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Development and validation of a novel large field of view phantom and a software module for the quality assurance of geometric distortion in magnetic resonance imaging

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ABSTRACT

Objective: To develop and validate a large field of view phantom and quality assurance software tool for the assessment and characterization of geometric distortion in MRI scanners commissioned for radiation therapy planning.

Materials and Methods: A purpose built phantom was developed consisting of 357 rods (6 mm in diameter) of polymethyl-methacrylat separated by 20 mm intervals, providing a three dimensional array of control points at known spatial locations covering a large field of view up to a diameter of 420 mm. An in-house software module was developed to allow automatic geometric distortion assessment. This software module was validated against a virtual dataset of the phantom that reproduced the exact geometry of the physical phantom, but with known translational and rotational displacements and warping. For validation experiments, clinical MRI sequences were acquired with and without the application of a commercial 3D distortion correction algorithm (Gradwarp™). The software module was used to characterize and assess system-related geometric distortion in the sequences relative to a benchmark CT dataset, and the efficacy of the vendor geometric distortion correction algorithms (GDC) was also assessed.

Results: Results issued from the validation of the software against virtual images demonstrate the algorithm's ability to accurately calculate geometric distortion with sub-pixel precision by the extraction of rods and quantization of displacements. Geometric distortion was assessed for the typical sequences used in radiotherapy applications and over a clinically relevant 420 mm field of view (FOV). As expected and towards the edges of the field of view (FOV), distortion increased with increasing FOV. For all assessed sequences, the vendor GDC was able to reduce the mean distortion to below 1 mm over a field of view of 5, 10, 15 and 20 cm radius respectively.

Conclusion: Results issued from the application of the developed phantoms and algorithms demonstrate a high level of precision. The results indicate that this platform represents an important, robust and objective tool to perform routine quality assurance of MR-guided therapeutic applications, where spatial accuracy is paramount.

1. Introduction

Technological advances in magnetic resonance imaging (MRI) have led to an evolution of its role from primarily a diagnostic imaging modality, to a powerful and versatile tool for the guidance of localized therapies such as surgery, radiation therapy (RT) and high-intensity focused ultrasound (HIFU) therapy [1–3]. MRI provides excellent soft tissue contrast and resolution as well as functional imaging capabilities, allowing for the spatial and physiological characterization of disease [4]. The premise of MR-based image guidance is to accurately localize the target which permits reduced safety margins required for successful therapeutic outcomes [1]. This can translate into substantial reduction in treatment-related morbidities, and in the context of cancer treatments such as radiation therapy, into the ability to escalate and/or intensify prescription dose [5]. Hence, the development of therapy devices co-localized to the reference frame of the MR-imaging unit is an active area of clinical investigation.

For any image-guided therapy application, spatial accuracy and geometric fidelity are paramount. One of the historical criticisms of MRI is the presence of system-related and object-induced geometric distortion within the produced images.

System-related distortions, which have been addressed in this study, are mainly caused by the inhomogeneities in the main magnetic field (B_0) and the nonlinearities of the gradient coils within

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the scanner while object-induced geometric distortions are caused by susceptibility and chemical shift variations in the sample.

The spatial localization of MR signals relies on the assumption of a specified relationship between position and magnetic field strength. Therefore, any unknown distortion of the magnetic field across the sample during the imaging process will lead to image distortions. In modern scanners, three gradient coils producing orthogonal, highly linear field gradients across the imaging volume are used. However, the demand for shorter bore magnet along with faster and stronger gradient systems in order to increase patient comfort and to reduce the effects of patient movements, have led to an increase in the gradient field nonlinearity which results in image distortions [6]. Furthermore, since the static field inhomogeneity and gradient non-linearity increase with distance from the magnet isocenter, the system-related geometric distortions will increase in such regions of the magnet.

Therefore, geometric distortions need to be measured over a large distance for each set of coils, and corrections must be applied.

Each type of geometric distortion has been extensively described in the literature, and correction strategies are the focus of current research.

The system-related geometric distortion component, has been extensively analyzed and reported in the literature, and several different approaches have been presented to characterize and assess these distortions [7–10,6,11–13]. Vendor-specific geometric distortion correction (GDC) algorithms are commonly supplied with most modern MR systems [14,6]. However, existing protocols and phantoms do not allow for the detailed characterization of geometric distortion for large field of view (FOV) acquisitions, nor for assessment and monitoring of the performance of vendor-specific geometric distortion correction algorithms. Most studies have been performed for relatively small fields of view [15,7,9,10,6,11]. These considerations are particularly critical in image-guided radiotherapy, where large FOV acquisitions are required to provide a geometrically accurate representation of the tumor, the organs at risk as well as the entire patient body contour for the anatomical region of interest imaged.

The work is a part of a larger quality assurance program aimed at the characterization of system-related geometric distortion of MRI scanners used for image-guided radiotherapy. A novel large FOV phantom and associated software has been developed to assess spatial accuracy of typical pulse sequences used in RT planning, over clinically relevant scan lengths/volumes. The accuracy of vendor-specific geometric distortion correction algorithms is quantified by measuring geometric image distortion before and after the application of the 2D and 3D correction algorithms. The results were used to develop a benchmark reference for periodic quality control (QC) to assess the stability and reproducibility of geometric accuracy for the MR system under study.

2. Materials and methods

2.1. Phantom construction and validation

A custom-built phantom — see Fig. 1 — was commissioned consisting of a water-filled cylinder containing 357 rods (6 mm diameter each) of polymethyl-methacrylat separated by an interval of 20 mm providing an array of control points at known spatial locations over a large field of view. The total diameter of the phantom is 420 mm with a total weight of 29 kilograms. The rods have varying lengths with a range of 125 mm to 215 mm allowing for in-plane distortion assessment over the typical scan lengths used for medical image guidance.

In order to verify that the phantom had been manufactured within relevant tolerances, a CT image data set with 75 slices, each 3 mm thick and no gap, a field of view of 500 mm, and a pixel size of 1.27 mm^2 was acquired with a SIEMENS SOMATOM Sensation CT simulator. This procedure allows also the construction of a theoretical grid against which MR geometric distortion is evaluated.

2.2. Geometric distortion

The mathematical description of the three dimensional geometrical distortion has been previously described [16] as a set of deviations of the positional displacement vector measured at the control points,

$$\begin{aligned} d_x(i,j,k) &= x'(i,j,k) - x(i,j,k) \\ d_y(i,j,k) &= y'(i,j,k) - y(i,j,k) \\ d_z(i,j,k) &= z'(i,j,k) - z(i,j,k) \end{aligned} \tag{1}$$

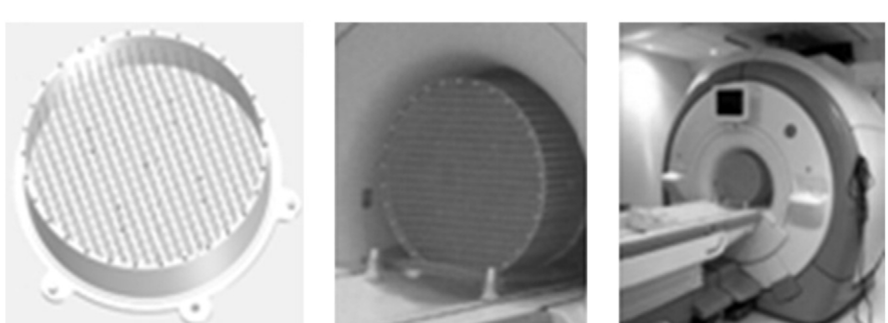

Fig. 1. Large field of view phantom.