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Original Research Article

Evaluating the repeatability and set-up sensitivity of a large field of view distortion phantom and software for magnetic resonance-only radiotherapy

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ABSTRACT

Background and purpose: Magnetic Resonance (MR)-only radiotherapy requires geometrically accurate MR images over the full scanner Field of View (FoV). This study aimed to investigate the repeatability of distortion measurements made using a commercial large FoV phantom and analysis software and the sensitivity of these measurements to small set-up errors.

Materials and methods: Geometric distortion was measured using a commercial phantom and software with 2D and 3D acquisition sequences on three different MR scanners. Two sets of repeatability measurements were made: three scans acquired without moving the phantom between scans (single set-up) and five scans acquired with the phantom re-set up in between each scan (repeated set-up). The set-up sensitivity was assessed by scanning the phantom with an intentional 1 mm lateral offset and independently an intentional 1° rotation.

Results: The mean standard deviation of distortion for all phantom markers for the repeated set-up scans was <0.4 mm for all scanners and sequences. For the 1 mm lateral offset scan 90% of the markers agreed within two standard deviations of the mean of the repeated set-up scan (median of all scanners and sequences, range 78%–93%). For the 1° rotation scan, 80% of markers agreed within two standard deviations of the mean (range 69%–93%).

Conclusions: Geometric distortion measurements using a commercial phantom and associated software appear repeatable, although with some sensitivity to set-up errors. This suggests the phantom and software are appropriate for commissioning a MR-only radiotherapy workflow.

1. Introduction

Magnetic Resonance (MR) imaging is increasingly being used within the radiotherapy planning pathway to delineate tumours and organs at risk. Delineation uncertainties are currently some of the largest uncertainties within the radiotherapy planning and delivery pathway [1], with the poor soft tissue contrast of Computed Tomography (CT) images being a significant reason [2]. MR has superior soft tissue contrast which reduces inter-observer variability in delineation and so reduces that uncertainty [3]. In addition functional MR scans such as diffusion weighted and dynamic contrast enhanced have shown potential for demonstrating active tumour sub-volumes which could receive dose boosts [4–6]. All these advantages have motivated incorporating MR imaging into the radiotherapy planning pathway.

In current practice the radiotherapy planning MR is typically registered with the planning CT, with the MR delineated contours being associated with the CT via this registration. However the MR-CT registration has its own uncertainty, which will contribute to the overall delineation uncertainty [7]. This has driven investigations into an MR-only radiotherapy planning pathway which aims to use the good soft-tissue contrast of the MR without the uncertainty of a MR-CT registration [8,9].

It is essential that images used for radiotherapy planning are geometrically accurate and MR images can suffer from significant geometric distortions [10]. MR image reconstruction assumes that the combination of the static magnetic field (B_0) and the gradient magnetic fields will vary linearly with position and uses this variation to encode spatial information [11]. Therefore inhomogeneities in the static magnetic field, gradient non-linearities and patient magnetic susceptibility effects will all cause geometric distortion by causing the magnetic field to vary non-linearly with position [12]. These first two causes are often called system distortions because they depend on the scanner (and

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acquisition sequence) but not on the patient [13]. This enables them to be characterised for a particular scanner and acquisition sequence. The system geometric distortions tend to be largest towards the edges of the MR scanner field of view [14]. For most diagnostic imaging and for radiotherapy planning utilising MR-CT registration this is not a significant issue because the anatomy of interest will typically be positioned in the centre of the field of view, where the distortion is least. However geometric distortion at the periphery of the field of view is a serious concern for MR-only radiotherapy planning since distortions in the patient external contour could significantly affect the calculated dose distribution and introduce errors in patient set-up [15–17]. This makes it vital to be able to measure the geometric distortion over the entire scanner field of view.

MR geometric distortion in general has been well-studied [18] and there have been several studies investigating geometric distortion throughout the entire scanner field of view using in-house phantoms and analysis software. These phantoms have consisted either of orthogonal grids [19,20] or 3D arrays of points [21–23]. These studies have demonstrated that the geometric distortion can be measured throughout the entire scanner field of view and that gradient distortion correction software can significantly reduce the measured distortions. Several commerical large field of view distortion phantoms have also been investigated [24,25]. Tadic et al. demonstrated that measurements of the geometric distortion at a limited number of points, combined with a spherical harmonic analysis method, enables the geometric distortion across the full field of the scanner to be characterised [24]. Antolak et al. demonstrated that the vendor supplied gradient distortion correction software reduced the measured distortions on both MR scanners and combined MR-radiotherapy treatment machines [25].

A large field of view distortion phantom is important both in optimising MR sequences for radiotherapy planning purposes and in carrying out regular quality assurance testing of the MR scanner. In order to use this phantom it is important to ensure that the measurements made are repeatable and to characterise the sensitivity of the measurements to small set-up errors. Wang et al. investigated repeat geometric distortion measurements without moving the phantom between acquisitions and demonstrated very small differences [19]. However this does not take into account any set-up differences, which are necessary to produce a repeatability measurement which applies to the clinical use of the phantom. Price et al. investigated the set-up repeatability of their phantom using repeat CT acquisitions with independent phantom set-up for each acquisition [23]. This does not assess the repeatability of distortion measurements made by the phantom however, just the repeatability of the phantom set-up. To the best of our knowledge the repeatability of geometric distortion measurements using a large field of view phantom and software have not been reported in the literature.

The purpose of this study was to fill this gap by evaluating the repeatability and set-up sensitivity of a commercial large field of view phantom and associated software for distortion measurements on three different MR scanners in three different centres. The focus of this study was evaluating the phantom for a MR-only radiotherapy workflow, however the results are relevant to the wider MR community.

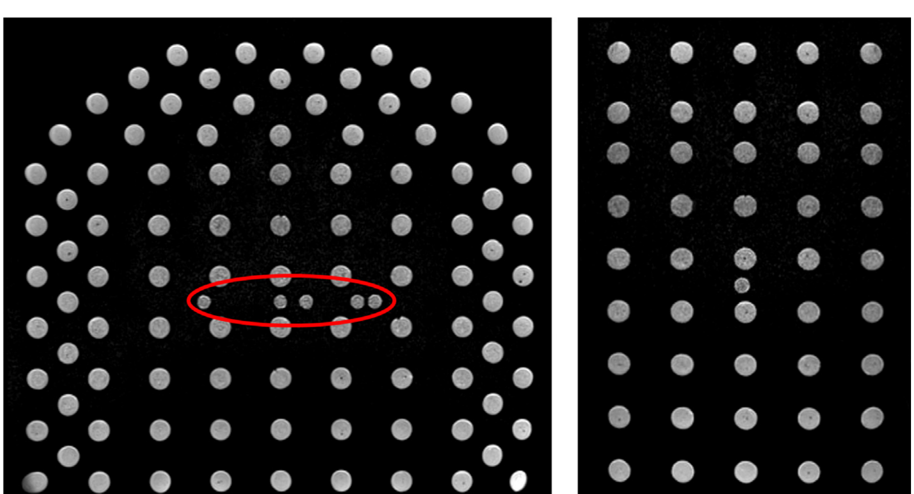
2. Materials and methods

2.1. Distortion phantom and software

The phantoms used in this study were two GRADE phantoms (Spectronic Medical AB, Helsingborg, Sweden), consisting of approximately 1,200 small spherical markers at known positions embedded in expanded foam. This enables the phantom to be large enough to assess the full scanner field of view but still weigh less than 10 kg. The markers are made of polyethylene glycol and have a diameter of 17 mm. Spectronic Medical AB customise the external dimensions of the GRADE phantoms to a particular MR scanner. This customisation permits the full scanner field of view to be sampled whilst ensuring the phantom is small emough to fit in the scanner bore. Two different GRADE phantoms were used in this study, one customised for a 3 T Magnetom Prisma (Siemens, Erglangen, Germany) and one customised for a 1.5 T Magnetom Espree (Siemens). The two phantoms were of similar design but slightly different sizes to fit the different scanner bores. The second phantom was also used for measurements on a 3 T Signa PET-MR (GE Healthcare, Wisconsin, USA). An MR image of the second phantom is shown in Fig. 1. The markers are in a grid pattern with a spacing of approximately 50 mm. The spacing between markers near the edges of the phantom is smaller (30 mm), to give a more precise measure of the distortion in the periphery of the scanner field of view.

All distortion analyses were carried out using the associated Spectronic Medical AB GRADE evaluation software. This is an entirely automatic process with a number of steps. First a unique pattern of markers in the centre of the phantom (see Fig. 1) are analysed to identify the phantom and determine its orientation. Secondly the software carries out a deformable registration between the acquired MR image and the reference image of the phantom contained within the software. The deformation field is used to determine the geometric distortion in the MR image. Distortion is given on a marker by marker basis and for the nth marker is given by

$$D_n = \sqrt{(x_{n,im}-x_{n,ref})^2 + (y_{n,im}-y_{n,ref})^2 + (z_{n,im}-z_{n,ref})^2}, \tag{1}$$



(a) Axial view (b) Sagittal view

Fig. 1. Axial (left) and sagittal (right) planes from MR images of the Spectronic Medical GRADE distortion phantom. The small central markers used to identify the phantom and determine its orientation and position can be seen in the middle of the axial view (red circle). (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this article.)