Optical ballistocardiography for gating and patient monitoring during MRI: an initial study

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Abstract

During magnetic resonance imaging (MRI), information about the cardiac activity is required for gating in cardiovascular MRI (CMR) and for patient monitoring. This can be achieved using electrocardiogram (ECG) signals. However, ECG signals are affected by the different magnetic fields of the MR scanner which can hamper the R-peak detection. Ballistocardiograms (BCG) are an alternative method to gather information about cardiac activity and the cardiac cycle.

For this study, displacement BCGs were acquired from four healthy subjects using a Moiré phase tracking system. Velocity BCGs were derived from the displacement BCGs. Both BCG types were evaluated with respect to their usage during MRI for gating and monitoring purposes. Simultaneously acquired 12-lead ECGs were synchronised with the BCG signals and used as a gold standard reference. R-peaks in the ECG and corresponding J-peaks in the BCG were annotated and used for the evaluation.

Average delays between the R- and J-peaks of 237 ms to 275 ms and of 167 ms to 230 ms occurred in the displacement and velocity BCGs of the different subjects. The jitter of the BCG's J-peaks ranged from 7 ms to 22 ms. Average heart rates estimated from the BCGs agreed with those obtained from the ECG signals. BCG measurements were shown to be sensitive to macroscopic motion artefacts.

Heart rate monitoring using the optical BCG is feasible but needs to be validated with arrhythmic patients. Further experiments are required to investigate how the jitter of the BCG affects retrospectively gated CMR sequences.

Keywords—**BCG, ECG, Gating, HRV, MRI, Patient monitoring**

1. Introduction

Measuring a patient's cardiac activity during magnetic resonance imaging (MRI) is required for gating in cardiovascular magnetic resonance (CMR) or functional magnetic resonance imaging (fMRI) and for patient monitoring [1, 2]. Gating is required to synchronize the cardiac phase with the acquisition of MR data. Monitoring during MRI is required for patients who are in a critical health condition, who are under anaesthesia or for patients undergoing a cardiac stress MRI utilizing drugs such as adenosine or dobutamine [2, 3]. Both, gating and monitoring, can be usually achieved using R-peak obtained from the electrocardiogram (ECG). One main challenge for R-peak detection during MRI is the magnetohydrodynmic (MHD) effect which is caused by the flow of blood perpendicular to the MR scanner's static magnetic field [4].

Ballistocardiograms (BCG) could constitute a further alternative for cardiac gating and patient monitoring during MRI. BCGs measure the repetitive mechanical body movements which are caused by the ejection of blood into the major blood vessels [5]. Camera based systems are one way to acquire BCGs during MRI by measuring microscopic head movements [6]. Such techniques are used to compensate head movements during high-resolution MRI scans of the brain [7].

This work investigates the relation between optical BCG and 12-lead ECG signals acquired in an MR scanner. Based on the delay and the variation between both measurements it is analysed if an optically acquired BCG signal is suitable for CMR gating purposes or for patient monitoring during MRI.

2. Material and Methods

2.1. Signal acquisition

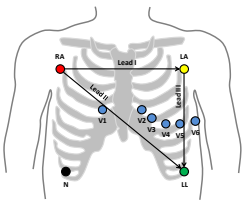
All ECG and BCG records were acquired from four healthy subjects (three male, one female; aged between 25 and 30 years) inside a 3 T MRI scanner (Magnetom Skyra, Siemens, Germany). MRI imaging was switched off during the experiments. 12-lead ECGs were acquired with a portable Holter ECG device (Cardiomem CM3000-12, GETEMED, Germany) with a sampling rate of 1024 Hz, a resolution of 12 bit, an input voltage range of ± 6 mV and

an analogue bandwidth ranging from 0.05 Hz to 100 Hz. The ECG electrode configuration used during the experiments is shown in Fig.1a.

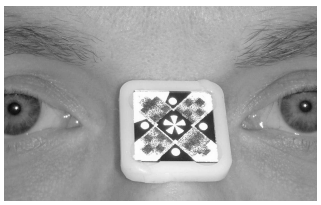
An MR-compatible camera system (MT 384ib, Metria Innovation, USA) was used to measure head movements. The camera was attached in the center of the bore facing directly downwards on the subject's head. A moiré phase tracking (MPT) marker was attached to the nasal bridge as depicted in Fig. 1b. The MPT marker allows the measurement of six degrees of freedom [6]. Images of the marker were acquired with a frame rate of 63 fps or 85 fps and an exposure time of 300 µs. Compared to respiratory movements and other types of head motion, BCG induced movements are relatively small. To avoid additional movements which could superimpose the BCG induced movements, the head of the subject was placed inside a multichannel head coil and was fixated with a cushion.

2.2. Signal preprocessing and annotation

R-peak detection in the ECG signals was performed using a method based on independent component analysis (ICA) [8]. The camera signal was linearly interpolated and equidistantly resampled with a frequency of 256 Hz. In order to suppress respiratory signal components from the acquired camera signals, a 1st order elliptical high pass filter with a cutoff frequency of 0.5 Hz was used. The filtered version of this signal is referred to as the BCG signal. Two different versions of the BCG signal were defined: *1)* the displacement BCG and *2)* the velocity BCG. The former one is the signal which was measured by the camera and corresponds to the displacement of the marker along the head-feet-direction. The latter one was obtained by taking the temporal derivatives of the displacement BCG. The first maxima in the displacement BCG signal occurring 150 ms to 300 ms after the ECG's QRS complex were annotated as J-peaks [9]. One J-peaks was defined for the displacement BCG (J_d) as depicted in Fig. 2a. To keep the notation simple, two different J-peaks were defined for the velocity BCG ($J_{v,1}$ and $J_{v,2}$) as it is shown in Fig. 2b.

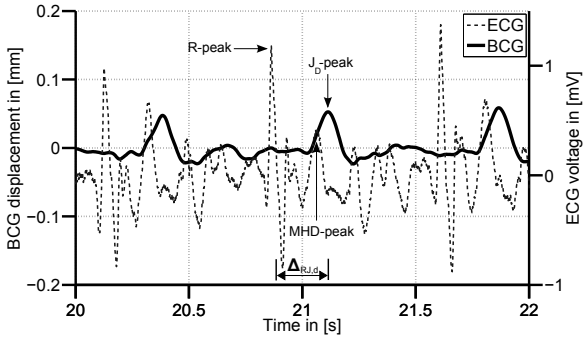


(a) Electrode positions of the 12-lead ECG.

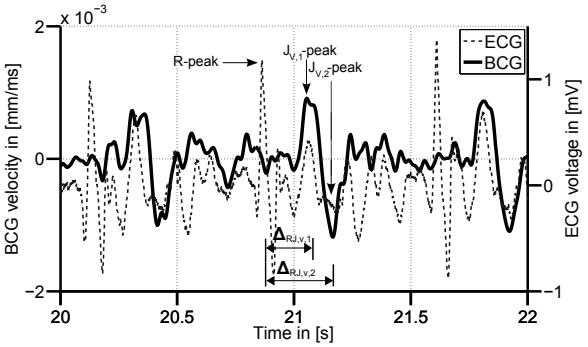


(b) MPT marker placed on nasal bridge of one subject.

Figure 1: Experimental setup for the ECG and the BCG measurements.



(a) ECG lead II and displacement BCG_d. The J_d-peak was used for the analysis.



(b) ECG lead II and velocity BCG_v. Both, the $J_{v,1}$- and $J_{v,2}$-peaks were used for the analyis.

Figure 2: Exemplary measurements of ECG lead II synchronised with the BCG_d (a) and the BCG_v (b) signals. The ECG is contaminated by MHD signals which are caused by the flow of blood perpendicular to the static magnetic field.

2.3. Evaluation

For possible applications such as gating in CMR, the delay $\mu_{\Delta_{RJ}}$ and jitter$\sigma_{\Delta_{RJ}}$ between the ECG's R-peak and the corresponding J-peaks play an important role. The delay $\mu_{\Delta_{RJ}}$ was defined as the average difference between the positions of corresponding R-peaks and J-peaks. Mean heart rates (HR) were estimated for each subject based on the ECG and BCG signals.

The morphology of the optically acquired BCG signals was investigated qualitatively in order to determine possible error sources for future applications. Artefacts in the BCG signal which can be caused by macroscopic head movements were considered as well.

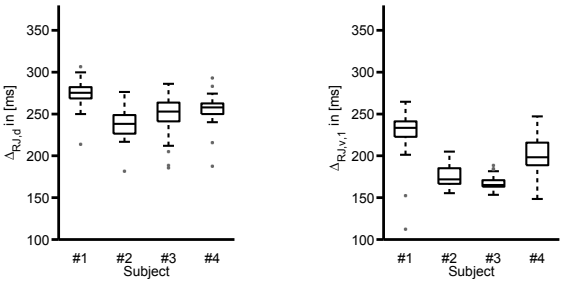
3. Results

Figure 2 depicts the relation between the displacement and velocity BCG time series and the ECG signal. The ECG

Table 1: Delays between the ECG's R-peaks and the manually annotated J_d- and J_v-peaks in the BCG. For a physiologically correct delay between the R-peaks and J-peaks, the delay introduced by the camera needs to be subtracted from the measured delays $\mu_{\Delta_{RJ}}$.

Subject		Displacement BCG		Velocity BCG, 1st peak			Velocity BCG, 2nd peak			Camera	
#	HR_{ECG} [bpm]	$\mu_{\Delta_{RJ,d}} \pm \sigma_{\Delta_{RJ,d}}$ [ms]	HR_{BCG_d} [bpm]	$\mu_{\Delta_{RJ,v,1}} \pm \sigma_{\Delta_{RJ,v,1}}$ [ms]	$\mu_{\Delta_{RJ,v,1}}$ - $\mu_{\Delta_{RJ,d}}$ [ms]	HR_{BCG_v} [bpm]	$\mu_{\Delta_{RJ,v,2}} \pm \sigma_{\Delta_{RJ,v,2}}$ [ms]	$\mu_{\Delta_{RJ,v,2}}$ - $\mu_{\Delta_{RJ,d}}$ [ms]	HR_{BCG_v} [bpm]	Delay [ms]	Frame rate [fps]
1	69	275 ± 11	69	230 ± 18	-45	69	328 ± 10	54	69	19	85
2	56	237 ± 21	56	175 ± 12	-62	56	297 ± 22	60	56	23	63
3	67	250 ± 19	67	167 ± 7	-83	67	298 ± 20	48	67	22	63
4	82	256 ± 13	82	202 ± 19	-54	82	303 ± 12	46	82	23	63

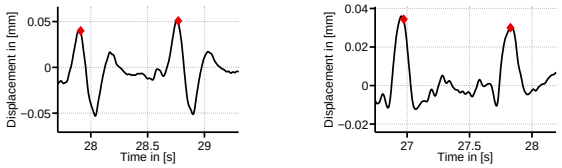
bpm: beats per minute; HR_{ECG}: mean HR estimated from the ECG; $\mu_{\Delta_{RJ}}$ and $\sigma_{\Delta_{RJ}}$: mean delay and jitter between the R-peak and the J-peak; HR_{BCG}: mean HR estimated from the BCG.



(a) Delays between the R-peaks and the J_d-peaks.

(b) Delays between the R-peaks and the $J_{v,1}$-peaks.

Figure 3: Box-Whisker plots of the delay between the ECG's R-peaks and the corresponding J_d-peaks in the displacement BCG (a) and the $J_{v,1}$-peaks of the velocity BCG (b).



(a) Morphology of the BCG signal in subject #1.

(b) Morphology of the BCG signal in subject #4.

Figure 4: BCG signal morphology of different subjects. In subject #1, a head-ward movement is followed by a feet-ward movement (a) whereas the BCG of subject #4 is dominated by a head-ward movement.

is contaminated by the MHD effect since it was acquired inside the MR scanner. In the given example, the J_d-peak reached its maximum 250 ms after the R-peak. In the velocity BCG depicted in Fig. 2b, the first derivative caused a shift of the J_d-peak in the negative time direction. The delay between the R-peak and the $J_{v,1}$-peak was 190 ms which corresponds to a decrease of 60 ms. The $J_{v,1}$-peak coincides with one of the peaks caused by the MHD effect. Table 1 gives a detailed summary of the estimated parameters for all datasets. High inter-subject variations of the delay times $\mu_{\Delta_{RJ,d}}$, $\mu_{\Delta_{RJ,v,1}}$ and $\mu_{\Delta_{RJ,v,2}}$ were observed. Variations of the delay times are summarized in the Box-Whisker plots shown in Fig. 3. The mean heart rate was correctly estimated in all datasets by the two different BCG methods. The morphology of the BCG signal of two different subjects is depicted in Fig. 4.

4. Discussion

Regarding the clinical applications, a precise R-peak or J-peak detection is important for gating in CMR. The ECG signal provides a reliable method for gating CMR sequences up to 3 T. In contrast to the ECG's R-peaks, the J-peaks of the BCG show a higher variation or jitter. The jitter of the manually annotated BCG signal itself is higher than the automated R-peak detection in a severely distorted ECG signal as shown in a previous study [8]. This can be partly explained by the morphological variability of the BCG signal as it is depicted in Fig. 5. A minimum delay of 167 ms was observed for J-peak the velocity BCG with respect to the R-peak. This limits the applicability of the BCG for prospective gating purposes in CMR.

Besides gating, patient monitoring during MRI is another important application for measuring the cardiac activity. The same average heart rates could be obtained from the ECG and BCG signals. However, this study was restricted to healthy subjects. It is not clear how arrhythmic episodes affect the optical BCG signal. Since arrhythmias can change the cardiac output or stroke volume, e. g. during ventricular extrasytoles, it can be expected that the optical BCG signal varies as well. To ensure patient safety during MRI, the detection of cardiac arrhythmias is mandatory. Additionally, the quality of CMR images depends on the detection of arrhythmic periods. Hence, a reliable patient monitoring and gating is only possible if cardiac arrhythmias can be observed and automatically detected from the optical BCG signal.

Varying morphologies of the BCG signals were ob-

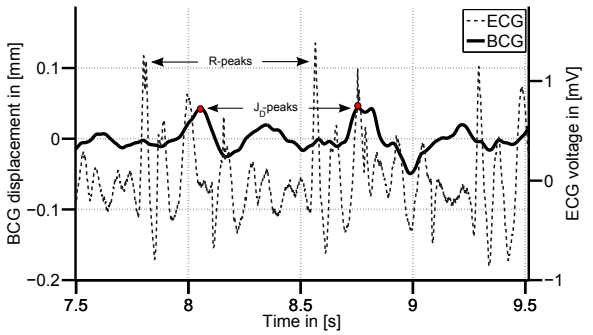


Figure 5: Different BCG signal morphologies lead to different delay times between the R-peaks and the corresponding BCG-peaks. In this example, there was a delay of 250 ms between the first and a delay of 186 ms between the second pair of these peaks.

served in the different subjects as it was depicted in Fig. 4. Although the peaks could be clearly identified during the manual annotation procedure, the different morphologies could hamper the peak detection using automated algorithms.

5. Conclusion

The optically acquired BCG signals enable a sophisticated, non-contact measurement of the cardiac's mechanical activity. Several parameters were studied using the simultaneous measurements of 12-lead ECGs and the optical BCGs acquired from four healthy subjects. Due to the high delay between the ECG's R-peak and the BCG's J-peak, the BCG signal is not suitable for prospective gating in CMR applications. For prospectively gated sequences, the ECG's R-peak is still predestinated because it occurs prior to the ventricular systole. The present study showed that the BCG enables a correct estimation of the average heart rate.

Future work will compare ECG- and BCG-gated (prospectively and retrospectively) CMR images in order to draw final conclusions with respect to the achieved CMR image quality. Arrhythmic subjects will be included in an additional study to investigate if cardiac arrhythmias can be detected from the optical BCG.

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