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Advanced Navigator Techniques

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Abstract:
The purpose of this study was to investigate and to optimize the performance of the real-time navigator technology on a clinical scanner for use in cardiac imaging. The studies involved experiments performed on phantoms and in vivo. The performance of the 2D RF pulses used for pencil beam excitation was found to be highly sufficient, provided a proper pulse design, accurately trimmed gradients and reasonable pulse parameters were used. The capability of the navigators for free-breathing, real-time gated coronary artery imaging was studied for several volunteers. Using a diaphragmatic gating window of 5 mm a reproducible image quality was achieved. To study spatial and temporal correlations of respiratory motion multiple navigator pulses were applied in different anatomical regions. For the correlation diaphragm-heart strong deviations from the linear model reported in literature were found. The results indicate, that a more complex model, including patient dependent hysteretic effects, might further improve the performance of real-time gating and prospective motion correction.

Keywords: Navigator, coronary artery imaging, real-time gating, 2D RF pulses

Introduction

Respiratory motion can severely deteriorate the image quality of long cardiac-triggered

MR imaging sequences. Therefore, gating based on navigator echoes [1,2] was introduced to reduce these artefacts. By means of a navigator, the position of the diaphragm can be monitored [3] and used as an input for the accept/reject decision of the gating algorithm. Furthermore, the navigator information may be used to perform prospective motion correction like slice-tracking to improve image quality and/or to allow a larger gating window [4]. On the other hand, robust real-time gating makes several demands on the performance of the navigator technique. The displacement of a selected anatomical region has to be monitored with high accuracy and destructive interference of the navigator pulse with the imaging volume has to be avoided. The navigator sequence should be short enough to allow versatile integration into MR imaging protocols. In addition, a fast evaluation of the measured displacements is necessary for real-time gating. Furthermore, an appropriate model for the respiratory motion of the heart is required, if prospective motion correction is performed. The purpose of this study was to investigate and to optimize the performance of a navigator on a clinical scanner with respect to these demands.

Methods

In vivo experiments with several healthy volunteers and phantom experiments were performed on a 1.5 T whole body scanner (GYROSCAN ACS NT, Philips Medical Systems) with self-shielded gradients (23 mT in 0.2 ms).

Navigator pulse design

For the navigator 2D RF pulses are used [5]. These excite a spatially restricted volume of pencil beam shape, which is read out using a gradient echo. This allows to monitor in-vivo motion along one direction (fig.1). The 2D RF pulses are based on a spiral k-space trajectory (fig. 2), played out by the gradient system in the presence of a B_1-field. To attain optimal results, the gradient performance, a proper pulse design and the aliasing problem have to be considered. The quality of the gradient system employed affects the performance and positioning accuracy of a navigator pulse. Due to the discrete k-space covering of the spiral trajectory aliasing rings are excited, which degrade the 1D navigator profiles. To shift the aliasing rings out of the body, the number of k-space turns has to be increased. Due to gradient constraints this is accompanied by an increase of the pulse duration and, hence, of the off-resonance sensitivity of the 2D RF pulse. It is always necessary to find an appropriate compromise between the pencil beam diameter, the aliasing and the off-resonance sensitivity [6]. To investigate the spatial distribution of magnetization of the pencil beam, the 2D RF-pulse was used for excitation in an imaging sequence. Phantom and in-vivo experiments were performed to study the positioning accuracy, the spatial selectivity and the aliasing of the 2D RF pulse.

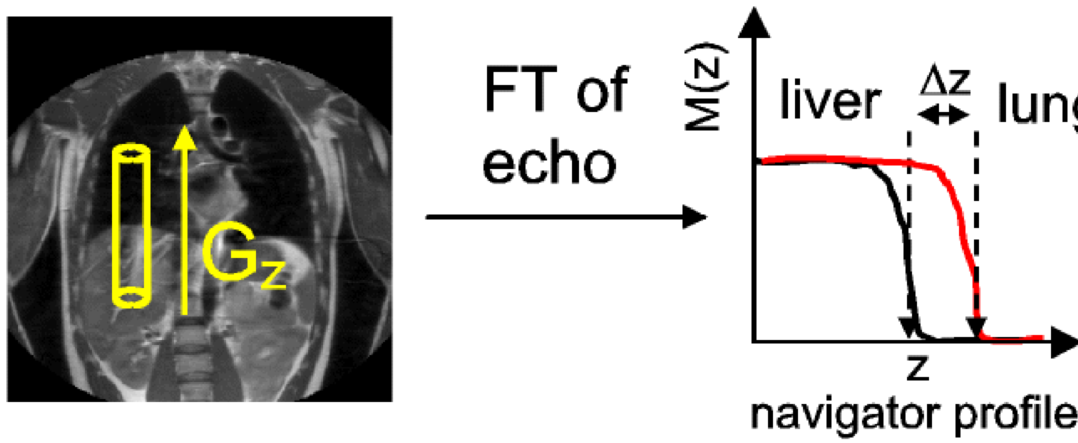

Figure 1. Coronal survey with pencil beam through diaphragm (left). The Fourier transform of the gradient echo yields the projection of the pencil beam's magnetization onto the z-axis, the so-called navigator profile, which is sketched on the right for two different diaphragm positions. The contrast change between liver and lung results in a step-like shape. The displacement of the step with respect to a reference profile is determined in real-time by a cross-correlation algorithm. The total duration of the navigator pulse sequence including exciation, acquisition and evaluation is currently 20 ms.

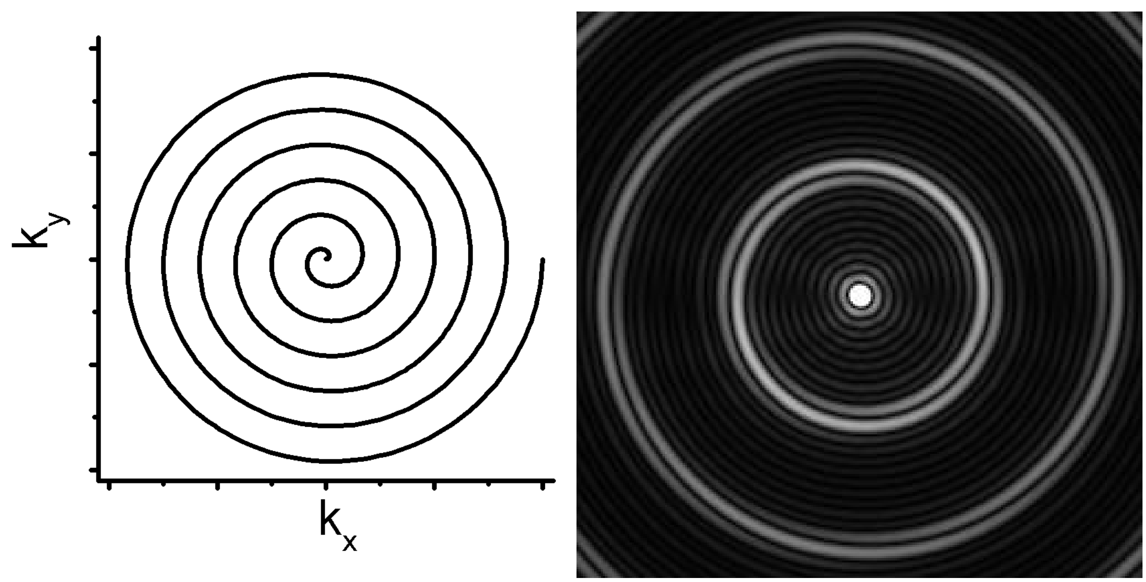

Figure 2. Spiral trajectory of 2D-RF pulse (left) and corresponding point spread function (right). The aliasing rings appear due to the discrete k-space covering of the spiral. The central peak is used as a pencil beam navigator.

Real-time gating

The capability of the navigators for real-time respiratory gating was examined in free-breathing coronary MR angiography, where the pencil beam was applied through the right hemidiaphragm. The proximal portions of the right coronary arteries (RCA) and the left anterior descending artery (LAD) were imaged using an ECG-triggered segmented k-space 3D gradient echo sequence (TR=8.6 ms, TE = 3.2 ms, flip-angle = 30°, 512x358 pixel matrix). For respiratory gating an acceptance window of 5 mm was chosen.

Multiple navigators

To study the respiratory motion of the heart during free breathing multiple navigator pulses were used. The scan software was extended to provide up to four independent navigator pulses, which can be positioned and angulated freely in space. The respiratory motion of right hemidiaphragm, left ventricle, chest wall and abdominal wall was recorded over 10 minutes, using a pure navigator sequence with high temporal resolution (20 ms per navigator). The correlation between the different navigators was analyzed in 2D-histograms.

Results

Navigator pulse performance

The navigator performance was found to be highly sufficient for most applications. Using a simple eddy-current precompensation scheme for the gradient waveforms to correct for residual short-term eddy currents, an accuracy of positioning of the pencil beam better than 7 mm was achieved, which is only a fraction of a typical pencil beam diameter of 25 mm. Using strong gradient slew-rates (100 mT/m/ms) it was always possible to shift the aliasing rings out of the body without inducing off-resonance problems due to the longer pulse length (fig. 3). The spatial selectivity of the 2D-RF pulse was improved by proper weighting of the RF waveform. The navigator profiles obtained from the navigator echo show a well defined change in contrast at the lung-tissue interface (fig. 4). Hence, the displacement of the navigator profiles could be determined reliably by the cross-correlation algorithm. By sub-pixel interpolation an accuracy better than 1mm was achieved.

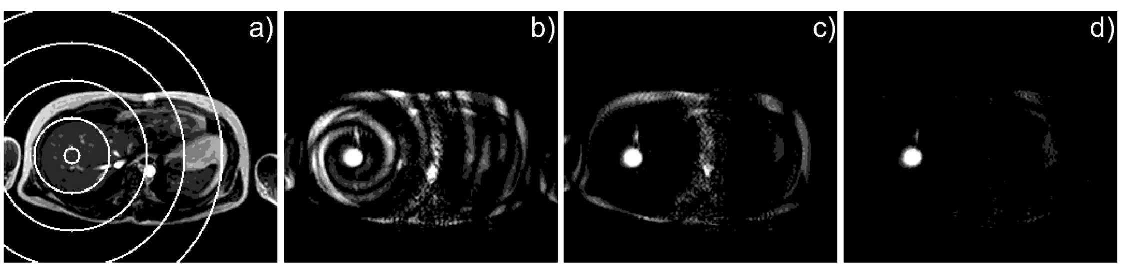

Figure 3. Transversal spin-echo images of the pencil beam excitation in the abdominal region (b-d). In the transversal survey (a) the expected positions of the central beam and the aliasing rings for a 3-turn spiral are indicated by white circles. With increasing number of k-space turns (b-d: 3,6,12) the rings are shifted out of the body. The corresponding pulse lengths are 1.7ms, 2.8 ms, and 5.7 ms, respectively.

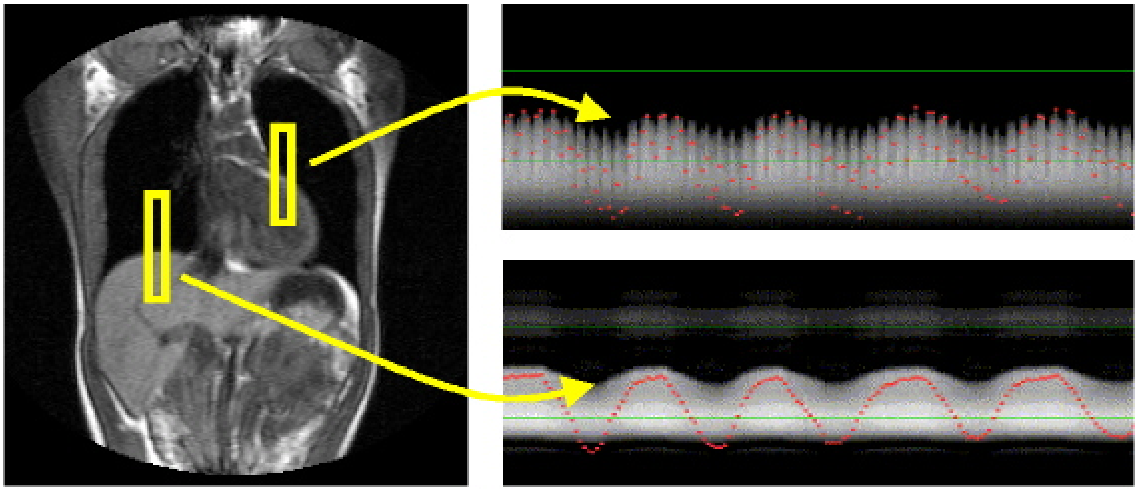

Figure 4. Coronal survey indicating navigator positions (left), and corresponding navigator profiles (right). The red points indicate the respiration curves determined by cross-correlation in real-time. For the navigator through the heart a contribution from cardiac motion is superimposed.

Coronary artery imaging

In figure 5 a vessel-based maximum intensity projection of the RCA and the LAD is shown for one selected volunteer. The branching out of the vessels is well resolved, indicating the efficacy of the gating approach. In the volunteer experiments the gating efficiency was between 20% and 60 %, dependent on the individual motion pattern of the subject. For the applied imaging protocol this corresponds to scan times between 10 and 30 minutes.

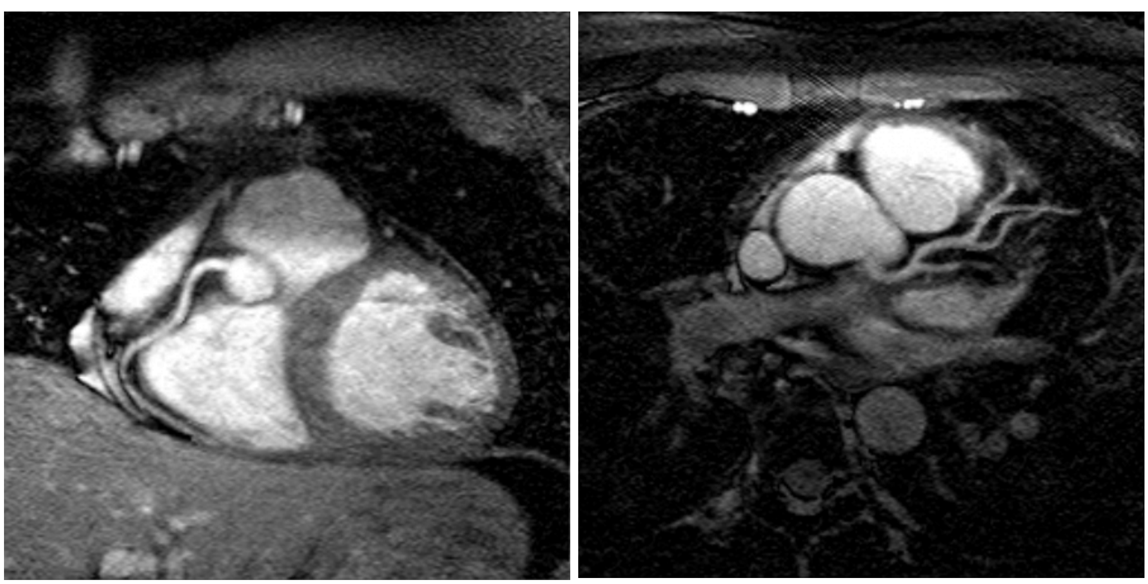

Figure 5. RCA (left) and LAD (right) of a healthy volunteer. The in-plane resolution of the 3D data set was 0.7 mm, the through-plane resolution 1.5 mm.

Respiratory motion of the heart

The 2D histograms in fig. 6 show the correlation between the diaphragmatic motion and the superior-inferior motion of the left ventricle for four selected volunteers. For all volunteers, well defined trajectories without much scattering were found. This indicates a good correlation between diaphragm and heart. However, the histograms show also hysteresis loops with different branches for expiration and inspiration. Hysteresis means, that a certain diaphragm position corresponds to different heart positions for inspiration and expiration, respectively. This hysteretic behavior is strongly patient dependent, for some volunteers a perfect linear relationship is observed, for others a large gap up to 6 mm with respect to the heart position was found. These results indicate, that a simple linear mapping of the diaphragmatic motion onto the respiratory motion of the heart as suggested in the literature [7], may lead to considerable errors in case of tracking the imaging slab. Instead, a patient dependent calibration of the correlation diaphragm-heart should be performed prior to the MR imaging scan by using multiple navigators.

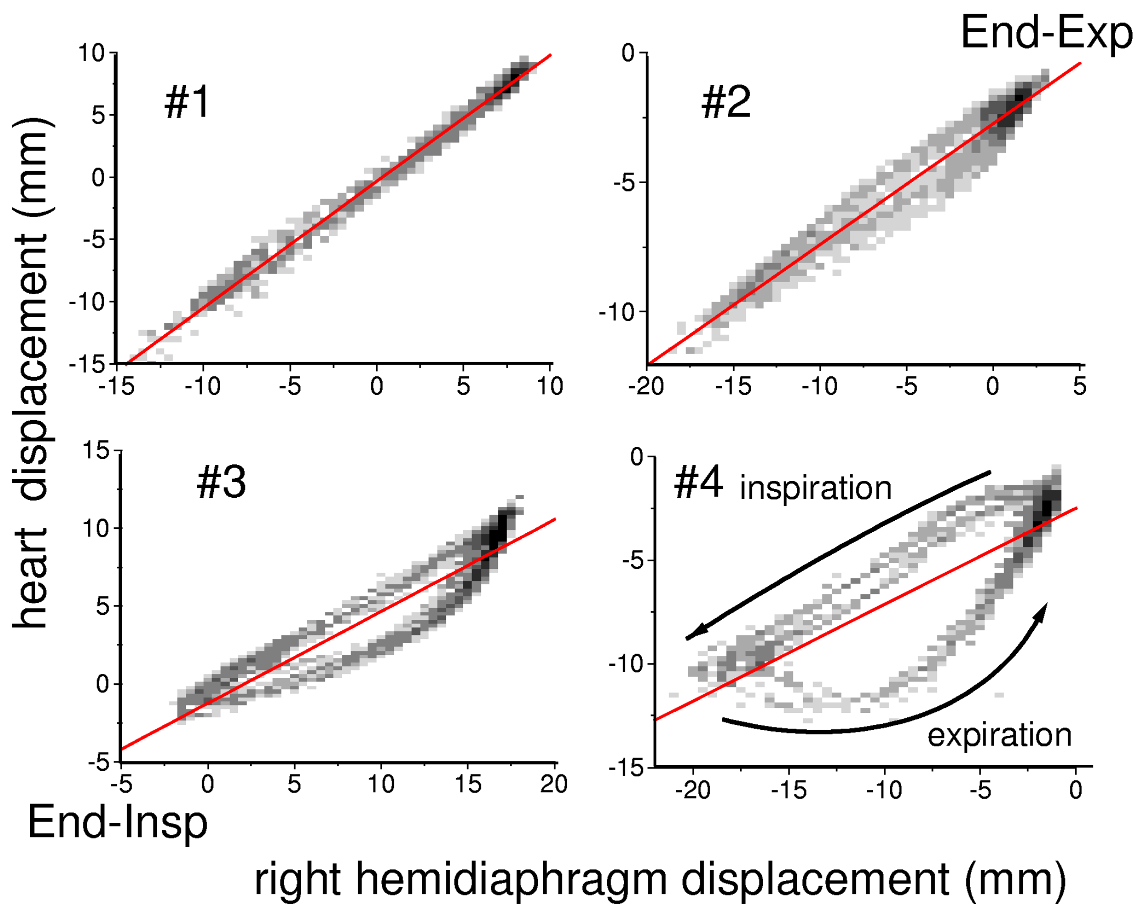

Figure 6. 2D histogram plots of the correlation heart-diaphragm for four selected volunteers. The corresponding navigator positions are shown in fig.4. Black bins indicate many counts, light bins indicate few counts. The red lines are linear fits to the data.

Conclusions

Pencil beam navigator pulses represent a powerful approach to monitor in vivo motion. When used for real-time gating high resolution coronary artery images can be obtained with reproducible quality during free breathing. The multiple navigator results indicate, that a proper model for the correlation diaphragm-heart, including patient dependent hysteretic effects, might further improve image quality or decrease scan time, when used for prospective motion correction. Multiple navigator pulses offer the potential for an automatic, patient dependent calibration of such a model.

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