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Parallel imaging compressed sensing for accelerated imaging and improved signal-to-noise ratio in MRI-based postimplant dosimetry of prostate brachytherapy

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ABSTRACT

PURPOSE: To investigate the feasibility of using parallel imaging compressed sensing (PICS) to reduce scan time and improve signal-to-noise ratio (SNR) in MRI-based postimplant dosimetry of prostate brachytherapy.

METHODS AND MATERIALS: Ten patients underwent low-dose-rate prostate brachytherapy with radioactive seeds stranded with positive magnetic resonance-signal seed markers and were scanned on a Siemens 1.5T Aera. MRI comprised a fully balanced steady-state free precession sequence with two 18-channel external pelvic array coils with and without a rigid two-channel endorectal coil. The fully sampled data sets were retrospectively subsampled with increasing acceleration factors and reconstructed with parallel imaging and compressed sensing algorithms. The images were assessed in a blinded reader study by board-certified care providers. Rating scores were compared for statistically significant differences between reconstruction types.

RESULTS: Images reconstructed from subsampling up to an acceleration factor of 4 with PICS demonstrated consistently sufficient quality for dosimetry with no apparent loss of SNR, anatomy depiction, or seed/marker conspicuity when compared to the fully sampled images. Images obtained with acceleration factors of 5 or 6 revealed reduced spatial resolution and seed marker contrast. Nevertheless, the reader study revealed that images obtained with an acceleration factor of up to 5 and reconstructed with PICS were adequate-to-good for postimplant dosimetry.

CONCLUSIONS: Combined parallel imaging and compressed sensing can substantially reduce scan time in fully balanced steady-state free precession imaging of the prostate while maintaining adequate-to-good image quality for postimplant dosimetry. The saved scan time can be used for multiple signal averages and improved SNR, potentially obviating the need for an endorectal coil in MRI-based postimplant dosimetry.

Keywords: MRI; Compressed sensing; SNR; Prostate brachytherapy; Endorectal coil

Introduction

Accurate postimplant dosimetry of low-dose-rate (LDR) prostate brachytherapy requires high-resolution images that can be used to visualize the radioactive seeds, prostate anatomy, and adjacent organs at risk. X-ray CT is the current standard of practice for postimplant dosimetry of LDR prostate brachytherapy because of its high spatial resolution and high seed contrast (1, 2). However, CT has poor soft tissue contrast, which makes it difficult to

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delineate and contour the prostate and surrounding anatomical structures.

MRI is well known for its excellent soft tissue contrast (3). Furthermore, the image contrast in MRI can be adjusted for a desired application by varying the pulse sequence types and scan parameters. These characteristics make MRI an attractive alternative to CT for postimplant imaging of the prostate. Positive MRI signal seed markers with high T1 contrast have recently been developed for postimplant seed localization (4, 5). These seed markers are placed between the radioactive seeds in the stranded brachytherapy needles, thus providing a reliable and convenient means of indirectly locating the seeds. Previously, three-dimensional (3D) T1- and T2-weighted images were acquired for visualizing the radioactive seed markers and the prostate anatomy, respectively (6, 7). However, this approach requires two separate sets of images, which prolongs the acquisition; the images also need to be either coregistered or cross-referenced to perform dosimetry.

Recently, Ma *et al.* demonstrated the feasibility of visualizing both the radioactive seed markers and anatomical structures in a single acquisition using a 3D fully balanced steady-state free precession (SSFP) pulse sequence (8). Compared with T1- and T2-weighted sequences, the fully balanced SSFP pulse sequence provides a mix of T1 and T2 contrast and maximizes the signal-to-noise ratio (SNR) by using all the coherent signal pathways of the spin magnetization (9−11). Several variants of the fully balanced SSFP sequence are commercially available (e.g., trueFISP/constructive interference in steady-state (CISS), from Siemens; FIESTA/FIESTA-C, from GE; Balanced FFE, from Philips). Despite its intrinsically high SNR, 3D postimplant imaging using the fully balanced SSFP sequence currently takes 3−5 minutes and requires the use of an endorectal coil (ERC) to achieve images of an acceptable quality.

Although providing intrinsically superior SNR, the use of an ERC, in general, reduces patient comfort, increases the overall time and cost of the study, and requires 20−30 minutes to set up the examination. Therefore, circumventing the use of an ERC would be desirable for patients and for the expanded use of MRI for postimplant dosimetry of prostate brachytherapy. To do so, methods must be developed to recover the SNR loss due to the lack of an ERC without compromising the spatial resolution or increasing scan time (12).

In general, MRI scan time is directly proportional to the number of phase-encoding lines acquired (13). By reducing the number of phase-encoding lines acquired, the image acquisition can be accelerated to reduce the total scan time. Several acceleration strategies exist that exploit either the Hermitian symmetry in k-space (e.g., partial Fourier imaging) (14, 15) or the spatial redundancies in the data collected from multiple receiver channels (e.g., parallel imaging [PI]) (16−24). However, the scan time reduction in partial Fourier imaging is limited to a maximum of 50%. Moreover, the image SNR in PI approaches suffer from the geometry factor (g-factor), which amplifies noise as a result of the skipped phase-encoding lines (18). In general, the g-factor depends on the amount of acceleration used and the number and location of the receiver coils used for imaging and can vary across the image producing spatially variant noise amplification.

Compressed sensing (CS) has been applied successfully in several MRI applications to substantially improve the imaging speed beyond that offered by partial Fourier and PI approaches without a corresponding loss in image quality. CS relies on the sparsity of an imaged object in a transformed domain and an iterative nonlinear image reconstruction of a pseudorandomly sampled k-space acquisition (25). With CS, the phase-encoding lines can be sampled substantially below the Nyquist requirement without producing aliasing in the image. Moreover, the SNR in CS image reconstructions does not suffer from the g-factor effect (21). Therefore, scan time can be drastically reduced without significantly impacting the inherent image SNR. CS has also been shown to be compatible with PI, which can improve the reconstruction quality by incorporating additional information about the spatial variations in the sensitivity profiles of different radiofrequency (RF) receiver channels positioned around the patient.

The purpose of this work was to investigate the feasibility of using PI and CS to reduce scan time and improve SNR for MRI-based postimplant dosimetry of prostate brachytherapy without an ERC. Fully sampled magnetic resonance (MR) acquisitions of postimplant prostate brachytherapy patients were gradually subsampled in k-space with increasing acceleration factors and reconstructed using PI and CS algorithms. The images reconstructed with the fully sampled data and different levels of acceleration were blindly evaluated for image quality and for visualization of the radioactive seeds/markers and prostate and surrounding anatomical structures.

Methods and materials

Patient setup

Ten patients were scanned on a 1.5T Siemens Magnetom Aera scanner operating under the VE11A software environment (Siemens Healthcare, Erlangen, Germany). Two 18-channel external pelvic arrays were used in combination with a 2-channel rigid ERC (Invivo, Gainesville, FL). The two-channel rigid design, which provides higher SNR than the single-channel balloon design, deformed the prostate in a manner similar to that of the transrectal ultrasound probe used during seed implantation (26). All patients were implanted with stranded radioactive seeds placed next to the positive MR signal seed markers (Sirius, C4 Imaging, Houston, TX). All MRI scans were performed on the day of the implant surgery using an