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Optimizing MRI sequences and images for MRI-based stereotactic radiosurgery treatment planning

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ABSTRACT

Aim: Development of MRI sequences and processing methods for the production of images appropriate for direct use in stereotactic radiosurgery (SRS) treatment planning.
Background: MRI is useful in SRS treatment planning, especially for patients with brain lesions or anatomical targets that are poorly distinguished by CT, but its use requires further refinement. This methodology seeks to optimize MRI sequences to generate distortion-free and clinically relevant MR images for MRI-only SRS treatment planning.
Materials and methods: We used commercially available SRS MRI-guided radiotherapy phantoms and eight patients to optimize sequences for patient imaging. Workflow involved the choice of correct MRI sequence(s), optimization of the sequence parameters, evaluation of image quality (artifact free and clinically relevant), measurement of geometrical distortion, and evaluation of the accuracy of our offline correction algorithm.
Results: CT images showed a maximum deviation of 1.3 mm and minimum deviation of 0.4 mm from true fiducial position for SRS coordinate definition. Interestingly, uncorrected

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MR images showed maximum deviation of 1.2 mm and minimum of 0.4 mm, comparable to CT images used for SRS coordinate definition. After geometrical correction, we observed a maximum deviation of 1.1 mm and minimum deviation of only 0.3 mm.

Conclusion: Our optimized MRI pulse sequences and image correction technique show promising results; MR images produced under these conditions are appropriate for direct use in SRS treatment planning.

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1. Introduction

Magnetic resonance imaging (MRI) is the imaging modality of choice for target definition for stereotactic radiotherapy due to its superior soft tissue resolution, not only in the brain but in extracranial sites as well. In cases of intracranial stereotactic radiotherapy, MRI can also be used for dosimetry planning as the brain is considered homogenous. The advantages of using MRI alone in intracranial SRS include avoiding systematic errors that may occur due to CT-MRI registration, and the risks associated with ionizing radiation exposure from CT scans.

Although MR images have an excellent soft-tissue contrast, allowing superior visualization of gross tumor volume (GTV) and organs at risk (OAR), the geometrical distortion of MR images is one of the main obstacles to their optimal use in SRS planning; therefore, CT is still commonly used to obtain geometrically accurate reference images. CT images also provide electron density data and can be registered with MR images for geometrical distortion correction.[1]

One motivation for the solo use of MRI for SRS planning is that most centers use Tissue Maximum Ratio (TMR) tables for SRS treatment planning; these tables do not account for brain tissue inhomogeneity. This technique is faster, simpler and no information about tissue electron density is required; however, many groups are working on synthetic CT images which make use of MR images.

With the use of synthetic CT images derived from MR images, we still retain the option to use convolution/superposition algorithms in SRS treatment planning for more accurate dose calculation.

The geometrical accuracy of MR images can be compromised by both system- and patient-specific distortions. System related distortion is mainly caused by main magnetic field (B_0) inhomogeneity and gradient nonlinearity. These effects are reproducible for each scanner, but vary for different field strengths and vendors, and must be evaluated during the commissioning process.[2]

The B_0 of an MRI is measured in parts per million (ppm) over a diameter of spherical volume (DSV) extending out from the scanner isocenter. We expect a nominal homogeneity of 1.1 ppm across a 37 cm DSV for a 1.5 T scanner; this corresponds to a frequency offset of 70.2 Hz. This offset resonance frequency along the frequency encoding direction creates discrepancies in signal location which manifest as image intensity variation and distortion.

Gradient coils localize the MRI signal within the body to visualize the anatomy. Many newly developed fast MRI pulse sequences have been used in the clinic to minimize artifacts due to motion and provide patient comfort. These sequences need strong gradients, but there is always a tradeoff between gradient strength and linearity. The gradient linearity error should be less than 2% of the gradient strength over a 40-cm diameter of spherical volume (DSV).[3]

Modern MRI scanners have homogenous magnetic fields; therefore, the main source of image distortion is gradient non-linearity. Most vendors provide post-processing offline correction algorithms, which are applied in 2 and 3 dimensions,[4–6] but still there is a need to evaluate the efficiency of such corrections with periodic phantom measurements.

Patient-specific distortion originates from the effect of tissue magnetic susceptibility (χ) on the local magnetic field. These random distortions are not corrected by standard MRI post-processing correction algorithms and need careful consideration, especially when MR images are being used as a sole source for SRS planning. Patient-specific distortion may cause tumor and normal tissue dislocation, significant error in stereotactic coordinates definition, and MRI-CT co-registration difficulty, especially when targets in the brain are very close to air cavities, or away from the magnet isocenter.

Several methods have been suggested to correct patient-specific distortion. One is an increase in receiver bandwidth, but increasing the bandwidth leads to a reduction in the signal-to-noise ratio (SNR).[7,8] Another is to use manual and high-order shimming to render the magnetic field more locally homogenous by minimizing the effect of magnetic susceptibility, chemical shift and eddy current through the region of scan.[9–11] Finally, a B_0 field map, very commonly used in functional MRI (fMRI) studies, has been used to correct for geometrical distortions in echo planar imaging (EPI) images.[12] All of these methods have their own advantages and disadvantages, but for our purposes, to be used in the SRS clinic, their accuracy, clinical flow and compatibility with SRS treatment planning system are vital factors.[12]

Different MRI sequences (different contrasts) are being used for GTV and OAR contouring in SRS treatment planning systems. Depending on the clinical protocol implemented, CT and MRI images may initially define the stereotactic coordinates, and then CT image set is co-registered rigidly to MR images to correct for any noticeable geometrical distortion. Importantly, to accurately correct MR images they must be registered deformably not rigidly with CT images which is not an option with the current SRS Gamma Knife treatment planning systems. Specifically, distortions are more noticeable when MR images are collected in a 2D mode, with different slice