Feasibility Study: Free-Breathing 3-D CINE Imaging with Respiratory Gating Based on Pilot Tone Navigation

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Synopsis

Respiratory monitoring during continuous, free-breathing acquisitions is challenging. Using self-navigation, a respiratory signal can be derived from the imaging data, but requires frequent sampling of the k-space center. Pilot Tone navigation promises continuous respiratory monitoring independent of the imaging sequence. In this feasibility study, we compared both strategies for free-breathing 3-D CINE imaging. We found good agreement between both respiratory signals, and an excellent match in both reconstructed images and computed ventricular function parameters. Pilot Tone navigation can thus be considered an alternative to self-navigation, with the benefit of working with arbitrary imaging sequences.

Introduction

The measurement of a respiratory signal for free-breathing acquisitions is necessary in order to address respiratory motion during reconstruction. This is especially challenging for continuous acquisitions, e.g. 3-D CINE imaging, where there is no time to acquire dedicated data for an image-based navigator. Respiratory bellows are feasible, but have limited precision [1]. The self-navigation principle [2] reuses imaging data to compute a respiratory signal, but requires a specialized acquisition sequence that frequently samples the k-space center. The recently introduced Pilot Tone (PT) navigator [3] allows the acquisition of a continuous respiratory signal independent of the image acquisition. In this feasibility study, we compare its performance to a self-navigation based approach for free-breathing 3-D CINE imaging.

Methods

Free-breathing 3-D CINE imaging was performed in one healthy volunteer (male, age 26) on a $1.5\,\mathrm{T}$ clinical MR scanner (MAGNETOM Aera, Siemens Healthcare, Erlangen, Germany).

As in [3], a commercial signal generator produced a small-amplitude PT with a fixed frequency outside the frequency band of the MR signal, but inside the received frequency band. The PT was transmitted into the magnet bore by a non-resonant pick-up coil taped to the outer cover close to the funnel of the bore. Modulation of the PT received by the local MR coils was processed to characterize respiratory motion. To generate ground truth for the respiratory motion, we acquired sagittal image streams of the right liver dome using standard fluoroscopic sequences (GRE, frame rate: $513\,\mathrm{images}$, $5\,\mathrm{images/s}$, TE $= 2\,\mathrm{ms}$, TR $= 4.5\,\mathrm{ms}$). For every received line and channel, we extracted one PT amplitude value as described in [3].

For CINE imaging, a 3-D volume-selective, ECG-gated, balanced-SSFP prototype imaging sequence with the following parameters was used: TR = $2.8\,\mathrm{ms}$, TE = $1.2\,\mathrm{ms}$, $\alpha = 38^\circ$, FOV = $395 \times 239 \times 122\,\mathrm{mm}^3$, acquired voxel size $1.9 \times 2.1 \times 2.5\,\mathrm{mm}^3$, interpolated to $(1.9\,\mathrm{mm})^3$, temporal resolution $42\,\mathrm{ms}$, fixed acceleration factor of 2.6 compared to the fully sampled matrix and a receiver bandwidth of $1000\,\mathrm{Hz/Px}$. For signal reception, $18 + 12$ elements of an anterior + posterior local coil matrix were used. Respiratory gating was then performed using two methods, based on k-space center lines acquired repeatedly during the scan using the self-navigation principle [2] and on the signal from the PT navigator. For the PT navigator, ground truth motion of the liver dome over time $\boldsymbol{g}$ from the fluoroscopic calibration images was used in a linear regression model to determine optimal weights $\hat{\boldsymbol{w}}$ from the PT signal over time $\boldsymbol{p}_c$ for each coil $\boldsymbol{c}$ ($\boldsymbol{c} \in [1, C]$) as:

$$\hat{\boldsymbol{w}} = \underset{\boldsymbol{w}}{\operatorname{argmin}} \| \underbrace{[\boldsymbol{p}_1 \ \cdots \ \boldsymbol{p}_C]}_{:=\boldsymbol{P}} \boldsymbol{w} - \boldsymbol{g} \|_2^2 = \boldsymbol{P}^\dagger \boldsymbol{g},$$

where $\boldsymbol{P}^\dagger$ denotes the Moore-Penrose pseudo-inverse of $\boldsymbol{P}$. These weights were then used to compute a respiratory signal $\tilde{\boldsymbol{g}} = \widetilde{\boldsymbol{P}}\,\hat{\boldsymbol{w}}$ from the PT signal $\widetilde{\boldsymbol{P}}$ acquired during the 3-D CINE scan. A flow chart of these steps is given in Figure 1. After respiratory gating, an iterative image reconstruction as described in [4] was performed.

For evaluation, we compared the respiratory signals derived from self-navigation and PT navigation directly, as well as ventricular function (VF) parameters computed in corresponding slices from reconstructions gated with the respective signals.

Results and Discussion

A comparison of the respiratory signals derived from self-navigation and PT navigation is given in Figure 2. The Pearson correlation between both signals is 0.72. Ventricular function parameters for self-navigation (PT navigation) were $144.0\,\mathrm{ml}$ ($141.7\,\mathrm{ml}$) for end-diastolic volume and $67.8\,\mathrm{ml}$ ($69.6\,\mathrm{ml}$) for end-systolic volume. Qualitative results of the 3-D CINE gated with both types of respiratory signals are shown in Figure 3.

Both respiratory signals show a good match. The slight baseline drift of the PT signal is possibly due to sensor heating during the acquisition. For the purpose of gating, local maximum detection instead of a global threshold for end-expiration was used for the PT signal to account for the drift. Both qualitative image comparison and quantitative results show excellent agreement.

Conclusions

We have demonstrated the feasibility of using PT navigation for respiratory monitoring of continuous, free-breathing acquisitions such as 3-D CINE imaging. PT navigation can be used with arbitrary imaging sequences, removing the need to frequently sample the center of k-space and the coupling of the orientation of readouts to the orientation of respiratory motion that can be detected. Additionally, the temporal resolution of the PT navigator is higher, so the respiratory state could be determined for each individual readout. It is also possible to derive a higher-dimensional respiratory signal from the PT navigator, e.g. to differentiate chest and abdominal breathing.

Acknowledgements

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References

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Figures

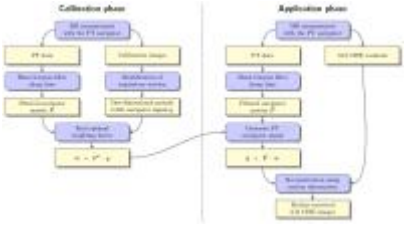

Figure 1: Flow chart of a PT-based free-breathing 3-D CINE acquisition. In the calibration phase, ground truth of the liver dome position is determined from calibration images. The weights for a linear combination of the PT signal that best approximates this ground truth is computed. In the application phase, 3-D CINE data is acquired and the simultaneous PT signal multiplied by the previously determined weights gives a respiratory signal for each readout.

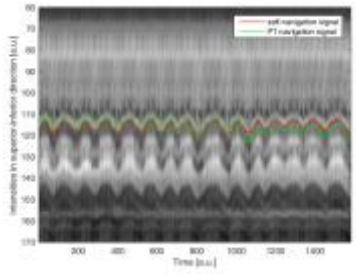

Figure 2: Respiratory self-navigation signal (red) and PT navigation signal (green) plotted over the Fourier transform of k-space center lines, from which the self-navigation signal is derived.

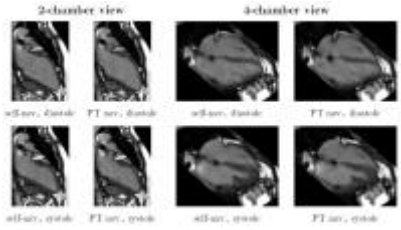

Figure 3: Comparison of self-navigation (odd columns) and PT navigation (even columns) images in 2-chamber view (left columns) and 4-chamber view (right columns) for diastole (first row) and systole (second row).