Image Registration Strategy of T₁-Weighted and FIESTA MRI Sequences in Trigeminal Neuralgia Gamma Knife Radiosurgery

Tony J.C. Wang^a Ronald Brisman^b Zheng Feng Lu^c Xiang Li^d
Steven R. Isaacson^a Jinesh N. Shah^a Emi J. Yoshida^e Tian Liu^e

Departments of ^aRadiation Oncology, ^bNeurological Surgery and ^cRadiology, Columbia University Medical Center, New York, N.Y., ^dDepartment of Radiation Oncology, University of Pittsburgh Cancer Institute, Pittsburgh, Pa., and ^eDepartment of Radiation Oncology, Emory University School of Medicine, Atlanta, Ga., USA

Key Words

Gamma Knife • Registration • Targeting • Trigeminal neuralgia • FIESTA MRI

Abstract

Background/Aims: In Gamma Knife radiosurgery, T₁ MRI is most commonly used and is generally sufficient for targeting the trigeminal nerve. For patients whose trigeminal nerves are unclear on T₁ MRI, FIESTA MRI supplements anatomical structure visualization and may improve trigeminal nerve delineation. The purpose of this study was to develop a registration strategy for T₁ and FIESTA MRIs. **Methods:** We conducted a retrospective study on 54 trigeminal neuralgia patients. All patients were scanned with T₁ and FIESTA MRIs. We evaluated 4 methods of registration: automatic image definition, superior-slice definition, middle-slice definition and inferior-slice definition. Target discrepancies were measured by deviations from an intracranial landmark on T₁ and FIESTA MR images. **Results:** The overall range in registration error was 0.10–5.19 mm using superior-, 0.10–1.56 mm using middle- and 0.14–2.89 mm using inferior-slice definition. Registration error >2 mm was observed in 11% of the patients using superior-, 4% using middle- and 7% using inferior-slice FIESTA MRI definition. **Conclusions:** Among patients

for whom FIESTA and T₁ MRI are used, registration based on middle-slice definition reduces registration error and improves targeting of the trigeminal nerve.

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Introduction

Gamma Knife radiosurgery is an effective treatment for many patients with trigeminal neuralgia [1–3]. The success of this treatment is dependent on image guidance and requires precise delineation of the trigeminal nerve as well as nearby structures, including blood vessels and the brainstem [4]. While T₁-weighted MRI is commonly used and, in most cases, provides sufficient visualization of the trigeminal nerve, the nerve may be difficult to image in a subset of patients with anatomical distortions. Cheuk et al. [5] reported that approximately 10% of the patients who received MRIs for Gamma Knife radiosurgery had poorly visualized trigeminal nerves. In our experience, the nerve is more difficult to image using T₁-weighted MRI in patients with anatomical distortions, such as an atrophic trigeminal nerve, short cisternal segment, prominent blood vessels or previous microvascular decompression.

Fig. 1. Axial FIESTA MRI scan with clear visualization of the trigeminal nerves (arrows). **a** Axial image of the whole brain showing the 6 dots (fiducial markers) on the side used for image registration. **b** A magnified view of the trigeminal nerves.

Fig. 2. MRI scan of a 57-year-old man with right-sided trigeminal neuralgia previously treated with radiofrequency electrocoagulation and glycerol injections. Compared with the axial T_1 MRI scan (**a**), the FIESTA MRI scan (**b**) shows enhanced visualization of the cisternal trigeminal nerve (arrow).

To improve image guidance, many groups have investigated various MRI sequences, which provide higher spatial resolution and better contrast than T_1 -weighted MRI [6, 7]. At the University of California, Los Angeles, in 2005, Chavez et al. reported that fast imaging employing steady-state acquisition (FIESTA) MRI supplies improved contrast and more precise imaging in the trigeminal nerve region [8]. FIESTA provides higher contrast resolution between cerebrospinal fluid in the cerebello-pontine angle and the adjacent structures as well as enhanced visualization of the cisternal trigeminal nerve (fig. 1) [9, 10]. In 2007, we adopted the use of FIESTA MRI in addition to T_1 -weighted MRI for Gamma Knife radiosurgery of the trigeminal nerve. Figure 2 shows a patient with an atrophic trigeminal nerve due to a previous denervating procedure. The trigeminal nerve is better visualized on the FIESTA image compared to the T_1 image.

Despite improved visualization of anatomical structures, achieving a high degree of registration concor-

dance between the T_1 and FIESTA MRI sequences remains a challenge. We evaluated 4 methods of T_1 and FIESTA MRI registration: automatic image definition, superior-slice definition, middle-slice definition and inferior-slice definition. Registration errors were measured by deviations from an intracranial landmark on T_1 and FIESTA MR images. In this report, we address a T_1 -weighted and FIESTA MR image registration strategy to optimize trigeminal nerve delineation.

Methods

Fifty-four trigeminal neuralgia patients were retrospectively studied under an institutional-review-board approved protocol (patient characteristics are listed in table 1). All patients were treated with Gamma Knife radiosurgery at the Columbia University Medical Center between January 2007 and October 2008. Treatment plans were developed in Leksell Gamma Plan G (version 5.34) with MR images and were delivered in a single 4-mm

Table 1. Patient characteristics at the time of Gamma Knife radiosurgery

Clinical characteristics	
Total patients	54
Female	37 (69)
Male	17 (31)
Unilateral TN	53 (98)
Bilateral TN	1 (2)
Right TN	36 (67)
Left TN	17 (31)
Age, years	
Median	70
Mean	68
Range	40–92
Previous surgery (pre-GKRS)	
Patients with >1 procedure	
RFE	4 (7)
Glycerol	2 (4)
MVD	4 (7)
Second GKRS	12 (22)
Third GKRS	4 (7)
Patients who underwent previous procedures	
0 procedure	33 (61)
1 procedure	13 (24)
2 procedures	5 (9)
≥3 procedures	3 (6)

Figures in parentheses are percentages. RFE = Radiofrequency electrocoagulation; MVD = microvascular decompression; GKRS = Gamma Knife radiosurgery.

collimator shot using a Leksell Gamma Knife model B unit (Elekta Instruments, Atlanta, Ga., USA). For their first radiosurgery, the patients received a radiation dose of 75–85 Gy to the proximal cisternal part of the trigeminal nerve. For repeat radiosurgeries, they received an additional 50-Gy dose to the site. All patients were managed by the same neurosurgeon (R.B.) and radiation oncologist (S.R.I.). Both physicians had >10 years of experience in Gamma Knife radiosurgery.

T₁ and FIESTA MRI Sequences

MRI scans were performed on a GE Signa 1.5-T MRI System (General Electric Medical Systems, Milwaukee, Wisc., USA). Each patient was scanned with a contrast-enhanced T₁-weighted MRI and a FIESTA MRI. With injection of contrast (15 ml of either Gd-diethylenetriamine penta-acetic acid or gadobenate dimeglumine), 3-dimensional T₁-weighted MR images were obtained through the area at which the trigeminal nerve exits the brainstem. T₁-weighted gradient echo data were acquired at: 20° flip angle, 30-ms TR, 7-second TE, 15.63 bandwidth, 256 × 256 matrix, 256 frequency, 256 phase, 1 excitation, 24-cm field of view and 0.8-mm thickness with no overlap. The T₁-weighted scans comprised 28 axial slices and the average acquisition time was approximately 3 min. The FIESTA MR images were acquired at: 65°

flip angle, 8.2-ms TR, 2.3-ms TE, 62.5 bandwidth, 256 × 256 matrix, 448 frequency, 256 phase, 4 excitations, 24-cm field of view and 0.4-mm thickness with 0.4-mm overlap. The FIESTA scans comprised 48–60 axial slices and the average acquisition time was approximately 4 min.

MR images were acquired with a special MRI indicator box that was attached to a fitted Leksell® coordinate frame. The purpose of the indicator box was to impose the fiducials, using cupric sulphate solution, onto the acquired images (as shown in fig. 1). The coordinates provided by the fiducials may be determined manually or automatically by Gamma Plan. T₁-weighted and FIESTA MRI were registered using these coordinates.

T₁ and FIESTA MRI Registration in Gamma Plan

Gamma Plan uses the term ‘study definition’ to refer to the assignment of MR image coordinates (fig. 3). These coordinates are determined applying the fiducials. We adjusted the image grayscale (contrast and level) such that the fiducial markers were clearly visible. Two main approaches are used to define MR images: automatic definition and manual definition. In automatic definition, the Gamma Plan software recognizes the fiducial markers from each side. Manual definition is an alternative if the automatic definition procedure fails due to artifacts or other imaging problems. In manual definition, the physician is able to choose the location and number of slices (>5) on which to place the fiducial markers. In this study, we selected 10 slices in 3 locations (superior, middle and inferior regions). Once T₁-weighted and FIESTA MR images had been defined, the image coordinates were determined and registration was completed.

Comparison of Various Image Registration Methods

We evaluated 4 methods of T₁ and FIESTA MRI registration: automatic image definition, superior-slice definition, middle-slice definition and inferior-slice definition. Target discrepancies were measured by deviations from an intracranial landmark on T₁ and FIESTA MR images. The intracranial landmark was a structure chosen near the trigeminal nerve such as a blood vessel on the T₁ and FIESTA MR images. We recorded the 3-dimensional coordinates of the intracranial landmark after each registration method. We calculated the distance using the difference *r* between post-registration and pre-registration landmark location as follows:

$$r = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \quad (1)$$

where *x*, *y* and *z* are measures along the left-right, anterior-posterior and superior-inferior axes, respectively; *x*₁, *y*₁, *z*₁ and *x*₂, *y*₂, *z*₂ represent the pre- and post-registration landmark locations, respectively.

Registration errors were studied using mean, range and standard deviation. A paired *t* test was computed with *p* < 0.05 considered to be statistically significant.

Validation Using an Inhouse Landmark-Based MR Image Registration

We have previously developed a landmark-based brain MRI registration algorithm to fuse the T₁ and FIESTA MRI scans [11]. To verify our findings in Gamma Plan registration, we used this inhouse registration method to determine the discrepancy of superior-, middle- and inferior-slice registration. Because the brain can be considered a rigid body, the transformation matrix be-

Fig. 3. The procedures of Gamma Knife radiosurgery treatment planning.

tween the 2 MRI scans, T , is composed of 6 parameters: 3 translations (t_x , t_y and t_z) and 3 rotations (θ_{xy} , θ_{yx} and θ_{xz}) (eq. 2). t_x , t_y and t_z are translations along the x, y and z axes; θ_{xy} , θ_{yx} and θ_{xz} are the rotations in the x-y, y-z and x-z planes. Corresponding landmarks were selected in both MRI sequences and the transformation matrix was determined accordingly [12].

$$T = \begin{bmatrix} & & t_x \\ R & & t_y \\ & & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2a)$$

$$R = \begin{bmatrix} \cos\theta_{xy} & \sin\theta_{xy} & 0 \\ -\sin\theta_{xy} & \cos\theta_{xy} & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{yz} & \sin\theta_{yz} \\ 0 & -\sin\theta_{yz} & \cos\theta_{yz} \end{bmatrix} \cdot \begin{bmatrix} \cos\theta_{xz} & 0 & \sin\theta_{xz} \\ 0 & 1 & 0 \\ -\sin\theta_{xz} & 0 & \cos\theta_{xz} \end{bmatrix} \quad (2b)$$

Results

For T_1 MRI scans, no difference in registration error was found using automatic or manual definition. Complete automatic image definition was successful in 50 of 54 patients (91%). Failures were due to missing or incorrect placement of the fiducial markers. No change in the coordinates of the intracranial landmark among superior-, middle- and inferior-slice registrations was observed for T_1 -weighted images ($p > 0.05$). The T_1 -weighted mean registration error was 0.30 ± 0.17 mm for the superior-, 0.27 ± 0.15 mm for the middle- and 0.35 ± 0.25 mm for

Table 2. FIESTA MRI registration error (mm)

	Superior-slice definition	Middle-slice definition	Inferior-slice definition
Mean	0.99	0.45	0.92
SD	1.00	0.41	0.62
Range	0.10–5.19	0.10–1.56	0.14–2.89

the inferior-slice definition. For consistency, we used the middle-slice definition for all T_1 -weighted MRI scans in the subsequent registration study.

For FIESTA MRI scans, the most accurate image registration strategy was achieved using the middle-slice manual definition. Complete automatic image definition was successful in 7 of 54 patients (13%). Failures were due to artifacts of the fiducial markers. Registration errors using various FIESTA MRI definition strategies are displayed in table 2. A registration error >2 mm was observed in 11% using the superior-, 4% using the middle- and 7% using the inferior-slice definition. The range of registration error was 0.10–5.19 mm through superior- and 0.14–2.89 mm through inferior-slice FIESTA MRI definition. The most accurate registration strategy for FIESTA MRI was achieved using the middle-slice definition with an error range of 0.10–1.56 mm ($p < 0.01$). Among the x (left-right), y (anterior-posterior) and z

(superior-inferior) axes, the largest axial variation in FIESTA imaging was along the z axis with a mean error of 0.83 ± 0.99 mm (fig. 4).

The importance of proper image definition/registration using T₁-weighted and FIESTA MRI sequences is illustrated in the following case of a 70-year-old woman with right-sided trigeminal neuralgia. Figure 5 shows the Gamma Plan T₁-weighted and FIESTA MR image registrations. The superior-slice definition of FIESTA MRI (fig. 5a) showed greater trigeminal nerve discrepancy than the middle-slice definition (fig. 5b). The trigeminal nerve contoured on the T₁-weighted MRI (shown in orange) is 1.8 mm inferior to the nerve contoured on the FIESTA MRI using the superior-slice definition (shown in purple) with an overall deviation of 2.2 mm. The middle-slice definition of FIESTA resulted in an overall deviation of <0.5 mm between the trigeminal nerves contoured on T₁-weighted and FIESTA MRI scans (fig. 5b). To verify our clinical study, we performed T₁-weighted and FIESTA image fusion using inhouse registration software on the same patient (fig. 6). T₁-weighted MRI is shown in black and white, whereas FIESTA MRI is displayed in red. Figure 6a is an image registration using T₁-weighted and FIESTA superior slices in which a mismatch of 2.7 mm for the trigeminal nerve occurred, a finding consistent with that using Gamma Plan. By contrast, figure 6b is a FIESTA middle-slice registration in which the mismatch was <0.5 mm. This is consistent with the results using Gamma Plan.

Discussion

The efficacy of trigeminal neuralgia Gamma Knife radiosurgery is dependent on precise targeting. While T₁ MRI is commonly used and can visualize the trigeminal nerve in most cases, the nerve may be difficult to image in a subset of patients with substantial anatomical distortions – such as after previous trigeminal neuralgia treatment or when distorted by a tumor or blood vessel. For these patients, the addition of 3-dimensional FIESTA MRI may benefit targeting in Gamma Knife radiosurgery. The introduction of FIESTA MRI poses the concern that it may not precisely overlap in stereotactic space with the T₁ MRI sequence during registration, resulting in discrepancies of the trigeminal nerve locations on the 2 MRI sequences. Our results indicate that registration errors >2 mm, and in some cases 5 mm, may occur depending on the registration method. In this study, we demonstrated an optimal method for T₁-weighted and FIESTA MR

Fig. 4. Mean registration errors of the FIESTA MRI sequence analyzed along 3 axes: left-right (L-R), anterior-posterior (A-P) and superior inferior (S-I). The 3 registration methods are manual registration using superior slices, middle slices and inferior slices.

image registration in order to achieve more precise targeting and concordance between both sequences.

Our results show that while the majority of patients using both T₁ and FIESTA MRI sequences had <1 mm registration error in all registration methods, the frequency of registration error >2 mm was significantly higher when defining superior (11%) or inferior (7%) slices of the MRI scans compared to middle slices (4%). Because Gamma Knife radiosurgery – especially in trigeminal neuralgia – relies on high precision, targeting the trigeminal nerves with a registration error >2 mm may impact the clinical outcome. We also observed that the overall range of registration error tended to be greater for the superior- and inferior-slice definitions. The shifts in the superior-inferior direction may be clinically important as the seventh and eighth cranial nerves are relatively close to the trigeminal nerve. In the event that excessive registration error occurs along the inferior direction, facial palsy, imbalance and hearing loss may become potential complications. Therefore, in order to reduce the frequency of substantial registration error when FIESTA MRI is added to T₁ MRI, we recommend using the middle-slice registration method.

In the clinic, another common registration method is target-centered definition in which the center of definition focuses on a radiosurgical target such as the trigeminal nerve. Typically, during preradiosurgical brain imaging, the center of the MRI field of view is on the trigeminal

Fig. 5. Comparison of 2 image registration methods shown in 8 consecutive axial MRI scans. The brainstem is contoured in red. The right trigeminal nerve is contoured on T₁-weighted images (blue) and FIESTA images (orange). **a** Registration using the superior-slice definition resulted in a large discrepancy between the trigeminal nerves contoured in T₁ and FIESTA MRI scans. **b** Registration using the middle-slice definition shows improved concordance of the trigeminal nerves contoured in T₁ and FIESTA MRI scans.

Fig. 6. Comparison of image registration methods using superior slices (**a**) and middle slices (**b**). We used an inhouse rigid registration software. The T₁-weighted MR images (black and white) are superposed onto the FIESTA (red) MRI scans. **a** Superior-slice registration shows a 2.7-mm minimum discrepancy for the trigeminal nerve. **b** Middle-slice registration shows minimal mismatch (<0.5 mm) between T₁ and FIESTA MRI.

nerve or target of interest. With most targets located at the center of the image acquisition, target-centered registration is virtually the same as middle-slice registration. On rare occasions, the target is imaged outside of the middle slices. Nevertheless, our experience shows that in these cas-

es, a standardized method of registration using the middle-slice definition will achieve more accurate targeting.

Massager et al. [13] listed 4 main sources of targeting imprecision during Gamma Knife radiosurgery procedures including frame fixation, image acquisition, brain

shift and mechanical inaccuracy of the Gamma Knife device. In terms of image registration, some factors contributing to misregistration include target shifting during MRI data acquisition as well as MRI artifacts, including inhomogeneity, chemical shift and partial volume effect. At Columbia University, T₁ and FIESTA MRI data acquisition differ in that FIESTA images are obtained in 0.8-mm slices with 0.4-mm overlap, while T₁ is a volume acquisition. Image inhomogeneity and distortion occur mainly at the outer edge of the images [14], which may explain why the fiducial markers on some FIESTA images are blurred and the middle-slice definition improves accuracy. Furthermore, partial volume effect occurs in the superior-inferior direction, which may explain why the largest deviation among the 3 axes was in the superior-inferior direction in our study.

One limitation of our study is that we could not evaluate the absolute accuracy of the MRI registration. Johnson et al. [15] reported that the accuracy for a brain MRI-MR image registration algorithm is very high, at the level of 0.2 ± 0.5 mm. Our T₁-weighted and FIESTA MR image registration through the middle-slice definition had a mean accuracy of 0.45 ± 0.41 mm. Although this study was designed to improve the image registration

strategy for trigeminal neuralgia Gamma Knife radiosurgery, it may also prove to be useful for other Gamma Knife radiosurgery procedures in which multiple MRI sequences, such as T₂ MRI, are used.

Conclusions

Targeting precision is particularly crucial in Gamma Knife radiosurgery for trigeminal neuralgia. When T₁-weighted MRI is insufficient to visualize the trigeminal nerves, the addition of FIESTA MRI may benefit trigeminal nerve delineation in radiosurgical treatment planning. In cases for which FIESTA MRI is added to T₁ MRI, we suggest a standardized registration method using the middle-slice definition to reduce registration error and improve targeting of trigeminal nerves.

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