINE imaging provided faultless trigger recognition for the ECG's R-wave and the phonocardiogram's 1st heart tone and hence produced images free of motion artifacts, while traditional ECG gated 2D CINE FLASH images acquired at 7.0 T were found to be susceptible to motion induced blurring due to mis-synchronization between data acquisition and cardiac activity.

References: [1] Frauenrath, T. et al., J Cardiovasc Magn Reson 12 (1): 67 (2010), [2] Frauenrath T. et al., Invest Radiol 44 (9): 539-547 (2009), [3] von Knobelsdorff-Brenkenhoff, F. et al., Eur Radiol 20 (12): 2844-2852 (2010), [4] Thalhammer C. et al., ISMRM Proceedings #1512, Montreal, (2011)