The Effect of Sub-Pixel MRI shifts on Radiosurgical Dosimetry for Vestibular Schwannomas.

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Abstract

Objective: We identified subpixel MRI shifts of intracanalicular vestibular schwannomas with respect to the internal auditory canal as imaged on CT. We investigated the source of imaging related localization errors in radiosurgery and the effect of such shifts on the dosimetry for small targets.

Methods: When comparing the stereotactic coordinates of intracanalicular vestibular schwannomas as imaged on MRI, shift of the tumor with respect to the location of the internal auditory canal as imaged by CT represents an error in localization. A shift vector places the tumor within the internal auditory canal and measures the CT/MRI discrepancy. The shift vectors were measured in a series of 10 largely intracanalicular vestibular schwannomas (all less then 1.5 cm3 in volume). Using dose volume histogram measurements, the overlap between shifted and unshifted tumor and radiosurgical treatment plans were measured.

Using plastic and bone phantoms and TLD measurements, the correspondence between targets imaged by MRI and CT and treatments delivered in the Leksell Gamma Knife® were measured. Combining these measurements, the correspondence between intended vs. actual treatments was measured.

*Conclusion*s: The delivery to CT imaged targets was accurate to our limits of measurement (~0.1mm). The MRI shifts seen in the Y-axis averaged 0.9 mm and in the Z-axis 0.8 mm. The corresponding percent tumor coverage with respect to target shifted so as to be centered within the internal auditory canal decreased from 98 to 77%. This represents a significant potential error when targets are defined solely by MRI imaging.

Introduction

The goal of the radiosurgical treatment of small vestibular schwannomas is to arrest tumor growth while minimizing the risk of neurological morbidity, namely loss of hearing and injury to the facial nerve. In general the goal of radiosurgery is to deliver a therapeutic does of radiation within a

three dimensionally defined target volume while delivering as little as possible radiation to the normal structures outside the target volume. Toward this goal, many centers, in recent years, have reduced the dose given to the periphery of vestibular schwannomas to 12 Gy, the minimum dose that appears to be needed to reliably arrest tumor growth. With the advent of high-speed computers, Gamma Knife treatment planning has evolved in the 1990s toward highly conformal plans using multiple isocenters. When using highly conformal treatment plans with radiosurgical devices having a sharp dose falloff, positioning errors become critical.

MRI spatial distortion has long been known and has been well documented [2-6,8,9,11, 12 ,16-21]. It has been found that such errors may be within the dimensions of a single pixel [10, 20]. We have investigated with source and effect of imaging related positional shifts on the quality of radiosurgical dosimetry for small vestibular schwannomas with the goal of improving both the effectiveness of treatment and preservation of hearing.

Materials and Methods:

Fifteen small largely intracanalicular vestibular schwannomas were selected for statistical purposes all having a volume less than 1.5 cm3. In all cases the patients were scanned on a Siemens Symphony 1.5 Tesla MRI to which spatial corrective software had been applied. CT images were obtained on Siemens Impact CT machines. In all cases image sequences included MPRAGE post-gadolinium (3D T1 weighted sequence) having a voxel size of 1x1x1 mm3, CISS (3D T2 weighted sequence) having a voxel size of 0.5x0.5x1 mm3, and high-resolution bone CT having a voxel size of 0.25x0.25x1mm. Tumor volumes were manually outlined on the MRI sequences. The internal auditory canal and cochlea was identified on the CT sequences.

Shift vectors were obtained after planning had been completed on the MRI determined target volume and percent isodose coverage was at least 98% at 12 Gy (50% isodose). By viewing the CT axial sequence, all of the isocenters or “shots” were selected and shifted in all cases posteriorly (Y axis) so that the 50% isodose curve was centered into the internal auditory canal. By then viewing the sagittal CT reconstruction, the isocenters were shifted upwards in the Z axis so that the 50% isodose curve was also within the internal auditory canal. In no cases was an X axis shift employed. The shift vector was thus determined by the Y and Z axis shifts.

Following shift of the 50% isodose curve into the internal auditory canal, the dose volume histogram was recomputed and measured at the 12 Gy (50% isodose) volume.

The relative accuracy of imaging by CT versus MRI was measured using phantom-based targets imaged on both CT and MRI and then treated in the Leksell Gamma Knife®. To simulate the internal auditory canal, 5 mm horizontal holes where drilled into beef bone into which Vitamin E capsules were inserted. The bone phantom was inserted into a humanoid “Rando” phantom that was fixed in the Leksell stereotactic frame to be imaged by MRI and CT. The images were transported using the DICOM protocol over the hospital Ethernet to the Leksell GammaPlan® workstation for analysis.

A plastic phantom was developed with channels filled by a mixture of the copper sulfate and iodine contrast. Target localization was performed using TLDs [4,6, 8 12]. Simulated treatments were carried out by placing the phantom in the Leksell frame into the Gamma Knife® at the targeted coordinate.

Experiments directed at identifying the cause and the development of corrective algorithms during MRI scanning using the above methods are underway and are outside the scope of this investigation (Tsai, J. et al., unpublished data, 2002).

Results

In all cases an obvious discrepancy between the target as imaged on MRI and the internal auditory canal as imaged on CT was apparent. The

resolution of isocenter positioning on the Gamma Knife and GammaPlan software is limited to 0.5mm steps. Measured shifts fell between –0.5 and –1.0 mm in both the Y and Z axes. The mean shift vector was (0.0, -0.9,-0.8) +/- 0.5 mm. An observable shift in the X axis was noted prior to application of the Siemens corrective software however due to the geometry of the internal auditory canal, X axis shifts are not easily measured by technique reported in this paper. In all cases a negative Y and Z axis shift was identified and this appeared relatively insensitive to the MRI sequence i.e. was present on both MPRAGE and CISS sequences.

The phantom experiments supported the measurements obtained on vestibular schwannomas in the internal auditory canal. Localization based on CT with respect to simulated treatments as measured by TLD had 0.0 mm +/- 0.25mm error in all directions to the limits of our ability to measure. MRI errors were (0.0, -0.5, -0.5) +/- 0.5 mm.

Dose volume histogram measurements were obtained of the percent target volume receiving at least 12 Gy (50% isodose). In all cases, plans were not accepted until at least 98% of the MRI imaged target volume was covered in a highly conformal fashion. After CT derived shift vectors were applied, the predicted dose volume histogram percent target coverage fell to an average of 77% with a range of 62 to 86 %. Note that the shift vector was relatively constant and hence the decrease in percent target coverage was a function of the target volume, smaller targets having a relatively lower coverage and larger targets having a relatively better coverage.

Discussion

It has been suggested that MRI targeting errors are within a single pixel in dimension.[10]. Sub pixel measurements are routinely dealt with in the field of digital imaging by a variety of algorithms. Pixelation is readily removed by oversampling algorithms. The figures in this paper have been significantly enlarged yet to do demonstrate significant pixelation due to the application of bilinear filtering. The presence of MRI shift is readily demonstrated as in the figures where the tumor as imaged by MRI appears to be shifted outside the internal auditory canal as imaged by CT. [Figures 1 -4]. Our measurement of such MRI targeting errors is entirely consistent with numerous previous demonstrations of MRI inaccuracy [2,10, 17-21]. We have demonstrated that it is possible to measure and correct for subpixel MRI targeting errors and that such errors are potentially significant.

This investigation has not directly addressed the cause of such MRI positioning errors but both magnetic susceptibility artifacts introduced at the tumor/bone interface as well as eddy currents may be factors. MRI distortion secondary to eddy currents has been well identified. [3,5,9].

The quality of a radiosurgical plan may be measured by a *quality factor* [1] that is simply a ratio of the (*percent tumor coverage* x *tumor volume*)/ *risk isodose volume*. When plans are conformal and have sharp dose falloff outside the tumor volume, such as is characteristic of gamma knife plans, the single most important factor affecting the plan quality is the presence of shifts [Figure 5].

Excellent long-term results have been reported with prescription isodose averaging 16 Gy [11]. In an attempt to improve the rate of hearing preservation, prescription isodoses have been lowered to the range of 12 – 13 Gy. Long term results, and when planning has used CT localization, have demonstrated the minimum effective dose appears to be 12 Gy [14,15] We have demonstrated that uncorrected MRI targeting errors in the range of 0.5 – 1 mm may cause a significant reduction in dose delivery to small complex targets. Generally a percent target coverage of 77% would be considered unacceptable in Gamma Knife dosimetry. It is certainly possible that shifts may occur either toward or away from the cochlear nerve or apparatus. In such cases when shifts are directed away from the cochlear apparatus, hearing may in fact show a higher rate of preservation than when the targeting is correct. However the tumor itself will be underdosed and long term results may be compromised. In order to correct for potential underdosing one may need to increase the amount of radiation to a prescription isodose of 16 Gy (50%), and hence the peripheral falloff will cover the tumor to a minimal isodose of 12 Gy. [Figure 6]. Although excellent results using a prescription isodose at 16 Gy are obtained with MRI targeting alone, we are concerned that when isodoses of 12 Gy are prescribed, both CT and MRI targeting should be used, unless the site has convincingly demonstrated a lack of significant MRI

shift on that particular machine. In such cases, the gamma knife quality assurance program should periodically test for MRI shifts as these may be introduced when any of the imaging parameters in the MRI are changed (software updates etc.).

It has been suggested that MRI spatial shifts are within a single pixel. This does not appear always to be the case. Figure 4 (a) demonstrates a 3D T1 MRI of a right facial neuroma. Note the extension of gadolinium contrast enhancement through the facial canal. Figure 4 (b) is the same tumor imaged with a high resolution 3D T2 sequence (CISS) having a 0.5 x 0.5 x 1mm voxel size. The dashed line represents the tumor volume as imaged on the T1 sequence and is not shifted. Figure 4 (c) is a CT of the same tumor which demonstrates the cochlea just anterior to the internal auditory canal. The tumor volume as outlined on the T1 MRI sequence is clearly shifted anteriorly and in this case the tumor volume overlaps the cochea itself. The 1 mm anterior shift is greater than the 0.5 mm pixel size of the CISS sequence. Such cases demonstrate the possibility that treatment on the basis of an uncorrected MRI might cause damage to the cochlea, and/or facial nerve within the internal auditory canal.

Conclusions

When small targets such as vestibular schwannomas are imaged by MRI as well as CT, small discrepancies in spatial localization are found. Such shifts, or positioning errors, are due to errors in MRI spatial localization. By comparing targets as derived from MRI with those derived from CT, a correction vector allows proper targeting of radiosurgical treatments. In our institution, this correction vector has a mean coordinate (0.0, -0.7, -0.8) mm but may vary from machine to machine.

When the MRI image is shifted anteriorly with respect to the internal auditory canal, the cochlea and/or facial nerve may receive higher doses of radiation than anticipated.

When treating small, largely intracanalicular vestibular schwannomas the overlap between corrected and uncorrected tumor volumes averages 77%. This indicates, given the magnitude of the subpixel error detected in our MRI device, that an average of 23% of tumors treated based on MRI alone, and without spatial correction would be underdosed.

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Figure Legend

Figure 1: High resolution 3D T2 (CISS). 0.5 x 0.5 x 1 mm voxel. Axial slice demonstrating vestibular schwannoma within the right internal auditory canal. The plan has been developed based on the MRI and the isocenters then shifted to place the 50% isodose line within the internal auditory canal as imaged on CT.

Figure 2: High resolution 0.25 x 0.25 x 1mm CT sagittal reformat through the internal auditory canal. The tumor as outlined on the MRI (Figure 1) is dashed. The 50% isodose curve has been shifted to correspond with the internal auditory canal.

Figure 3:

A: 3D T1 (MPRAGE) 1x1x1 mm volume acquisition axial slice through vestibular schwannoma entering the internal auditory canal.

B: High resolution CT axial slice at the same level as *A* demonstrating shift of the tumor as outlined on the MRI with respect to the internal auditory canal as seen on CT.

Figure 4:

A: T1 axial image of a facial neurinoma extending from the cerebellopontine angle through the right facial canal. The characteristic of the facial neurinoma which distinguishes this from a vestibular schwannoma is the extent of enhancement into the facial canal.

B: High resolution 3D T2 (CISS) sequence (0.5 x 0.5 x 1mm voxel size) demonstrates excellent contrast between CSF and tumor in the cerebellopontine angle and internal auditory canal. Nerve fascicles are readily imaged. The tumor outlined on T1 sequence is in the same spatial location as seen on this T2 sequence.

C: High resolution CT demonstrates the internal auditory canal and cochlea. The dashed line represents the tumor as outlined on the T1 MRI. The MRI image is shifted anteriorly with respect to the internal auditory canal as seen on this CT. The outlined volume overlaps the cochlea. In the absence of

a corrective shift vector applied to the treatment plan, the treatment dose prescribed to the tumor would instead be delivered to the cochlea, possibly resulting in hearing loss. Similarly planning on uncorrected MRI images might push higher isodose curves into the facial nerve.

Figure 5: Factors that affect the quality of radiosurgical plans. The *quality factor* is the (*percent target coverage x target volume*)/(*risk isodose volume*).[Borden et al, 2000] In the case of cerebral arteriovenous malformations, risk of complications is associated with the 12 Gy volume [Flickinger et al].

The white outline represents the target, the shaded outline represents the treatment isodose line. When the plan is not conformal, i.e. the treatment isodose falls significantly outside the target, the quality is low. When the plan is conformal, has a sharp dose falloff and is accurately positioned the quality is high. When the plan is conformal, has a sharp dose falloff yet not accurately positioned, the quality is low. This emphasizes the importance of accurate treatment delivery and the correction of imaging shifts.

Figure 6: The rate of tumor control is proportional to the minimum dose delivered to the tumor. When the treatment plan has been shifted due to an error in imaging (lightly shaded as seen on MRI) a significantly higher prescription isodose is needed to obtain a given minimum dose to the actual location of the tumor (striped, as seen on CT). The falloff from this higher prescription dose (e.g. 16 Gy) is represented by the darkly shaded area. Such doses will be accompanied by a respectively higher complication rate.