Phantom and Clinical Validation of 3T MRI for Gamma Knife® Radiosurgery Treatment Planning

B. Zhang[1], D. MacFadden[2], A. Z. Damyanovich[1], M. Rieker[3], K. K. Brock[1], M. Hodaie[4], N. Laperriere[1], M. Schwartz[4], M. Tsao[1], J. Stainsby[5], D. A. Jaffray[1], M. Bernstein[4], D. Mikulis[6], and C. Ménard[1]

[1]Radiation Medicine Program, Princess Margaret Hospital, Toronto, Ontario, Canada, [2]Faculty of Medicine, University of Toronto, Toronto, Ontario, Canada, [3]Physikalisch-Technische Gesellschaft für Radiologie mbH, Tübingen, Germany, [4]Division of Neurosurgery, Toronto Western Hospital, Toronto, Ontario, Canada, [5]Applied Science Laboratories, GE Healthcare, Mississauga, Ontario, Canada, [6]Department of Medical Imaging, University Health Network, Toronto, Ontario, Canada

Introduction

Gamma Knife® (GK) radiosurgery (RS) is a non-invasive technique for the high-precision delivery of high single-dose radiotherapy to small intra-cranial targets, while minimizing the risk of damaging healthy surrounding tissue. GK RS has established an important role in the treatment of patients with primary and secondary brain tumors, as well as arteriovenous malformation (AVM) and trigeminal neuralgia (TN) [1]. The high precision of GK RS demands an image-guidance modality that provides accurate target identification with stereotactic geometric fidelity. MRI is central to GK RS treatment planning, primarily due to its ability to provide high resolution images with high contrast between normal and abnormal tissues in the brain. Current standard clinical practice is to use 1.5T MR images for GK RS planning. 3T MRI provides better signal compared to 1.5T, which may enhance visualization and resolution of small targets, in turn improving the accuracy of radiation delivery. However, the increased potential for spatial error from magnetic susceptibility at high field strengths [2] may result in geometric inaccuracies, leading to compromised delivery. Previous phantom study in geometric accuracy of 3T MRI for GK RS warrants further investigation [3]. In this study we aim to explore the validity of using 3T MRI for GK RS planning. This study consisted of the investigation of both phantom and clinical geometric accuracies, and the investigation of 3T MRI in two clinical applications: 1) delineation of tumor target volumes and 2) treatment plan isocenter placement for TN.

Methods

Twenty-six GK RS patients were enrolled on a prospective clinical trial and received the following imaging studies after stereotactic frame and fiducial reference placement: 1) CT [Toshiba Aquilion 64: 120kV, 260mA, FOV 23.9, 512x512], 2) 1.5T MRI [GE Signa HD: 3D T1-FSPGR (TE 5.1, TR 12.0, ETL 1, BW 15.63, FOV 22.0, NEX 2, 256x256) and 3D T2-FRFSE (TE 113.2, TR 2000, ETL 32, BW 15.63, FOV 22.0, NEX 1, 384x384)], and 3) 3T MRI [GE Signa HDx: 3D T1-FSPGR (TE 3.7, TR 9.0, ETL 1, BW 31.25, FOV 22.0, NEX 2, 320x320) and 3D T2-FRFSE (TE 115.4, TR 2000, ETL 32, BW 31.25, FOV 22.0, NEX 1, 384x384)]. Slice thickness of 1mm was used in all imaging. Imaging parameters were chosen to optimize image quality at 3T and 1.5T while maintaining the same scan time (10 minutes) for all sequences. Higher spatial resolution was achieved in T1-FSPGR at 3T compared to 1.5T. *Geometric accuracy*: We utilized TOPAS (PTGR, Tübingen, Germany), a phantom and software package specifically designed for GK imaging geometric accuracy evaluation. TOPAS phantom consists of a cylindrical body filled with distilled water and 145 rods arranged equidistantly (10mm) within the phantom. TOPAS software calculates the deviation of rod location detected on the MR images from the ideal location of rods in stereotactic space. For 17 cases, phantom imaging was performed on 3T prior to patient imaging using the same stereotactic set-up and imaging sequences. All image sets were corrected for known gradient nonlinearities in 3D then imported into GammaPlan® (Elekta, Stockholm, Sweden) for stereotactic definition of fiducial references. Geometric accuracy in phantom was evaluated using stereotactic fiducial reference deviations from ideal reported by GammaPlan® as well as internal rod deviations reported by TOPAS. Geometric accuracy in patients was compared between 3T and 1.5T using fiducial reference deviations from ideal for all 26 patients, and displacement of the cochlea and semicircular canals relative to CT for 8 patients. *Clinical application*: Two radiation oncologists and two neurosurgeons delineated target volumes (TVs) for 4 patients (3 vestibular schwannoma, 1 meningioma), based on MRI at 3T and 1.5T. TV spatial congruency and reproducibility were determined using vector distances and volume overlap between delineation on 3T and 1.5T images. Two radiation oncologists and one neurosurgeon each generated single-isocenter TN treatment plans for 5 patients based on MRI at 3T and 1.5T. Spatial congruency and reproducibility of isocenter targeting at 3T and 1.5T were determined by comparing mean and variance of x, y, z coordinates of the isocenter.

Results

Geometric accuracy: T1-FSPGR on 3T yielded similar mean(standard deviation) stereotactic fiducial reference deviations [0.5(0.2)mm] compared to 1.5T [0.6(0.1)mm] for all 26 patients. Subsequent to 3T scanner hardware update, T2-FRFSE also yielded comparable stereotactic fiducial reference deviations between 3T [0.4(0.1)mm] and 1.5T [0.6(0.1)mm] in 21 patients. For the 17 cases when phantom imaging was performed on 3T prior to patient imaging, the mean stereotactic fiducial reference deviations correlated well between phantom and patient for both T1-FSPGR (R=0.81) and T2-FRFSE (R=0.87). The mean deviation of phantom internal rods in the axial plane at 3T were 0.4(SD=0.1)mm and 0.3(SD=0.1)mm for T1-FSPGR and T2-FRFSE respectively. The difference between mean anatomic landmark displacement at 3T and 1.5T (relative to CT) was 0.1(SD=0.3)mm.

Clinical application: For TV delineation, mean distance between representative TV surfaces defined in 3T and 1.5T was 0.7(SD=0.3)mm. No statistically significant differences (P=0.93) were found in TV volume congruence (92%[3T] vs. 92%[1.5T]) or TV mean surface vector distances between observers (0.6(SD=0.4)mm[3T] vs. 0.7(SD=0.4)mm[1.5T]). For TN isocenter targeting, no statistically significant difference (P=0.23) was found between mean or variance of isocenter coordinate locations based on images at 3T and 1.5T.

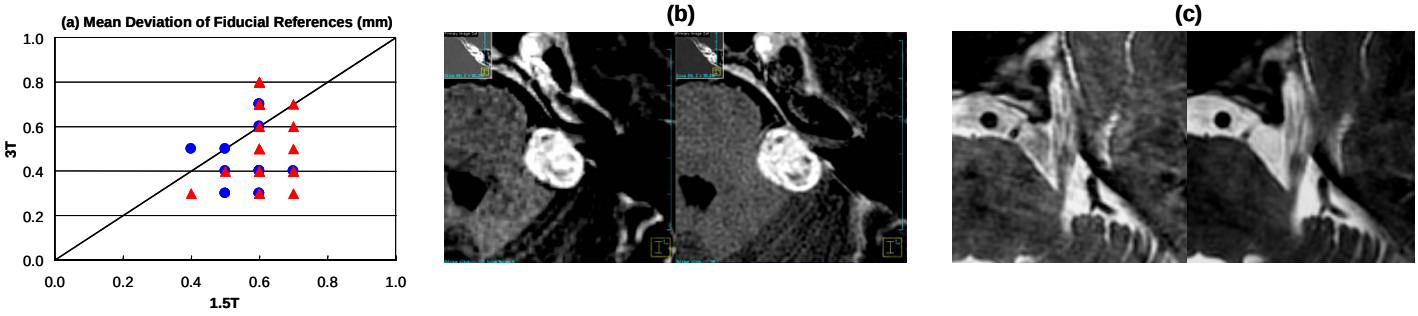

Figure 1. Patient results: (a) Mean deviation of stereotactic fiducial references (3T vs. 1.5T) for T1-FSPGR (blue) and T2-FRFSE (red). Data points visible in the figure are less than the actual number of cases due to overlap. (b) T1-FSPGR images for target volume delineation (left: 1.5T, right: 3T). (c) T2-FRFSE images at 1.5T(left) and 3T (right) used for TN isocenter placement, demonstrating superior image quality at 3T.

Conclusions

We have established the validity of using 3T MRI for GK RS treatment planning under the imaging conditions investigated. Geometric accuracy of stereotatic fiducial references and anatomic landmarks in 3T MRI are comparable to 1.5T MRI for GK RS planning. Target volume delineation and TN isocenter placement using 3T MRI for GK RS planning produced similar spatial congruency compared to 1.5T MRI. Despite a subjective improvement in image quality, we could not demonstrate an improvement in observer reproduciblity with 3T MRI compare to 1.5T MRI in a small subset of patients.

References and Acknowledgements

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The authors acknowledge Heather Sharpe, Garry Detzler, Eugen Hlasny, David Johnstone and financial support from Ontario Cancer Research Network (OCRN).