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Motion detection using Doppler radar: Towards subject- and organ-specific motion correction

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Synopsis

Keywords: Motion Correction, Motion Correction, radar; software-defined radio; cine MRI

Motivation: Limitations of existing motion-mitigation strategies continue to pose a barrier for clinical adoption of MRI in some patient groups and body regions.

Goal(s): To develop an RF-based sensor that utilizes the Doppler effect to detect various types of bulk and internal body motion, operating independently from the MRI scanner.

Approach: Implemented a continuous-wave Doppler radar with software-defined radio.

Results: In this pilot study focusing on respiration, the developed radar sensor generated motion curves comparable to reference techniques and reduced motion blurring in abdominal MRI.

Impact: Radar is a powerful tool for sensing motion. The independence from the MRI receive chain and frequency range offers advantages for detecting diverse types of motion across MR applications, body regions, and possibly even outside the scanner during interventional procedures.

Introduction

Due to the slow acquisition speed, motion-induced data corruption has plagued MRI since its inception. Despite great technical advancements, motion artifacts remain a major problem in clinical practice. Most motion-compensation techniques require a motion signal, derived from either the MR data itself or external sensors. Traditionally, respiratory belts or bellows have been utilized, but these sensors prolong the patient preparation and have limited reliability.
Recent interest has focused on contact-less RF-based sensors, such as coil-load or pilot-tone (PT) techniques(1,2). The PT technique transmits a signal with fixed frequency that is received with the MRI data. Respiratory motion leads to modulation of the signal due to coil-load changes. Therefore, motion information can be derived. However, because the MRI receive coil is utilized, the PT can operate only in a narrow range within the receive bandwidth. Here, we describe an alternative radar-based approach, which can operate over a wide frequency range, and we present preliminary results. The primary objective was to demonstrate its motion-detection capabilities and to evaluate the impact of the carrier frequency.

Methods

Radar sensor: Continuous-wave Doppler radar was implemented using software-defined radio as prototyping platform (Ettus USRP N310, GNU Radio; Fig.1). We utilized an ultra-wideband antipodal Vivaldi antenna design, optimized for near-field microwave applications. Antennas were mounted on a half-cylindrical scaffold in a bistatic configuration, angled at approximately 90° (Fig.1C). To suppress common-mode currents, cable traps (Fig.1C) and ferrite cores were attached to the antenna cables. A 1kHz tone was transmitted at various carrier frequencies (0.5-4GHz).
Signal processing: The Doppler phase shift between forward and reflected waves served as the motion signal. The MRI RF pulses were captured using the second radio channel (tuned to the Larmor frequency). The Doppler shift was smoothed using a Savitzky–Golay filter and synchronized with the imaging data using the recorded MRI RF pulses.
MR imaging: We evaluated the radar system on a 1.5T scanner (MAGNETOM Sola, Siemens Healthcare). First, 2D cine sequences (radial FLASH with sliding-window reconstruction at 11.8fps, or Cartesian b-SSFP at 4.2fps) were acquired, either during regular breathing or with breathing instructions. Data from the radar and from a respiratory sensor embedded into the system (BioMatrix) were recorded in parallel. Second, a 3D stack-of-stars GRE sequence (spatial resolution 1.4×1.4×3.0mm^3) was acquired during free-breathing. Motion-resolved images were reconstructed using respiratory binning, based on the Doppler shift and based on a self-gating signal. A total-variation constraint was applied along the motion dimension to compensate for undersampling resulting from the motion binning (3, 4).
Prospective gating: A T2w BLADE acquisition was triggered depending on the motion state, estimated in real-time by the radar system. This setup was evaluated using a phantom simulating internal body motion.

Results

At 1GHz carrier frequency, the Doppler shifts closely followed the respiration seen in the cine data. Noise became noticeable during shallow breathing, possibly representing the superposition of internal motion such as heartbeats or peristalsis (Fig.2).
At 4GHz, the radar performed better than the embedded respiratory sensor, which detects changes of the coil load. The radar was in excellent agreement with the self-gating signal derived from the stack-of-stars sequence (Fig.3).
When using the radar signal for motion-resolved reconstruction, motion blurring was significantly reduced. The effectiveness was comparable to self-gating (Fig.4).
When using the radar system for prospective gating, motion artifacts were eliminated in the phantom experiment (Fig.5).

Discussion

The described radar setup provided robust respiratory curves in close agreement with the cine-based ground truth, with an embedded coil-load sensor, and with the self-gating data from 3D radial scans. The radar technique offers several advantages.
First, the motion signal is independent from the k-space acquisition. In contrast, self-gating often fails after gadolinium administration and is feasible only for trajectories that sample the k-space center continuously. Dedicated navigators (5,6) can overcome this limitation, but require sequence modifications and may increase acquisition time.

Second, unlike the PT frequency, which must be close to Larmor frequency, the radar carrier frequency can be selected freely. Varying the frequency over a broad range allows targeting specific organs(7) because the propagation and scattering of electromagnetic waves varies with the electromagnetic properties of different tissues. Moreover, the RF parameters can be tuned dynamically at runtime using software-defined radio.
Third, the independent receive chain introduces high flexibility, which could enable use of advanced radar techniques, such as FMCW or pulsed radar, or allow using the radar outside the MR scanner, e.g. during radiotherapy or interventional procedures.
These strengths must be weighed against the increased complexity of deploying not just a transmitter, but also an independent receive chain in the MR environment.

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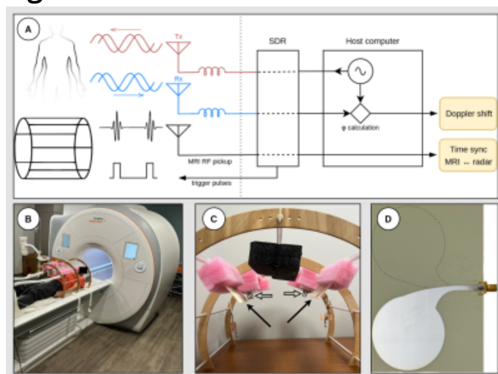
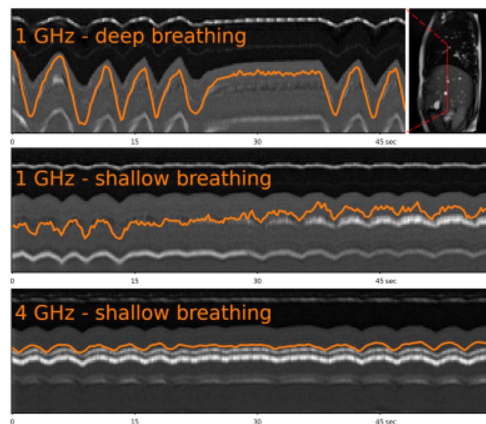
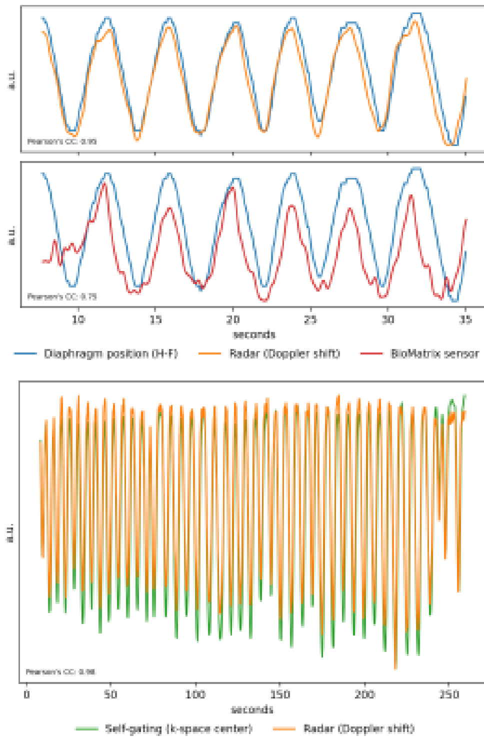
Figures



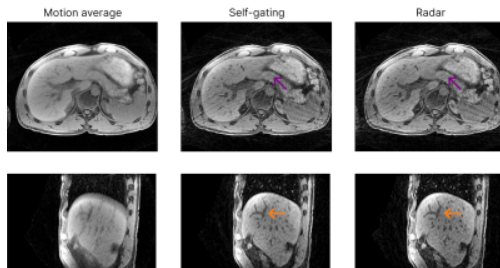
System overview: simplified scheme of signal paths for radar (Tx / Rx), MRI RF pickup, and trigger pulses for prospective motion correction (A); radar scaffold for volunteer studies on a 1.5 T system (B); close-up of the scaffold holding antennas (see arrows) and cable traps (double arrows) (C); close-up of UWB antipodal Vivaldi antenna (D).



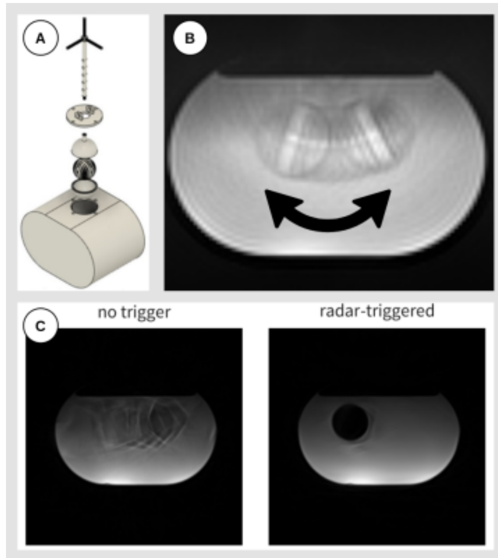
Comparison of the radar Doppler shift with an image-based reference (central image column plotted over time): At 1 GHz carrier frequency, the radar-derived motion curve showed excellent agreement with the diaphragm movement. Noise became noticeable during shallow breathing, possibly related to internal motion effects. At 4 GHz, by contrast, a robust respiratory curve was recovered even during shallow breathing.



Comparison of radar-based respiratory curves with reference techniques: the Doppler shift was compared to diaphragm motion (in head-foot direction) and to the signal provided by a coil-load sensor embedded into the MRI system (Siemens BioMatrix) (A). Using a 3D stack-of-stars acquisition, the radar Doppler shift was also compared to a self-gating signal derived from k-space center (B).



Retrospective motion correction using conventional signal processing: A 3D stack-of-stars sequence of the upper abdomen was acquired in free breathing. K-space lines were sorted into 5 respiratory bins according to the radar Doppler shift. For comparison, binning was also performed using self-gating. Both methods suppress respiratory artifacts, resulting in better depiction of structures such as intra-hepatic vessels (orange arrows) or the main pancreatic duct (purple arrows).



Prospective motion gating: With this in-house phantom, motion of the spherical inner compartment is induced pulling on the rod of the pendulum (actuated by a stepper motor located outside the magnet room); CAD drawing (A), time-average cine to illustrate the motion range of the inner compartment (B). Radar data was processed in real-time to capture a specific motion state and trigger data acquisition of a T2w BLADE sequence, eliminating motion artifacts (C). Inner compartment is filled with 10 mM gadobutrol and therefore hypointense on T2w.

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