

Assessment of Accuracy and Reproducibility of ECG, Pulse Oximetry and Phonocardiogram Gating of Cardiac MRI at 7T

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Introduction:

In current clinical cardiac MR, cardiac motion is been addressed by synchronization strategies exploiting pulse oximetry (POX) or ECG. At (ultra)high magnetic fields the artifact sensitivity of ECG recordings increases. This bears the risk of R-wave mis-registration which has been consistently reported for ECG triggered CMR at 7.0 T [1-3]. Realizing the constraints of conventional ECG, acoustic cardiac triggering (ACT) which uses the phonocardiogram has been proposed [4-5]. The clinical ACT has not been carefully examined yet. For this reason, this work scrutinizes the suitability, accuracy and reproducibility of ACT for CMR at 7.0 T. For this purpose, the trigger reliability and trigger detection variance derived from ECG, POX and ACT signal waveforms are examined together with an qualitative and quantitative assessment of image quality derived from 2D CINE acquisitions of the heart at 7.0 T using ECG, POX and ACT cardiac gating.

Method:

Assessment of ACT, ECG and POX trigger reliability builds on the analysis of signal waveforms recorded on a 7T MR system (Siemens Magnetom, Erlangen, Germany). For all subjects (n=9) vector ECG, POX and ACT were connected to record waveforms along with the trigger information simultaneously. This information was recorded together with the trigger detection tickmarks generated for ECG, POX or ACT triggering by the scanners monitoring unit. Respiratory traces were recorded simultaneously. Three sets of breath-held 2D CINE FLASH acquisitions of the heart were performed for each subject including ACT, ECG and POX based cardiac gating. Off-line analysis of the log-files was performed using LabVIEW (National Instruments, Austin, TX, USA) using a customized post-processing algorithm which includes: (i) Identification of breath hold periods using the respiratory trace. (ii) Segmentation and temporal realignment: The ECG waveform was segmented into individual RR intervals by using cross correlation between RR intervals. Temporal realignment was used to overcome the potential bias of (erroneous) trigger detection provided by the scanners output. (iii) Reassignment of the trigger detection tickmarks derived from the scanners CPMU to the realigned ECG, POX and ACT traces and assessment of the trigger variance across the cardiac cycle. (iv) Calculation of the mean value and the standard deviation of the R-R interval length for ECG, POX and ACT as an objective measure for trigger reliability. (v) Calculation of the offset between the ECG's R-wave and the trigger detection moment derived from the ECG, POX and ACT waveform as an objective measure for trigger reliability. For image quality (IQ) assessment overall quality of end-diastolic and end-systolic images was rated using a scale ranging from 0 to 3: 0) images with poor/non-diagnostic quality due to cardiac motion artifacts, 1) IQ impaired by cardiac motion which may lead to misdiagnosis, 2) good IQ, cardiac motion artifacts hard to recognize and 3) excellent IQ, no cardiac motion artifacts observed. Endocardial border sharpness (EBS) of the 2D CINE FLASH images derived from ACT, ECG and POX triggered acquisitions was determined using a dedicated algorithm [6].

Results:

ECG was susceptible to severe distortions at 7.0 T. POX and ACT provided waveforms free of interferences from electromagnetic fields or from magneto-hydrodynamic effects. Frequent R-wave mis-registration occurred in ECG-triggered acquisitions with a failure rate of up to 30 % resulting in cardiac motion induced artifacts as illustrated in Fig.1. ECG trigger mis-registration was not equally distributed across the entire cardiac cycle but occurred at cardiac phases with large amplitude or up-slope in the ECG waveform including (i) an initial peak which covers the R-wave and (ii) major waveform distortions at systole and end-diastole as illustrated in Fig. 2. In comparison, ACT and POX triggering produced images free of cardiac motion artefacts. The standard deviation of the RR interval length, which is a measure of the trigger detection accuracy is shown in Fig. 3. A close match in the standard deviation of the RR interval length derived from the assessment of the ECG, ACT and POX waveforms signifies correct trigger detection while a significant difference indicates trigger (mis)registration at cardiac phases other than that which mark the onset of cardiac activity. Four out of nine healthy subjects showed a standard deviation for the cardiac cycle derived from ECG waveforms which was at least 1.5 times larger ($SD_{ECG} \geq 1.5 \cdot SD_{ACT}$) than that obtained from ACT or POX waveforms. Image quality assessment showed that ACT substantially improved image quality as compared to ECG (image quality score at end-diastole: $ECG=1.7 \pm 0.5$, $ACT=2.4 \pm 0.5$, $p \text{ value}=0.04$) while ECG vs. POX gated acquisitions showed no significant differences in image quality (image quality score: $ECG=1.7 \pm 0.5$, $POX=2.0 \pm 0.5$, $p \text{ value}=0.34$). In case of faultless gating the EBS analysis revealed similar results for all synchronization techniques. ECG gated acquisitions showed an average EBS of (2.2 ± 0.3) pixels. ACT gated acquisitions yielded an average EBS of (2.1 ± 0.2) pixels, and POX gated acquisitions showed an average EBS of (2.1 ± 0.2) pixels. In case of erroneously ECG gated acquisitions EBS analysis was challenging due to heavily reduced blood and myocardium contrast caused by severe signal blurring across the endocardial border.

Discussion and Conclusions:

The intrinsic insensitivity of ACT to interference from electro-magnetic fields renders it suitable for cardiac gated MR at 7.0 T. ACT's trigger reliability was found to be superior to that of ECG and pulse oximetry. The efficacy and reliability of ACT was demonstrated by eliminating the frequently-encountered difficulty of mis-triggering due to ECG-waveform distortions or temporal jittering in pulse oximetry synchronization.

References:

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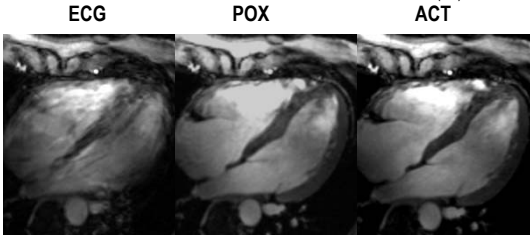


Fig. 1: 4 chamber, long axis views of the heart derived from left) ECG, middle) POX and right) ACT gated 2D CINE FLASH acquisitions at diastole using a 7.0 T MR system together with a 16 channel TX/RX surface coil array. In this example, ECG triggered CINE imaging was prone to severe cardiac motion artifacts (left) due to R wave mis-registration which induced reduction in myocardium/blood contrast and image sharpness. ACT provided images free of cardiac motion artifacts.

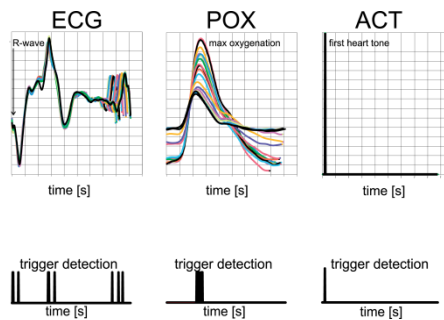


Fig. 2: Signal waveforms obtained from a single subject over 18 cardiac cycles after temporal realignment together with the trigger recognition tickmarks provided by the scanner. In this example vector ECG showed severe R wave mis-registration. ACT provided faultless trigger detection. Please note the scatter in the POX peak amplitude and peak width, causing a jitter ($\Delta t=72 \text{ ms}$) in the pulse oximetry trigger detection which constituted a synchronization problem.

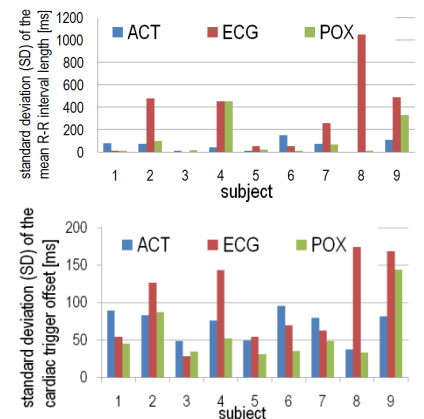


Fig. 3: top: SD of the mean R-R interval lengths deduced from the signal waveforms of ECG, POX and ACT triggered acquisitions. A significant difference in the SD of the R-R interval length deduced from ECG, ACT and POX waveforms indicates trigger mis-registration. bottom: SD of the cardiac trigger detection offset between the trigger recognition moments provided by the scanners CPMU and the trigger detection moments obtained after temporal realignment and reassignment of ECG, POX and ACT signal waveforms. A large SD of the offset between the ECG's R-wave and the trigger detection moment indicates trigger mis-registration.