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Original Research Article

Comparison of four dimensional computed tomography and magnetic resonance imaging in abdominal radiotherapy planning

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ABSTRACT

Background and Purpose: Four-dimensional (4D) computed tomography (CT) is widely used in radiotherapy (RT) planning and remains the current standard for motion evaluation. We assess a 4D magnetic resonance imaging (MRI) sequence in terms of motion and image quality in a phantom, healthy volunteers and patients undergoing RT.

Materials and Methods: The 4D-MRI sequence is a prototype T1-weighted 3D gradient echo with radial acquisition with self-gating. The accuracy of the 4D-MRI respiratory sorting based method was assessed using a MRI-CT compatible respiratory simulation phantom. In volunteers, abdominal viscera were evaluated for artefact, noise, structure delineation and overall image quality using a previously published four-point scoring system. In patients undergoing abdominal RT, the tumour (or a surrogate) was utilized to assess the range of motion on both 4D-CT and 4D-MRI. Furthermore, imaging quality was evaluated for both 4D-CT and 4D-MRI.

Results: In phantom studies 4D-MRI demonstrated amplitude of motion error of less than 0.2 mm for five, seven and ten bins. 4D-MRI provided excellent image quality for liver, kidney and pancreas. In patients, the median amplitude of motion seen on 4D-CT and 4D-MRI was 11.2 mm (range 2.8–20.3 mm) and 10.1 mm (range 0.7–20.7 mm) respectively. The median difference in amplitude between 4D-CT and 4D-MRI was −0.6 mm (range −3.4–5.2 mm). 4D-MRI demonstrated superior edge detection (median score 3 versus 1) and overall image quality (median score 2 versus 1) compared to 4D-CT.

Conclusions: The prototype 4D-MRI sequence demonstrated promising results and may be used in abdominal targeting, motion gating, and towards implementing MRI-based adaptive RT.

1. Introduction

Four-dimensional (4D) computed tomography (CT) is widely used in radiotherapy (RT) and remains the current standard for motion evaluation and delineation of an internal target volume (ITV) as per ICRU62 [1]. Unfortunately, 4D-CT has additional radiation exposure to a three-dimensional (3D) planning CT alone, and has poor soft tissue contrast. 4D-CT inadequately models respiratory motion for approximately 30% of patients [2]. Magnetic resonance imaging (MRI) has emerged as a potential replacement for CT in the RT planning process [3,4]. MRI has advantages of avoiding radiation exposure, and offering superior soft tissue delineation compared to CT, both are of enormous value in abdominal RT given the proximity of a number of organs at risk (OAR) and its potential use for adaptive replanning and real-time image guidance. The development of a clinically useful 4D-MRI sequence in abdominal radiotherapy has received much attention [5–8].

Until recently, ITV formation using MRI has involved unacceptable trade-offs between spatial resolution, acquisition time and signal to noise ratio. The majority of attempts to provide motion information with MRI have included acquisition of dynamic 2D-MRI images across all phases of respiratory cycle [9–11], sorting and reconstructing k space data [7,8], retrospective binning of 2D or 3D-MRI images [12], and use of motion vectors applied to 2D cine or 3D images [7,13].

True 4D MRI has recently become possible thanks to efficient sampling schemes using radial projections which acquire successive data through centre of k-space.

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In this paper we present a sequence utilising a stack of stars trajectory for use in abdominal radiotherapy planning. This sequence uses incremental projections taken at the 'golden angle' which provides an optimal distribution of the radial data. We compare motion information between 4D-CT and the 4D-MRI sequence in phantom and patients. Using a previously published scoring system, we assess the 4D-MRI sequence image quality in the parameters of noise, artefact, structure delineation and overall image quality for upper abdominal viscera in healthy volunteers. We also assess and compare imaging quality between 4D-CT and 4D-MRI in patients. There is little published literature comparing image quality and motion information of 4D-MRI acquired through a stack of stars trajectory, with 4D-CT.

2. Materials and methods

The prototype 4D-MRI sequence was tested in: (1) a respiratory simulation phantom; (2) ten healthy volunteers; and (3) ten patients undergoing abdominal RT.

For human imaging, volunteers and patients were scanned in an abdominal RT planning position with a customized vacuum bag (BlueBAG, Elekta, Stockholm, Sweden) for immobilization and a flat wing board (MTWB09 Wingboard, CIVCO Medical Solutions, Orange City, IA) and arms above the head. All MR imaging was performed on the departmental RT dedicated 3.0 Tesla simulator wide bore MRI (Siemens MAGNETOM Skyra, Erlangen, Germany) with a flatbed insert (CIVCO Medical Solutions, Orange City, IA) using a 32-channel posterior in-table RF coil and 18-channel flexible RF coil array. Sequences included T2-w HASTE gated with phase navigation, breath hold T1-w volumetric interpolated breath hold examination (VIBE) and multiphasic (Arterial, venous and transitional phases) breath-hold T1-w VIBE enhanced with 0.1 ml/kg Gadobutrol (Gadovist, Bayer). Additionally, the new 4D-MRI sequence was acquired in all volunteers and patients. The 4D-MRI sequence is a respiratory phase-resolved 3D T1-w gradient echo (VIBE) radial acquisition with self-gating (Siemens, Erlangen, Germany). K-space sampling was performed using a stack-of-stars radial trajectory with golden angle increment [14] (radial encoding for read-out and Cartesian encoding for slices). The sequence used data from the centre of k-space to extract a respiratory motion surrogate signal, which permits self-gating [15,16]. The self-gating respiratory signal was then used for retrospective binning of the k-space data to reconstruct the images in defined number of breathing states (respiratory phases). The RT treatment planning system (TPS) only permits contouring on 4D-CT in the axial plane. In order to directly compare 4D-CT and 4D-MRI, images were acquired in axial plane. The 4D-MRI sequence was acquired with resolution of $1.2 \times 1.2 \times 3.0\,mm^3$, 9 degrees flip angle, TR/TE of 4.33/1.98 ms, 320×320 base resolution with 2000 radial views and $380 \times 380\,mm^2$ field of view.

The 4D-MRI sampling scheme followed a "stack-of-stars" trajectory with radial read-out and Cartesian encoding of the slices. All slices were encoded for a given azimuth angle and then the acquisition angle was rotated by 111.25 degree (golden angle) [14]. Thus, for every acquired angle or "radial views", one readout was acquired in kz = 0 plane (k-space centreline). Thus with N radial views, N k-space centrelines were used to calculate a respiratory motion surrogate signal with N samples.

Based on the surrogate signal, the data from all radial views was equally divided into defined number of respiratory phases (number of bins) based on the respiratory amplitude where the data was acquired. For example, if the data was sorted into five bins, five respiratory amplitude bins could be resolved. The respiratory amplitude bin was defined based on the amplitude between end-exhale to end-inhale, not considering upward or downward side of the signal, i.e. hysteresis was not included in current version of the prototype. Each respiratory amplitude bin contained same amount of data. All the 4D-MRI reconstruction was performed on the scanner and all the images took on average 95 s to be reconstructed online. Gradient non-linearity such as subject induced distortions due to susceptibility and chemical shift effects were not accounted and corrected in this version of the work in progress (WIP) but has been planned for future version of the WIP release.

2.1. Phantom study

The accuracy of the 4D-MRI sequence was assessed using an MRI-CT compatible respiratory simulation phantom (QUASAR™, Modus Medical Devices Inc., London, Canada). The respiratory simulation platform was driven to move a 3 cm diameter sphere target filled with gadolinium doped water with various sinusoidal waveforms (10–15 mm amplitude, 10–20 breaths per minute) and two patient specific respiratory waveforms. The 4D-MRI acquisition time was 3 min in the phantom study. The phantom experiment was performed on a CT simulator (Brilliance™ CT, Philips Medical Systems, The Netherlands) using the gold standard 4D-CT technique that produces ten respiratory bins over a complete expiration to expiration cycle. The experiments were repeated using the 4D-MRI sequence with reconstruction of three, five, seven and ten bins, over expiration to inspiration. All 4D datasets were imported into image analysis software (MiM Maestro™, Cleveland, USA) for target contouring. Four dimensional structure sets were created by propagating the manually drawn contours from one frame of 4D data series to other frames and compared to known values. Four dimensional structure sets were created using deformable propagation with manual editing to contour sphere on all phases.

2.2. Volunteer study

Ten healthy volunteers were scanned using the prototype 4D-MRI sequence using a stereotactic body radiation therapy (SBRT) positioning system (Omni V®, Bionix Radiation Therapy, Ohio, USA). The first two volunteers were scanned with 4D-MRI using three bins, five bins and ten bins. With information from phantom study and first two volunteers, an optimal number of bins was determined for use in the subsequent volunteers by two radiation oncologists and MRI radiographer. The optimal number of bins was determined for clinical use and provided an appropriate compromise between imaging quality and motion information. The volunteers were not given any respiratory coaching, and were instructed to breathe normally. Artefact, noise, structure delineation and image quality were graded on a previously published four-point scale [17] for 4D-MRI (see Supplementary Material) for liver, right kidney, duodenum and pancreas by two radiation oncologists and an MRI radiographer. Lower scores in this scoring system indicate a higher quality image. Scores were obtained by consensus. Artefact was defined as presence of signal wrap, ghosting and distortion that impairs the definition of structures on the MRI, or motion artefact resulting in poor reconstruction of the 4D segmented scan. Image noise refers to the visible reduction in signal-to-noise ratio. Structure delineation was a composite score assessing ability to delineate structure and is impacted by noise and artefact. An overall image quality score was also given.

2.3. Patient study

Patients undergoing abdominal RT including 4D-CT and a planning MRI were consented prospectively via an opt-out process for an additional ten-minute 4D-MRI sequence. Ethics approval was obtained through South Western Sydney Local Health District (SWSLHD) Human Research and Ethics Committee (HREC) (LNR/17/LPOOL/259). 4D-MRI was performed on the same day immediately following the planning CT and 4D-CT.

Clinical and demographic details were collected including gender, histology, primary site and site of RT from patient electronic medical records and RT TPS (Pinnacle^3, Philips Medical Systems, The Netherlands). Each patient had tumour (or a surrogate within the region of interest (ROI) in the case of adjuvant RT) selected for the