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Physics Contribution

Four-Dimensional Magnetic Resonance Imaging Using Axial Body Area as Respiratory Surrogate: Initial Patient Results

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Summary

This study performed preliminary patient validation of the accuracy of tumor motion measurements and the improvement of tumor-to-tissue contrast-to-noise ratio in the proposed 4D-MRI technique using body area as the respiratory surrogate. Seven patients with liver cancer(s) were enrolled in the IRB-approved study. The results demonstrated that this 4D-MRI technique was a promising technique for more accurately imaging tumor respiratory motion, with improved soft-tissue contrast.

Purpose: To evaluate the feasibility of a retrospective binning technique for 4-dimensional magnetic resonance imaging (4D-MRI) using body area (BA) as a respiratory surrogate.

Methods and Materials: Seven patients with hepatocellular carcinoma (4 of 7) or liver metastases (3 of 7) were enrolled in an institutional review board-approved prospective study. All patients were simulated with both computed tomography (CT) and MRI to acquire 3-dimensinal and 4D images for treatment planning. Multiple-slice multiple-phase cine-MR images were acquired in the axial plane for 4D-MRI reconstruction. Image acquisition time per slice was set to 10-15 seconds. Single-slice 2-dimensinal cine-MR images were also acquired across the center of the tumor in orthogonal planes. Tumor motion trajectories from 4D-MRI, cine-MRI, and 4D-CT were analyzed in the superior−inferior (SI), anterior−posterior (AP), and medial−lateral (ML) directions, respectively. Their correlation coefficients (CC) and differences in tumor motion amplitude were determined. Tumor-to-liver contrast-to-noise ratio (CNR) was measured and compared between 4D-CT, 4D-MRI, and conventional T2-weighted fast spin echo MRI.

Results: The means (±standard deviations) of CC comparing 4D-MRI with cine-MRI were 0.97 ± 0.03, 0.97 ± 0.02, and 0.99 ± 0.04 in SI, AP, and ML directions, respectively. The mean differences were 0.61 ± 0.17 mm, 0.32 ± 0.17 mm, and 0.14 ± 0.06 mm in SI, AP, and ML directions, respectively. The means of CC comparing 4D-MRI and 4D-CT were 0.95 ± 0.02, 0.94 ± 0.02, and 0.96 ± 0.02 in SI, AP, and ML directions, respectively. The mean differences were 0.74 ± 0.02 mm, 0.33 ± 0.13 mm, and 0.18 ± 0.07 mm in SI, AP, and ML directions, respectively. The mean tumor-to-tissue CNRs were 2.94 ± 1.51, 19.44 ± 14.63, and 39.47 ± 20.81 in 4D-CT, 4D-MRI, and T2-weighted MRI, respectively.

Conclusions: The preliminary evaluation of our 4D-MRI technique results in oncologic patients demonstrates its potential usefulness to accurately measure tumor respiratory motion with improved tumor CNR compared with 4D-CT.

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Introduction

Respiration-induced organ motion poses significance challenges to treatment with radiation. Suboptimal management of organ motion can lead to degradation of the delivered dose distribution to the irradiated volume, with underdosage of target tissues and overdosage of surrounding normal tissues (1). Four-dimensional computed tomography (4D-CT) has been widely used in clinical radiation therapy to acquire patient-specific respiratory motion data (2-7). However, 4D-CT involves a substantial image radiation dose to nontarget tissues, owing to multiple volumetric data acquisitions at the same body location, and has relatively poor soft-tissue contrast, potentially resulting in inaccurate tumor delineation (8-10). As an alternative, the emerging 4D magnetic resonance imaging (4D-MRI) technique is able to image respiratory associated organ motion with improved soft-tissue contrast and zero nontarget ionizing radiation.

Several 4D-MRI techniques have been recently reported (11-14). Hu et al (11) introduced a prospective amplitude-based 4D-MRI technique using a respiratory triggering system. Although this technique improved the tumor-to-tissue contrast-to-noise ratio (CNR) by acquiring T2-weighted 4D-MRI image datasets, the acquisition efficiency was affected by inconsistent breathing patterns between the preparation and data acquisition stages. Tryggestad et al (12) demonstrated a retrospective 4D-MRI technique for dynamic MRI, which used a pneumatic device strapped around the subjects' upper abdomen to acquire the respiratory signals. Two-pass approaches were used in retrospective sorting to acquire "de-blurred 4D-MRI"; however, unavoidable artifacts in the first-pass "average 4D-MRI" limited the robustness of second-pass "de-blurred 4D-MRI."

We have previously demonstrated a retrospective 4D-MRI technique using body area (BA) as an internal respiratory surrogate. The technical feasibility of this approach has been tested and validated on a motion phantom, a digital phantom, and healthy human subjects (13).

The purpose of this study was to assess the effectiveness of our 4D-MRI technique in real cancer patients. We evaluated the accuracy of tumor motion measurement using 2-dimensional (2D) single-slice cine MR in 3 orthogonal directions (14) and 4D-CT and the improvement in tumor-to-tissue CNR of the 4D-MRI technique.

Methods and Materials

Patients and imaging study

Seven patients (3 male, 4 female, mean age 65.0 years) who had hepatocellular carcinoma (n=4) or liver metastases (n=3) were enrolled in this institutional review board-approved prospective study. Note that patient 7 had 2 tumors. Table 1 summarizes the patients' clinical characteristics. All patients underwent CT and MRI simulations on the same day for treatment planning. The CT scans were performed on a 4-slice CT scanner (Lightspeed; GE Healthcare, Milwaukee, WI) equipped with the Real-time Position Management (RPM) system (Varian Medical Systems, Palo Alto, CA) and Advantage 4D software (GE Healthcare). The CT simulation included a free-breathing helical 3-dimensional (3D)-CT scan, a breath-hold helical 3D-CT scan with contrast, and a cine 4-dimensional (4D)-CT scan. All patients were positioned head first supine in an immobilization device during the scans. The 4D-CT scan was acquired in the cine mode, in which the cine duration per slice was set to the patient's breathing period plus 1 second, and the cine time (image acquisition time per phase per slice) was set to one-tenth of the breathing period. The following imaging parameters were used: 120 kV, 290 mA, 2.5-mm slice thickness, gantry rotation of 0.5 seconds per cycle, reconstruction matrix of 512 × 512, field of view of 450-500 mm.

All MR scans were performed on a 1.5-T (Signa; GE Healthcare) or a 3.0-T MR system (MAGNETOM Trio; Siemens Healthcare, Erlangen, Germany). An immobilization device was used when it was possible to fit the device with the patient inside the MR scanner bore. The MR simulation included a 4D-MRI scan, multiple free-breathing cine MR scans, and a breath-hold T2-weighted MR scan using a respiratory-triggered fast relaxation fast spin echo sequence.

The unsorted 4D-MRI images were acquired in the axial plane using a fast steady-state acquisition imaging technique (labeled as FIESTA by GE and TrueFISP by Siemens), including multiple slices to cover a volume of interest. Scan time per axial slice was set to approximately 2 to 3 times the patient's breathing period. Magnetic resonance images were interpolated to 256 × 256 before further analysis.

Single-slice 2D cine MR images were acquired across the center of the tumor in 3 orthogonal planes (axial, sagittal, and coronal) for 30 seconds using the same sequence as the 4D-MRI scan. The orthogonal slices were acquired in separate but contiguous acquisitions. The MRI parameters were optimized to achieve fast image acquisition (>3 frames per second) while maintaining adequate spatial resolution: repetition time (TR)/echo time (TE): 3.005 ms/1.128 ms; field of view (FOV): 300-480 × 360-480 mm; flip angle: 50°; slice thickness: 5 mm; bandwidth: 976.562 Hz per pixel; acquisition matrix: 192 × 128.

The imaging parameters for T2-weighted MRI were as follows: TR/TE: 12,857.1 ms/64.196 ms; FOV: 350 × 227 mm; flip angle: 50°; slice thickness: 3 mm; bandwidth: 390.625 Hz per pixel; acquisition matrix: 256 × 192.

4D-MRI using BA as respiratory surrogate

Our 4D-MRI technique was achieved by using a fast 2D MR sequence to acquire axial images continuously throughout the breathing cycle, and then retrospectively sorting the MR images according to respiratory phase. The 4D-MRI technique and the use of BA as respiratory surrogate have been described in detail previously (13) and will only be briefly described here.

To determine the breathing signal, each MR image was first processed to determine the body contour. Individual breathing curves were then generated at each axial location by plotting the BA as a function of image acquisition time. The complete breathing signal was obtained by plotting individual breathing curves continuously, followed by removing the low-frequency component (called base BA) of the signal, which is caused by anatomic changes. To reconstruct the 4D-MRI, respiratory peaks of the complete breathing signal were determined using an automatic search algorithm, followed by a manual correction method to remove erroneous peak detections. Peaks were assigned to phase 50%, and the rest of the phases were then linearly interpolated. In cases in which a phase was missing, the nearest phase was instead used in the 4D-MRI reconstruction. In addition, the first 3 images in the image series at each axial location were