Two-Dimensional Respiratory-Motion Characterization for Continuous MR Measurements Using Pilot Tone Navigation

Lea Schroeder[1], Jens Wetzl[1,2], Andreas Maier[1,2], Robert Rehner[3], Matthias Fenchel[4], and Peter Speier[4]

[1]Pattern Recognition Lab, Department of Computer Science, Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany, [2]Erlangen Graduate School in Advanced Optical Technologies, Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany, [3]Magnetic Resonance, Research and Development, Hardware, Siemens Healthcare GmbH, Erlangen, Germany, [4]Magnetic Resonance, Product Definition and Innovation, Siemens Healthcare GmbH, Erlangen, Germany

Synopsis

Pilot Tone signals, generated by a commercial signal generator and received with standard MR local coils, were analyzed for multidimensional respiratory information. The ground truth for respiratory motion in two orthogonal directions ($\boldsymbol{g}_{SI}$ and $\boldsymbol{g}_{AP}$), generated by sagittal image streams of the right liver dome using standard fluoroscopic sequences, showed excellent correlation with the PT signal derived from a separate measurement (for $\boldsymbol{g}_{SI}$: 0.90 $\pm$0.13; for $\boldsymbol{g}_{AP}$: 0.82 $\pm$0.21). Our results demonstrate that PT navigation can provide two-dimensional characterization of regular and irregular respiratory motion without interfering with the MR measurement.

Introduction

Respiratory motion reduces cardiac and abdominal diagnostic magnetic resonance (MR) image quality significantly. It remains one of the major challenges for diagnostic MR imaging as well as for many image-guided surgical interventions and treatments in the region of thorax and abdomen. Most respiratory-navigation strategies treat respiratory motion as one-dimensional, limiting robustness and accuracy of navigation in cases of irregular respiration, or pronounced hysteresis. Some MR-signal-based navigation schemes can provide multiple respiratory directions, but interfere with the MR measurement [1,2]. Thus, there is a need for continuous multidimensional characterization of respiratory motion. Recently, a novel Pilot Tone (PT) navigator was proposed by one of the authors [3]. We investigate if the method can provide two-dimensional respiratory information.

Methods

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 magnet bore. The 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 recorded sagittal image streams of the right liver dome using standard fluoroscopic sequences (GRE, 513-1000 images, frame rate: 4-5 images/s, TE: 1-2 ms, TR: 4 ms, posterior spine array + anterior body array). Measurements on 6 volunteers were performed on MAGNETOM Skyra (3T) and MAGNETOM Aera (1.5T) (Siemens Healthcare, Erlangen, Germany). For every received line and channel, we extracted one PT amplitude value using a prototype image reconstruction program as described in [3].

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

Optimal channel combination coefficients $\boldsymbol{w}$ for PT navigators were determined by comparison to image-based ground truth in a separate calibration phase (see Figure 1) as follows: Incoming PT amplitudes were first Hann low-pass filtered (cutoff 0.1-0.5 Hz), yielding the navigator matrix $\boldsymbol{P}$. Optimal weights $\boldsymbol{w}$ were found by solving the least-square optimization problem

$$\boldsymbol{w}(\boldsymbol{g}) = \underset{\boldsymbol{w}}{\operatorname{argmin}} ||\boldsymbol{P} \cdot \boldsymbol{w} - \boldsymbol{g}||_2^2 = \boldsymbol{P}^\dagger \cdot \boldsymbol{g}$$

where $\boldsymbol{P}^\dagger$ is the Moore-Penrose pseudo-inverse of $\boldsymbol{P}$.

Respiratory ground truth signals $\boldsymbol{g}_{SI}$ and $\boldsymbol{g}_{AP}$ were generated from deformation vector fields generated by elastic registration of the calibration images to a key frame by averaging one vector component over manually selected ROIs: the superior-inferior (SI) component $\boldsymbol{g}_{SI}$ from a region centered around the liver dome, and an additional anterior-posterior (AP) component $\boldsymbol{g}_{AP}$ from a region centered on the sternum (see Figure 2).

The resulting weights $\boldsymbol{w}_{SI}$ and $\boldsymbol{w}_{AP}$ were applied in subsequent measurements to generate PT navigators (right side of Figure 1).

We evaluated the quality of the resulting PT navigators $\boldsymbol{g}_{SI}$ and $\boldsymbol{g}_{AP}$ by sorting the calibration images according to the PT navigator values into bins. In the last step, the mean structural similarity index (SSIM [4]) of all images in a given bin is calculated.

Volunteer experiments included model experiments with instructed regular breathing patterns and experiments featuring complex free-breathing patterns.

Results

Over all experiments, PT navigators derived with weights from a separate calibration measurement showed excellent correlation with the ground truth in those directions (for $\boldsymbol{g}_{SI}$: 0.90 $\pm$0.13; for $\boldsymbol{g}_{AP}$: 0.82 $\pm$0.21).

Figure 3 shows PT navigators for instructed interleaved abdominal and chest breathing: The two respiration modes can be clearly distinguished using $\boldsymbol{g}_{SI}$ and $\boldsymbol{g}_{AP}$.

Figure 4 shows PT navigators for a case of irregular free-breathing.

The result of binning and averaging the images according to the PT navigators is shown for the free-breathing example of Figure 4 in Figure 5: The top left image shows the average over all bins, the top column the average over all $\boldsymbol{g}_{SI}$ bins, the leftmost column the average over all $\boldsymbol{g}_{AP}$ bins, all other images are binned according to both navigators. Binning in two dimensions improves image sharpness especially for extreme positions of the diaphragm, as also indicated by higher SSIM values.

Conclusion

Our results demonstrate that PT navigation can provide two-dimensional characterization of regular and irregular respiratory motion without interfering with the MR measurement and should thus be considered as an promising alternative to established navigation methods.

Acknowledgements

The MATLAB module for elastic registration was kindly provided by Marie-Pierre Jolly (Imaging and Visualization Department of the Siemens Corporate Research from Princeton).

The authors gratefully acknowledge funding of the Erlangen Graduate School in AdvancedOptical Technologies (SAOT) by the German Research Foundation (DFG) in the framework of theGerman excellence initiative.

References

[1] T. Nguyen *et al.* A novel navigator technique for fast and direct detection of 3D displacement of the coronary arteries. In Proc. 9th Annu. Meeting ISMRM,173, 2001.

[2] M. Lustig *et al*. Butterfly: a self navigating Cartesian trajectory. In Proceedings of the Joint Annual Meeting ISMRM-ESMRMB, Berlin, Germany, 865, 2007.

[3] 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. ESMRMB, 129:97–98, 2015. doi: 10.1007/s10334-015-0487-2.

[4] Z. Wang *et al.* Image quality assessment: from error visibility to structural similarity. Image Processing, IEEE Transactions on, 13(4):600–612, 2004.

Figures

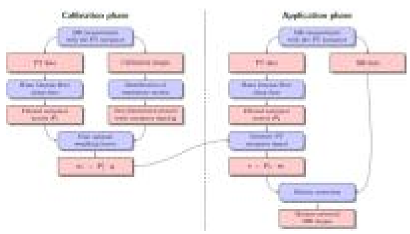

Figure 1: Flowchart for the motion correction algorithm based on the PT signal. In a calibration phase (left), the coefficients for optimal channel combination are determined. The coefficients are then used in the subsequent application phase (right) to generate PT navigators for motion correction.

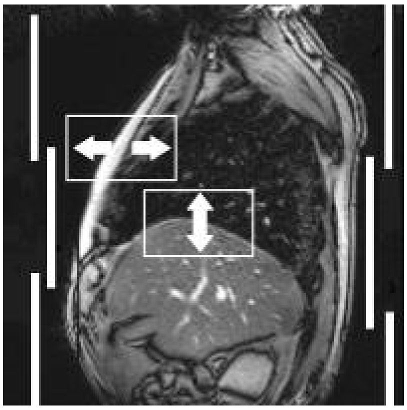

Figure 2: Example calibration image with regions of interest for deformation field analysis. Arrows indicate the analyzed deformation direction, white bars show the local receive coil geometry. Anterior: six elements, posterior: four elements in left-right (LR) direction. Between one and four posterior coils were selected.

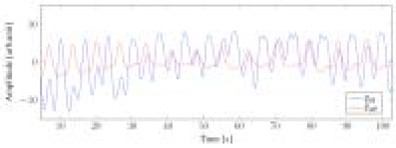

Figure 3: Experiment with alternating breathing direction (sternal and abdominal). The PT signal in AP direction ($\boldsymbol{g}_{AP}$) was optimized based on a ground truth measured with a ROI on the sternum. Ground truth of the SI motion ($\boldsymbol{g}_{SI}$) was calculated from a ROI centered on the liver dome.

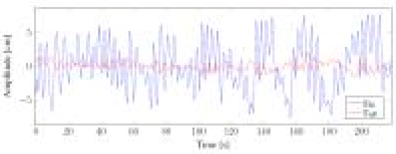

Figure 4: PT navigator signals $\boldsymbol{g}_{SI}$ and $\boldsymbol{g}_{AP}$ of a free-breathing volunteer with irregular respiratory pattern having a correlation with the image-based ground truth of 0.98 for $\boldsymbol{g}_{SI}$ and 0.95 for $\boldsymbol{g}_{AP}$. These signals form the basis for the binning shown in Figure 5.

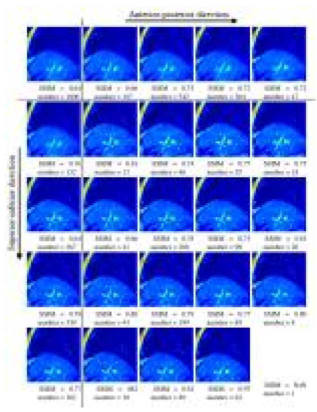

Figure 5: Averages of binned images in two directions. The image seen in the top left is the mean image of all images. The first row (column) represents one-dimensional binning according to the PT navigator $\boldsymbol{g}_{SI}$ ($\boldsymbol{g}_{AP}$). The remaining images are binned in two dimensions. For each bin the average SSIM is given.