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Physics Contribution

Four-Dimensional Magnetic Resonance Imaging With 3-Dimensional Radial Sampling and Self-Gating–Based K-Space Sorting: Early Clinical Experience on Pancreatic Cancer Patients

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Summary

Cine 2D-MRI is useful when monitoring abdominal tumor motion, owing to its superior soft-tissue contrast. To quantify 3D tumor motion, current 4D-MRI methods are 2D-based and limited in resolution and by artifacts. In this study, a SG-KS-4D-MRI method based on 3D k-space sampling was implemented for pancreatic tumor motion monitoring. The resultant 4D-MRI images with high isotropic resolution showed fewer artifacts, better soft-tissue contrast, and more consistent

Purpose: To apply a novel self-gating k-space sorted 4-dimensional MRI (SG-KS-4D-MRI) method to overcome limitations due to anisotropic resolution and rebinning artifacts and to monitor pancreatic tumor motion.

Methods and Materials: Ten patients were imaged using 4D-CT, cine 2-dimensional MRI (2D-MRI), and the SG-KS-4D-MRI, which is a spoiled gradient recalled echo sequence with 3-dimensional radial-sampling k-space projections and 1-dimensional projection-based self-gating. Tumor volumes were defined on all phases in both 4D-MRI and 4D-CT and then compared.

Results: An isotropic resolution of 1.56 mm was achieved in the SG-KS-4D-MRI images, which showed superior soft-tissue contrast to 4D-CT and appeared to be free of stitching artifacts. The tumor motion trajectory cross-correlations (mean ± SD) between SG-KS-4D-MRI and cine 2D-MRI in superior–inferior, anterior–posterior, and medial–lateral directions were 0.93 ± 0.03, 0.83 ± 0.10, and 0.74 ± 0.18, respectively. The tumor motion trajectories cross-correlations between SG-KS-4D-MRI and 4D-CT in superior–inferior, anterior–posterior, and medial–lateral directions were 0.91 ± 0.06, 0.72 ± 0.16, and 0.44 ± 0.24, respectively. The average standard deviation of gross tumor volume calculated from the 10 breathing phases was 0.81 cm^3 and 1.02 cm^3 for SG-KS-4D-MRI and 4D-CT, respectively ($P = .012$).

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tumor volumes than those of 4D-CT.

Conclusions: A novel SG-KS-4D-MRI acquisition method capable of reconstructing rebinning artifact—free, high-resolution 4D-MRI images was used to quantify pancreas tumor motion. The resultant pancreatic tumor motion trajectories agreed well with 2D-cine-MRI and 4D-CT. The pancreatic tumor volumes shown in the different phases for the SG-KS-4D-MRI were statistically significantly more consistent than those in the 4D-CT.

Introduction

Accuracy of radiation therapy treatment is challenged by ventilation-induced tumor and organ motion, which is especially prominent for lung and upper abdominal tumors. Without precise knowledge of the motion, a generic margin is typically used. Because of individual variations in anatomy and breathing, the generic margins can over- or underestimate the actual motion and lead to dosimetric inaccuracies (1, 2). Therefore, quantification of respiration-induced motion for tumor and critical organs can help clinicians define individualized treatment margins and thus minimize normal tissue doses without compromising tumor dose coverage. Four-dimensional CT (4D-CT) has been widely adopted for lung cancer patients but is insufficient for abdominal organs, owing to both resorting artifacts and the poor soft-tissue contrast (3, 4). At the same time, use of MRI is particularly attractive for abdominal imaging, owing to superior soft-tissue contrast. Cine 2-dimensional MRI (2D-MRI) can be oriented to the dominant tumor motion plane for real-time imaging (5, 6).

However, unlike lung tumors, abdominal tumors are often surrounded by serial organs. A single 2D plane is likely insufficient to describe the complex motion of these organs. In the radiation therapy community, efforts at 4-dimensional MRI (4D-MRI) have been made from multiple groups. Cai et al (7) introduced a 4D-MRI protocol using body area as surrogate to retrospectively resort cine 2D-MRI images. Tryggestad et al (8) developed a longer-duration MRI and postprocessing technique based on cine 2D-MRI images to derive the average or most-probable state of mobile anatomy. Hu et al (9) used a navigator triggered image acquisition at preselected respiratory amplitudes for 4D-MRI, which was also based on 2D acquisition. Stemkens et al (10) compared 2 surrogate signals (external bellows and internal navigator) and 2 MR sampling strategies (Cartesian and radial) and constructed 4D-MRI by resorting 2D k-space data. All of these 4D-MRI methods have adopted similar concepts used in 4D-CT and have shown promise in capturing more comprehensive anatomical information; however, they have also inherited the same stitching artifacts resulting from 2D imaging-space resorting (7-11). Another significant limitation is the anisotropic resolution due to the large slice thickness of cine 2D-MRI.

To overcome these limitations, we have recently demonstrated the feasibility of a SG-KS-4D-MRI technique with 3-dimensional (3D) radial sampling and self-gating—based k-space sorting to provide respiratory phase resolved 3D-MRI images (12). The SG-KS-4D-MRI technique has several potential advantages over existing 4D-MRI methods, including an isotropic high spatial resolution of 1.56 mm, with a fixed scan time of 8 minutes and minimal intraphase motion artifacts. Demonstration of this novel 4D-MRI technique has been performed in phantom, healthy volunteers, and 2 liver patients, and geometric accuracy of the method has been studied (12).

The purpose of this study was to present our early clinical experience in assessing the effectiveness of SG-KS-4D-MRI, to evaluate pancreatic tumor motion, where 4D-CT has typically been inadequate. We compare the tumor motion trajectories measured from SG-KS-4D-MRI with those measured from cine 2D-MRI images in sagittal and coronal planes, and from 4D-CT.

Methods and Materials

Patients

This study included 10 patients (5 male and 5 female) with histologically confirmed locally advanced or borderline resectable pancreatic cancer. Tumors were located in the head and body of the pancreas in 5 and 4 patients, respectively, with 1 patient presenting with synchronously distinct tumors in the head and tail of pancreas. Gross tumor volumes (GTVs) ranged from 25 to 103 cm^3, with an average volume of 51 cm^3. Additional patient-specific variables are noted in Table 1.

Imaging study

All patients underwent CT and MRI imaging studies under a prospective protocol approved by the institutional review board. The interval between CT and MRI studies was less than 1 week. Patients were in a head-first supine position with arms up. Computed tomgraphy scans were performed on a 16-slice scanner (Optima CT580; GE Healthcare, Milwaukee, WI) equipped with the Real-time Position Management (RPM) system (Varian Medical Systems, Palo Alto, CA) and AdvantageSim 4D software (GE Healthcare, Milwaukee, WI). The 4D-CT scans were performed in cine mode with the following parameters: 120 kV, variable mA, gantry rotation period of 1 second, and slice thickness of