A Novel Method for Contact-Free Cardiac Synchronization Using the Pilot Tone Navigator

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Synopsis

We evaluate the information content of externally generated Pilot Tone signals, received with standard MR local coils, with respect to cardiac motion. Free-breathing and breathhold fluoroscopic measurements were performed with applied electrocardiogram leads to provide ground truth. Average mean correlation between RR intervals of our method and the ground truth was 0.95. Our early results indicate that locally generated PT signals contain information about cardiac motion and suggest that the proposed method could be developed into an electrocardiogram replacement by providing a continuous signal for retrospective gating with minimal hardware requirements.

Introduction

In cardiac MR imaging, prospective electrocardiogram (ECG) triggering and retrospective ECG gating are the established techniques to synchronize measurements to the patient's cardiac cycle. However, ECG placement takes time, inconveniences the patient and requires additional materials, e.g. electrodes. We propose a method for ECG-free detection of heartbeats, equivalent to detecting the pulse signal. Our method is based on the Pilot Tone (PT) navigator proposed by Speier et al. [1] for respiratory motion tracking. Our contributions comprise hardware improvements for the signal generator as well as an algorithm for automated heartbeat evaluation in the PT signal.

Methods

The PT signal is generated by an independent continuous-wave radio frequency (RF) source and is received by the standard MR local coils. Its modulation can be processed to extract respiratory and cardiac information. We designed a small, battery-driven autonomous RF source to replace the signal generation setup used in [1], which was located outside the bore of the MR scanner. This new transmitter generates the RF signal by means of a free-running crystal oscillator and is protected against disruptive RF pulses of the MR measurement. Thus the hardware can be placed anywhere in the MR bore close to the patient.

Measurements were performed on a 1.5 T MAGNETOM Aera (Siemens Healthcare, Erlangen, Germany) on four volunteers (1 female, age 38 $\pm$ 11), on one of them with ECG ground truth. Multiple acquisitions with different locations and distances to the volunteer (on the anterior coil, on the skin of the volunteer) of the navigator hardware were performed.

Free-breathing and breathhold fluoroscopic measurements (GRE, TR=4 ms, 4 images/s, resolution 2x2x10 mm^3) were performed for different placements of the PT transmitter. The prototype sequence recorded ECG timestamps every TR as ground truth for time after the R peak. A prototype reconstruction program processed PT signals into a navigator matrix containing one value per channel per TR.

Offline processing was performed in MATLAB (MathWorks, Natick, MA, USA).

To separate cardiac and respiratory motion, we adopted the algorithm of Zhang et al. [2] and expanded it to detect cardiac motion directly.

We assume that the cardiac motion is detected by at least one channel, and that at least one other channel contains a mixture of both cardiac and respiratory motion information. The problem of finding the best coils representing the cardiac motion can then be described as maximizing the correlation of R peak ground truth detection and peaks of the PT signal.

The proposed algorithm has the following major steps (visualized in Figure 1):

1. Calculation of the covariance matrix $C(i,j)$, which forms itself of the motion estimated from coil i and j, where X_i and X_j are the measured data of the coils:

$$C(i,j) = \mathrm{cov}(X_i, X_j) = E[(X_i - E[X_i])(X_j - E[X_j])]$$

2. Band-pass filtering to restrict motion information between 0.6 and 4.0 Hz using a Hann filter in frequency domain to construct $P(i, j)$.

3. Construction of a threshold reduced matrix $M(i, j)$, according to a threshold operator described as follows:

$$M(i,j) = \begin{cases} 1, & \text{if } |P(i,j)| \geq t \\ 0, & \text{otherwise} \end{cases}$$

4. Identification of existing correlations in M smaller than the threshold in $C(i, j)$.

$$R(i,j) = \begin{cases} 1, & \text{if } M(i,j) \geq 0 \text{ and } |C(i,j)| \leq t \\ 0, & \text{otherwise} \end{cases}$$

5. Selection of the set of channels $\{i|R(i, j) = 1\}$.

6. Time after the R wave from the PT navigator is determined by peak detection of the mean signal from the remaining coils. Here we selected the next peak after the ground truth R peak.

To validate the quality of the pulse detection, we compared the durations of cardiac intervals from PT navigator (RR_{pt}) with durations from ECG (RR_{ecg}).

Results

Signals consistent with cardiac motion could be detected in all volunteers. Average mean correlation between RR_{pt} and RR_{ecg} was 0.95 $\pm$ 0.038. The slope of the fitted regression line was on average 0.98 (an example is illustrated in Figure 2). A Bland-Altman plot of $RR_{pt} - RR_{ecg}$ (Figure 3) shows that the 95 % limits of agreement line lies slightly below 40 ms. The improvement using our adapted coil clustering can be seen in Figure 4.

Step 3 of the algorithm depends on the threshold parameter t. Good correlation with the ground truth was achieved for all tested transmitter positions for $t = 0.9$ or 0.95 as shown in Table 1.

Conclusion

Our early results indicate that PT signals, locally generated in proximity to the heart, contain information about cardiac motion, and suggest that the proposed method could be developed into an ECG replacement by providing a continuous signal for retrospective gating with minimal hardware requirements.

Acknowledgements

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References

[1] P. Speier *et al*. "PT-Nav: A Novel Respiratory Navigation Method for Continuous Acquisition Based on Modulation of a Pilot Tone in the MR-Receiver". Proc. ESMRMB 129:97-98. 2015. doi: 10.1007/s10334-015-0487-2.

[2] T. Zhang *et al.* "Robust self-navigated body MRI using dense coil arrays.". Magn Reson Med. 2015. doi: 10.1002/mrm.25858. [Epub ahead of print]

Figures

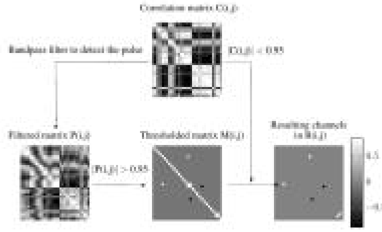


Figure 1: Detection of the channels containing the heartbeat. Bandpass filtering the covariance matrix $C(i, j)$ generates the filtered matrix $P(i, j)$. The channels where $|P(i, j)|$ is bigger and $|C(i, j)|$ is smaller than the threshold are selected for further processing.

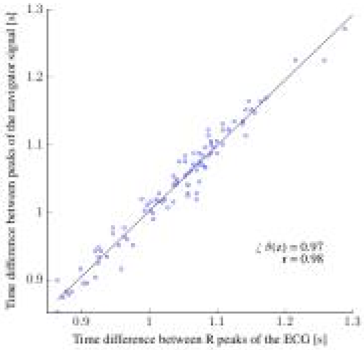


Figure 2: Scatter plot of the RR_{pt} against RR_{ecg} of one volunteer measurement with a fitted regression line. The correlation of the RR intervals amounts to 0.98 and the slope of the regression line constitutes 0.97.

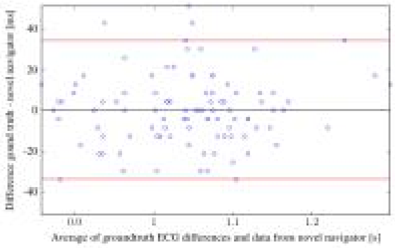


Figure 3: Bland-Altman plot of the RR_{pt} from our peak detection in comparison to the RR_{ecg} from the ECG ground truth.

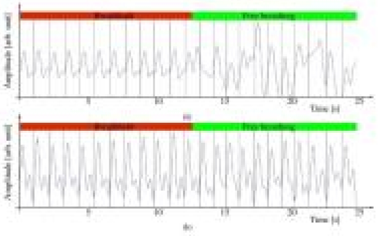
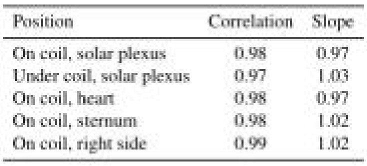


Figure 4: Mean signal of all navigator channels with and without breath holding (a). Mean signal of the resulting channels of our proposed algorithm (b). The time delay of the peak in the navigator data to the R peak and the form of the wave correlate well with the systolic phase.



Position	Correlation	Slope
On coil, solar plexus	0.98	0.97
Under coil, solar plexus	0.97	1.03
On coil, heart	0.98	0.97
On coil, sternum	0.98	1.02
On coil, right side	0.99	1.02

Table 1: Correlation with ground truth and slope of the regression line dependent on different locations.