



A Preliminary Investigation Report on Using Probabilistic Fiber Tractography to Track Human Auditory Pathways

Xuan Zheng, Jun Zhang, Li Dong, Fangye Li, Guochen Sun, Yue Zhao, Yuyang Liu, Bainan Xu

■ **BACKGROUND:** Diffusion tensor imaging is currently the only noninvasive way to map subcortical white matter tractography. Radiologists and neurologists often fail to reconstruct the complex auditory pathways when applying the most commonly used approach, deterministic fiber tracking, as this method is limited in spatial and angular resolution. A different fiber-tracking method involving a probabilistic approach could partly compensate for these limitations. We investigated efficiency and potential usefulness of probabilistic fiber tracking in depicting human auditory pathways in healthy individuals and patients with unilateral vestibular schwannoma (VS).

■ **METHODS:** Eight healthy volunteers and 14 patients with unilateral VS underwent diffusion tensor imaging. Probabilistic fiber tracking of the auditory pathways for each subject was carried out using FSL software. Tracking rate, reliability of results, fiber volume, fiber length, and fractional anisotropy values were considered in assessing reliability and sensitivity of this method. Fiber length and fiber volume were analyzed separately for the healthy group and VS group.

■ **RESULTS:** Good tracking sensitivity and consistency were shown in healthy subjects and patients with VS. For fiber length, the 8 healthy subjects exhibited significant between-sides differences, whereas the 14 patients with VS showed no such difference. For fiber volume, there was a statistically significant difference between groups, as the patients with VS displayed a smaller fiber volume on the nontumor side. Fractional anisotropy values revealed no

significant autologous or between-group differences. These results match results of previous anatomic and neurologic studies.

■ **CONCLUSIONS:** The auditory pathway can be depicted well by probabilistic fiber tracking. This method can compensate in part for weaknesses of the widely used deterministic tractography approach in depicting fine and complicated subcortical fibers.

INTRODUCTION

Diffusion tensor imaging (DTI) is so far the only accepted method for tracking subcortical white matter fibers in a three-dimensional (3D) fashion in vivo.^{1,2} The conventional tracking technique, deterministic fiber tracking, has a limited range of application.^{3,4} For instance, it often fails to track complex and crossing fibers, such as the human auditory fibers, which are considered one of the most intricate and important intracranial neurologic pathways.^{1,5-8} Its major limitation stems from a restricted spatial and angular resolution.²⁻⁴ New diffusion image sequences and fiber-tracking algorithms are continuously being developed to eliminate the flaws of deterministic fiber tracking, attempting to reproduce complex intracranial fibers accurately and precisely in a 3D manner.^{4,9-11}

Previous studies have described probabilistic fiber tracking as a completely different algorithmic method with a higher resolution that makes it capable of tracking more subtle crossing fibers. This strength of probabilistic fiber tracking has aroused further interest in investigating its capability to identify complex crossing fibers

Key words

- Auditory pathways
- Diffusion tensor imaging
- Hearing rehabilitation
- Probabilistic fiber tracking

Abbreviations and Acronyms

- 3D:** Three-dimensional
- DTI:** Diffusion tensor imaging
- FA:** Fractional anisotropy
- MRI:** Magnetic resonance imaging
- ROI:** Region of interest
- VS:** Vestibular schwannoma

Department of Neurosurgery, General Hospital of Chinese PLA (301 Hospital), Beijing, China

To whom correspondence should be addressed: Bainan Xu, M.D.

[E-mail: bnxu301@163.com]

Xuan Zheng and Jun Zhang are co-first authors.

Citation: *World Neurosurg.* (2019) 130:e1-e8.

<https://doi.org/10.1016/j.wneu.2019.03.066>

Journal homepage: www.journals.elsevier.com/world-neurosurgery

Available online: www.sciencedirect.com

1878-8750/\$ - see front matter © 2019 Published by Elsevier Inc.

while using the conventional DTI technique.^{1,12-14} The present study investigated the efficiency and potential applicability of the probabilistic fiber-tracking algorithm in depicting the auditory pathways of healthy individuals and patients with unilateral vestibular schwannoma (VS). Our preliminary results should be useful in guiding future studies of hearing rehabilitation in patients with VS.

MATERIALS AND METHODS

Participants

Our sample consisted of 8 healthy volunteers (6 men, mean age 28.4 years) and 14 patients with unilateral VS (9 men, mean age 37.1 years) surgically treated in the Department of Neurosurgery of 301 Hospital in Beijing, China, between November 2012 and July 2013. Written consent was obtained from each participant before testing. Patients with the following diagnoses were excluded from this study: 1) bilateral hearing loss indicated by auditory detection, 2) VS combined with hydrocephalus, 3) tumors <1 cm in diameter, (4) auditory dysfunction for <2 years, and (5) hearing loss due to reasons other than VS. Descriptive details of volunteers and patients with VS are presented in **Tables 1** and **2**, respectively.

Image Acquisition

All imaging data were generated by a 3T TIM Trio System (Siemens Healthcare, Erlangen, Germany). T₁-weighted 3D magnetization prepared rapid acquisition gradient echo sequences were obtained with the following specifications: 176 slices with a slice thickness of 1.1 mm, slice gap of 0.55 mm, repetition time of 2200 ms, echo time of 2.88 ms, field of view of 22 × 22 cm, and flip angle of 10°. These T₁ images were used as a basis for anatomic comparisons. A diffusion-weighted, spin-echo, double-refocused, echo-planar sequence was used to acquire 2 DTI datasets in about 18 minutes with the following specifications: 64 diffusion gradient directions with b value of 1400 seconds/mm², and 64 slices with a slice gap of 0 mm, slice thickness of 2.3 mm, repetition time of 7900 ms, echo time of 90 ms, voxel size of 2.3 × 2.3 × 2.3 mm, and field of view of 22 × 22 cm. We also acquired 10 additional images with a b value of 0 seconds/mm².

Table 1. Healthy Volunteers

Volunteer	Age (years)/Sex	PTA (dB)	SDS (%)	Dominant Hemisphere
1	28/F	18	97	Left
2	31/M	14	98	Left
3	27/F	13	100	Left
4	29/M	16	100	Left
5	28/M	11	96	Right
6	25/M	20	100	Left
7	33/M	14	98	Left
8	26/M	12	94	Left

PTA, pure tone audiogram; SDS, speech discrimination score; F, female; M, male.

Fiber Tracking Analysis

T₁ images were used as the anatomic reference, and ITK-SNAP software (www.itksnap.org) was applied to recognize and mark both sides of the inferior colliculus and the medial geniculate bodies of each participant (**Figures 1** and **2**). These 4 anatomic landmarks are the region of interest (ROI). In each subject, after a clear identification of the ROIs, all anatomic marks were transformed from the T₁ space to the DTI space for tractography. The transformation was performed by the FLIRT toolbox in FSL software (<https://fsl.fmrib.ox.ac.uk/fsl/fslwiki/FLIRT>).

The steps in the DTI data analysis are as follows:

1. Data transformation. The original Digital Imaging and Communications in Medicine image data were transformed into NIFTI image data using 3D Slicer software (<https://www.slicer.org/>).
2. Fiber tracking. The whole tracking course was accomplished via FSL software. All tracking details are available in the explanatory memorandum contained on the FSL open-source website (www.fmrib.ox.ac.uk/fsl). The single mask option was adopted. The terminal mask for fractional anisotropy (FA) was set at <0.1 to avoid tracking throughout the gray matter. The number of probabilistic tracking samples was 1000 with a curvature threshold of 0.2. A unit step length of 0.5 mm with a maximum limit of 2000 steps was set, considering the possible real length of our target fibers.
3. Postprocessing. 3D auditory pathway image reconstruction and analysis of the results were accomplished using 3D Slicer software (<http://www.Slicer.org>).

Data Analysis

All tracking data were processed by 2 different analysts (X.Z. and L.D.), who were not advised of the corresponding relationships between the image datasets and the participants. Autologous and between-individual differences were compared to assess the sensitivity and reliability of our study data. Conformity with accepted anatomic knowledge was also taken into consideration. The main parameters examined included the integrity of the fiber pathway, fiber volume, length, FA values, and conformity with common anatomic knowledge.

Statistical Analysis

All statistical analyses were performed using IBM SPSS Statistics Version 18.0 software (IBM Corporation, Armonk, New York, USA). After we confirmed that the data roughly fit the shape of a normal distribution, mean and SD were computed. Continuous variables were analyzed with independent-sample t tests, and categorical variables were analyzed using Wilcoxon test. Statistical significance was set at $P < 0.05$.

RESULTS

Healthy Volunteers

Reliability of Results. All the depicted fibers from DTI reconstruction showed excellent consistency with established anatomic knowledge regarding their location and course.

Table 2. Patients with Unilateral Vestibular Schwannoma

Patient	Age (years)/Sex	Tumor Side	Disease Course (months)	Tumor Size (cm)*
1	26/F	Left	24	3.1
2	35/M	Left	16	4.4
3	50/F	Right	15	3.4
4	31/M	Left	23	2.7
5	28/M	Left	17	5.1
6	43/M	Left	34	3.8
7	40/M	Right	70	4.9
8	40/M	Right	15	2.3
9	40/F	Left	32	3.2
10	42/F	Left	46	3.6
11	37/M	Right	17	2.5
12	42/M	Right	45	4.4
13	39/F	Left	17	2.7
14	27/M	Right	12	1.8

F, female, M, male.
*Values represent the largest diameter of the tumor.

Tracking Rate. The first image analyst confirmed that 11 of the 16 images in our dataset showed complete auditory pathways, whereas the remaining 5 images were either incomplete or absent, yielding a tracking rate of 68.8%. According to the second analyst, 10 of the 16 images were complete, and the other 6 images were incomplete or absent, for a tracking success rate of 62.5%. Comparison of the tracking success rates between analysts showed no significant statistical difference ($P = 0.764$).

Reliability. DTI is currently the only noninvasive neurofiber visualizing method in vivo, so there is no benchmark for comparison to assess the reliability of the tracking results. In the present study, typical anatomic structures in the auditory pathway, medial geniculate bodies, and auditory cortex were marked out on the T1

basic anatomic sequence before tracking to see whether the fiber tracked would go through the highlighted points to generally assess method reliability. The fibers were consistent with established anatomic knowledge.

Fiber Length. For the 8 healthy individuals, the length of the left auditory pathway was 57.4 ± 27.1 mm, and the length of the right auditory pathway was 73.6 ± 30.2 mm according to the first data analyst; the corresponding results from the second analyst were 51.3 ± 36.2 mm and 68.7 ± 24.3 mm, respectively. Results of both analysts showed significant differences ($P = 0.029$, $P = 0.034$) between the left and right sides. However, no statistically significant difference ($P = 0.453$, $P = 0.417$) was observed between the results of the 2 analysts.

Fiber Volume. The auditory pathway volume for the 8 healthy volunteers according to the first analyst was 1.74 ± 0.61 cm³ for the left side and 1.96 ± 0.57 cm³ for the right side; the corresponding results obtained by the second analyst were 1.57 ± 0.41 cm³ and 1.84 ± 0.53 cm³, respectively. There was no statistically significant difference between the 2 sides ($P = 0.017$, $P = 0.043$) or between the analysts ($P = 0.372$, $P = 0.457$).

Patients with Unilateral VS

Reliability of Results. All the depicted fibers from DTI reconstruction showed great consistency with general anatomic knowledge with regard to their location and course.

Tracking Rate. Among the 14 patients in the dataset processed by the first analyst, complete auditory pathways on both sides were successfully tracked in 11 patients; specifically, 12 auditory pathways were tracked on the tumor side, and 11 auditory pathways were tracked on the uninjured side. The corresponding counts obtained by the second analyst were 8, 9, and 11. No statistically significant difference ($P = 0.357$, $P = 0.289$) was observed between the injured and the uninjured sides in the combined results from both analysts.

Fiber Length. Average fiber length was 63.1 ± 24.1 mm on the injured side and 71.6 ± 29.2 mm on the uninjured side according to the first analyst; the corresponding results from the second analyst were 57.6 ± 28.1 mm and 65.7 ± 26.3 mm, respectively.



Figure 1. Seeking of inferior colliculus as region of interest (ROI). The red point refers to the ROI we chose; trans inferior colliculus section on axial

view was oriented; and the dark point within a white stripe-shaped structure refers to our target ROI, which is always about 10 voxels in size.



Figure 2. Seeking of medial geniculate body as region of interest (ROI). The yellow point refers to the ROI we chose; trans medial geniculate body section on axial view was oriented; and the dark point within a white

oval-shaped structure refers to our target ROI, which is always about 7 voxels in size.

The paired *t* test showed no significant difference ($P = 0.322$, $P = 0.476$) between the injured and the uninjured sides, and there was not a significant difference ($P = 0.476$, $P = 0.316$) between the 2 analysts.

Fiber Volume. Mean fiber volume was $1.44 \pm 0.51 \text{ cm}^3$ on the nontumor side and $1.92 \pm 0.41 \text{ cm}^3$ on the tumor side as measured by the first analyst, with corresponding results of $1.61 \pm 0.57 \text{ cm}^3$ and $2.01 \pm 0.53 \text{ cm}^3$ obtained by the second analyst. A statistically significant difference ($P = 0.031$, $P = 0.027$) was observed between sides, but no significant difference ($P = 0.273$, $P = 0.629$) was found between analysts.

FA Value of the Fiber. The average FA value of the auditory fiber tracked by the first analyst was 0.426 ± 0.071 on the injured side and 0.411 ± 0.092 on the uninjured side; the corresponding results for the second analyst were 0.431 ± 0.047 and 0.414 ± 0.061 . No statistical difference was found between the injured and uninjured sides ($P = 0.873$, $P = 0.761$) or between the 2 analysts ($P = 0.461$, $P = 0.637$).

Illustrative Cases

Case 1. In a 27-year-old healthy female volunteer, the tracking result of her right auditory pathway conformed quite well with our anatomic knowledge (Figure 3).

Case 2. In a 27-year-old man with right-side hearing loss for >1 year, magnetic resonance imaging (MRI) showed a 1.8-cm ball-shaped tumor located in the right cerebellopontine angle. His auditory pathway was tracked on both sides; the result indicated that the actual course of the auditory pathway varied from one side to the other (Figure 4).

DISCUSSION

Healthy Volunteers

Bilateral auditory pathway fiber tracking of each subject was performed by 2 analysts. Of a possible total of 16 auditory pathways, the 2 analysts successfully tracked 11 (68.8%) and 10 (62.5%) pathways, respectively. Tracking rates were comparable to rates of previously published reports and showed no difference between

the 2 analysts.^{15,16} We conjectured that the tracking course might suffer some degree of disruption owing to the limited DTI resolution or the idiosyncrasies of each participant, based on previous studies by Feigl and Yeh.^{16,17} Javad et al.¹ treated precise ROI detection as a make-or-break step for fiber tracking. Usually the more precise the selected ROIs are, the more favorable the results will be. Multiseed ROI fiber tracking may involve a tradeoff between obtaining a more favorable result and tolerating a longer algorithm computation time.¹⁸

We compared the tracking results with the anatomic atlas to assess the reliability of our study results.¹⁷ The auditory cortex generally accepts signals from 2 separate fibers: 1 strand from the inferior colliculus and the other from the medial geniculate bodies. In the lower segment, the anterior cochlear nuclei and posterior cochlear nuclei divide the auditory fibers into 2 separate parts. Our tracking results roughly matched the anatomic atlas but were unable to reveal the subtle details just mentioned.¹⁵ This drawback may be caused by the relatively low spatial and angular resolution, which may fail to discriminate 2 separate fibers within a single voxel. DTI fiber tracking is based on the hypothesis that free water molecule diffusion patterns reveal microscopic details about the routes followed by neurofibers. However, only 1 overall diffusion index can be obtained for a particular voxel, and the fact that 1 voxel may contain more than 1 neurofiber further complicates the issue at hand and can potentially obscure tracking results, especially for intricate cases such as the auditory pathway. In future studies, MRI could be set at a higher resolution to minimize such disadvantages and achieve greater precision.

There is neither a set or predefined length of the human auditory pathway nor a conventionally accepted means of taking such a measurement, owing to the diversity of individual variations.¹⁹ Personal, within-cohort, and between-cohort differences were accounted for in reliability assessments, and the significant observed differences essentially replicated the diversity and variations of the actual course of the auditory pathway in the general population.^{17,19,20} The similarity between the results obtained by the 2 analysts indicates the reliability of the method. However, we still cannot confidently describe the average length of the human auditory pathway owing to the small sample size. In the future,

larger sample sizes and high-quality studies could provide more information about the human auditory pathway.

Fiber volume is another important index for DTI fiber tracking. Our 8 healthy participants showed significant differences both in the fiber volumes on each side within each individual and between individuals in our sample. The results obtained by the 2 analysts did not differ significantly. These results underscore the individual differences in auditory fibers and the limitations of applying probabilistic fiber tracking to trace auditory pathways.

The current difficulties encountered in human auditory pathway tracking can be partially attributed to the poor ability of current DTI technology to differentiate between and represent microfilament-like fibers. The diversity and intricacy exhibited by the tissue architecture of those neurofibers make it even harder to arrive at any conclusive outcomes. The aim of this part of our study was to propose a less commonly applied, noninvasive method of human auditory pathway investigation and to consider its sensitivity and applicability. The results turned out to be promising, thereby justifying further research. We deem our work important because in-depth knowledge of the precise anatomic structure of human auditory pathways could greatly help us to understand their role in various physiologic or pathologic conditions. Future studies will be planned with a larger sample population and better techniques in the hope of obtaining more robust results.

Patients with Unilateral VS

Our 2 analysts also conducted auditory pathway fiber tracking of both the injured and the uninjured sides of 14 patients with VS. Thus, each analyst was asked to reconstruct 14 healthy and 14 tumor-affected unilateral auditory pathways. The final fiber tracking rate on the healthy side was 85.7% (12 of 14) and 64.3% (9 of 14) for the 2 analysts, respectively, compared with 92.8% (13 of 14) and 78.6% (11 of 14) on the side with VS. The first analyst tracked the auditory pathways in both the left and the right hemispheres of 9 participants (64.3%); the second analyst was successful in doing so with 8 subjects (57.1%). No statistically significant differences in tracking rate between the VS side and the uninjured side were observed, and there was not an evident

distinction between the tracking rates of the 2 analysts. The results prove that the condition of intracranial nerve fibers cannot be predicted simply by either conventional MRI or patients' hearing status.

A possible explanation of our observations is that tumor-caused mechanical compression and nerve distortion are considered the main causes of patients' hearing loss. Thus, only the lower part of the auditory pathway would be broken down by a tumor, whereas the upper portion would theoretically remain intact. The auditory systems of patients with VS remain physiologically functional when cochlear nerve damage caused by tumor compression is ignored.^{18,21} The results presented here conform well with results of previous research, providing some support and confidence for future studies.

Our research found no significant difference between the fiber integrity of the affected side and that of the unaffected side, thereby reinforcing the aforementioned inferences. It is known that auditory fibers above the superior olivary nucleus conduct bilateral downstream afferent impulses and acoustic signals up to the auditory cortex, which is located in the superior and transverse temporal gyrus.²²⁻²⁴ This fact implies that, generally speaking, both sides of a patient's auditory cortex and subcortical fibers will remain functional even when the cochlear nerve on one side is damaged by sporadic VS. The auditory cortex can still be activated if a stimulus is induced beyond the damage point.^{25,26} To some extent, our results provide supporting evidence for the hypothesis that the auditory cortex and subcortical fibers will remain functional for some time after the occurrence of cochlear nerve damage. Taking the exceedingly complicated composition and structure of neurofibers in the brainstem into account, we tracked only the upper course of the auditory pathway in this preliminary research. The primary purpose of this part of our study was to verify our initial hypothesis and to test the potential usefulness of applying the fiber-tracking method to auditory pathway reconstruction. Further investigations of complete full-course auditory fiber tracking are in progress to provide more evidence that could support our present speculations and, it is hoped, contribute more information to human auditory pathway studies.

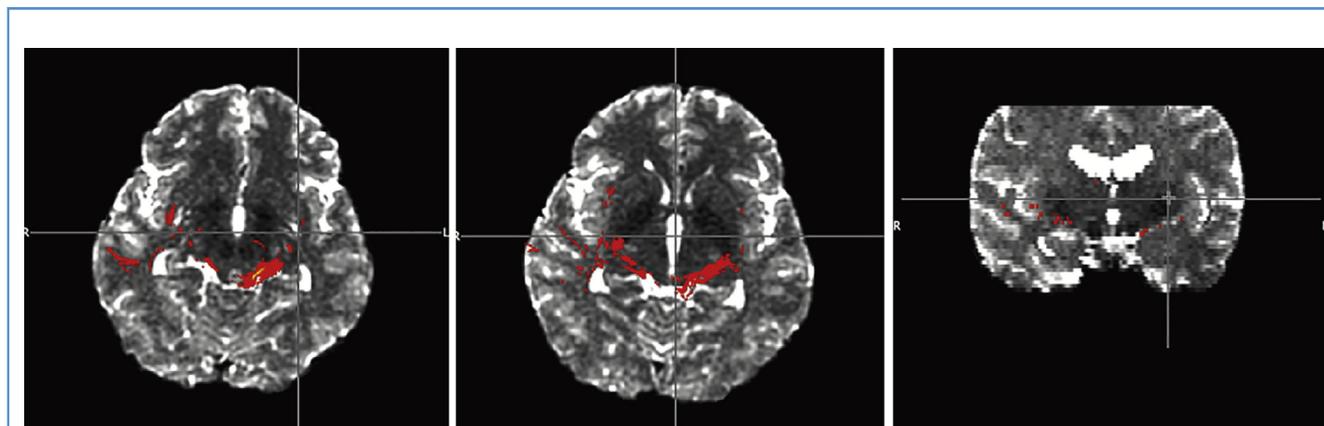
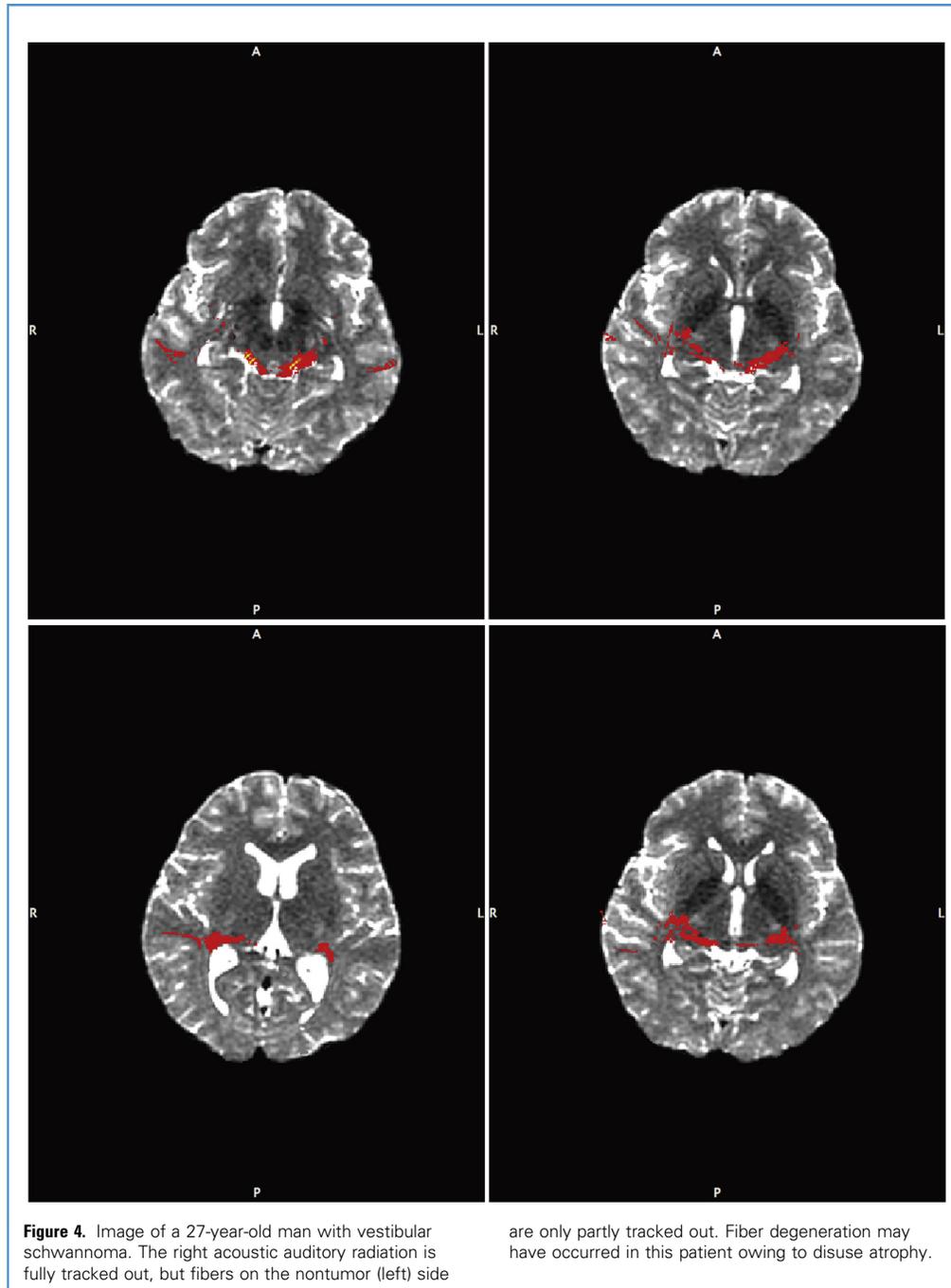


Figure 3. Image of a healthy volunteer. The red areas indicate the acoustic radiation. Both sides of the acoustic fibers are shown.



One notable inconsistency is that a significant difference in fiber length between sides was seen in the 8 healthy subjects, whereas no such difference was detected in the VS cohort. Such confusing results may have been caused by various factors, one of which is the small sample size. Interpreting statistical results can be tricky when the sample size is insufficient. We suggest treating our results and conclusions only as assisting the development of hypotheses at this point rather than as enabling us to draw

confident conclusions. We expect that the results will undergo modification as more evidence is accumulated.

As reported by both analysts, there was a marked lateral difference in acoustic fiber volume between the tumor side and the nontumor side. As we know from autopsies, the main course of acoustic radiation goes to the opposite side after the cochlear nucleus. Based on our results, we speculated that the higher acoustic neurofibers on the nontumor side may retrogress after

tumorigenesis. The reason behind this may be the gradual blocking or even termination of acoustic neural conduction owing to nerve compression from the tumor and the lack of sufficient electrophysiologic stimulus. This phenomenon is referred to as disuse atrophy. Based on our anatomic knowledge, we can subdivide those acoustic fibers above the superior olivary nucleus into 3 separate branches; the first 2, respectively, conduct downstream ipsilateral transitional impulses from the superior olivary nucleus and downstream afferent impulses from the cochlear nucleus directly to the auditory cortex without any interneuron. The third one, also regarded as the main branch, conducts downstream contralateral impulses from the superior olivary nucleus. We hypothesize that the third branch, if the neurofibers do not have sufficient and consistent electrical stimuli passing through them, may degenerate over time. We are unable to separate these 3 fibers with current limited-resolution MRI alone, but the results could be explained well based on previous anatomic knowledge and rational inference in addition to the aforementioned clinical techniques, confirming the reliability of our findings.²⁷⁻²⁹ The results explain the observed clinical phenomenon that the efficacy of implanted devices fades over time in patients with cochlear implants, auditory brainstem implants, or auditory midbrain implants.³⁰⁻³² Theoretically, auditory fibers should retrogress if they have no contact with auditory impulses for an extended period of time. It should be noted that we reached this conclusion without considering the fact that the auditory pathway exhibits lateral differences even in healthy individuals. Further studies with larger samples are still needed to arrive at more convincing conclusions.

FA value is another important index to evaluate the integrity and function of intracranial fibers. FA reduction may indicate fiber collapse, a condition that was not observed in our study.³³ The fiber retrogression on the tumor-injured side is considered as quantitative rather than qualitative change. As discussed previously, auditory fibers on the tumor-injured side may retrogress owing to disuse atrophy, but this happens only to the areas involved in ipsilateral impulse conduction. The function of the remaining fibers changes minimally, as shown by the lack of FA reduction.

Comparison of Deterministic and Probabilistic Tractography

The question of whether deterministic or probabilistic tractography is preferable has been discussed for some time without a clear resolution. The deterministic method has been more widely adopted by clinicians but has more problems with interference. The probabilistic approach offers higher reliability but is more difficult to perform.¹²

From our perspective, neither option is clearly better than the other, and accordingly the selection should be based on the specific situation. The rationale for the present investigation arose from the failure of the deterministic method to depict auditory radiation. However, we do not mean to declare the probabilistic method better in all instances. Rather, professionals should

choose the method that is most suitable for their clinical or research goals. The ideal method would be a combination of both, so as to obtain the advantages of both methods while overcoming their disadvantages.

One important consideration in this regard is time. Each depiction took us >12 hours to obtain a satisfactory result, which is much longer than depicting nerve fibers with the deterministic method. This long time requirement may have been partly due to the low computing power of our machine but arises primarily from the extremely complex algorithm used in this method, which makes it of limited value for clinical use, as previous researchers have noted.^{1,12,27}

Attempts to reduce the processing time required for fiber tracking are continuing. Downregulating the probabilistic tracking number is considered one possible approach but would require more detailed anatomic knowledge. Combining anatomic, pathologic, and DTI knowledge could be a promising way to solve this problem. Although we present statistical information in this article, our conclusions should be viewed as preliminary because of the small sample size. Further research is needed to establish more convincing results.

Limitations

This is only a preliminary investigation, and DTI is a sophisticated technique that requires years of practice to achieve a perfect result. Every detail parameter influences the tracking results. Our relative lack of experience with this process, along with the small sample size, limits the reliability of our results. Another limitation in our investigation was the relatively low quality of MRI. We obtained all images with a 3T coil. We believe strongly, based on our previous experience, that better tracking results could be achieved with higher-quality MRI. As this was a preliminary investigation, and as higher Tesla coils are not generally available, we began with a 3T coil. We hope to conduct future studies with higher-quality equipment. Because probabilistic tractography requires much higher algorithmic power and more time to obtain results, this method is still not as popular as the deterministic method. Future studies should attempt to shorten the tracking time and, in conjunction with the application of clinical and anatomic knowledge, simplify the tracking strategy.

CONCLUSIONS

Compared with the more widely used deterministic fiber tracking method, probabilistic fiber tracking can identify subtle crossing fibers well without any obvious discrepancies. Our preliminary study suggests that this method shows promise, as it demonstrated reliability in tracking and reconstructing the human auditory pathway in both healthy individuals and patients with VS. Better-designed studies with larger samples should be conducted in an effort to confirm or modify our results.

REFERENCES

1. Javad F, Warren JD, Micallef C, et al. Auditory tracts identified with combined fMRI and diffusion tractography. *Neuroimage*. 2014;84:562-574.
2. Gerganov VM, Giordano M, Samii M, Samii A. Diffusion tensor imaging-based fiber tracking for prediction of the position of the facial nerve in relation to large vestibular schwannomas. *J Neurosurg*. 2011;115:1087-1093.
3. Kwon HG, Kim MS, Kim SH, Jang SH. Neurological picture: injury of the oculomotor nerve in a patient with traumatic brain injury: diffusion tensor tractography study. *J Neurol Neurosurg Psychiatry*. 2013;84:1073-1074.

4. Yoshino M, Kin T, Ito A, et al. Diffusion tensor tractography of normal facial and vestibulocochlear nerves. *Int J Comput Assist Radiol Surg.* 2015; 10:383-392.
5. Malcolm JG, Shenton ME, Rathi Y. Two-tensor tractography using a constrained filter. *Med Image Comput Assist Interv.* 2009;12(Pt 1):894-902.
6. O'Donnell LJ, Golby AJ, Westin CF. Fiber clustering versus the parcellation based connectome. *Neuroimage.* 2013;80:283-289.
7. Wang Y, Salehian H, Cheng G, Vemuri BC. Tracking on the product manifold of shape and orientation for tractography from diffusion MRI. *Conf Comput Vis Pattern Recognit Workshops.* 2014; 2014:3051-3056.
8. O'Donnell LJ, Pasternak O. Does diffusion MRI tell us anything about the white matter? An overview of methods and pitfalls. *Schizophr Res.* 2015;161:133-141.
9. Skorpil M, Rolheiser T, Robertson H, Sundin A, Svenningsson P. Diffusion tensor fiber tractography of the olfactory tract. *Magn Reson Imaging.* 2011;29:289-292.
10. Fernandez-Miranda JC, Pathak S, Engh J, et al. High-definition fiber tractography of the human brain: neuroanatomical validation and neurosurgical applications. *Neurosurgery.* 2012;71:430-453.
11. Yeh FC, Verstynen TD, Wang Y, Fernandez-Miranda JC, Tseng WY. Deterministic diffusion fiber tracking improved by quantitative anisotropy. *PLoS One.* 2013;8:e80713.
12. Behrens TE, Johansen-Berg H, Jbabdi S, Rushworth MF, Woolrich MW. Probabilistic diffusion tractography with multiple fibre orientations: what can we gain? *Neuroimage.* 2007;34:144-155.
13. Rademacher J, Morosan P, Schormann T, et al. Probabilistic mapping and volume measurement of human primary auditory cortex. *Neuroimage.* 2001;13:669-683.
14. Jellison BJ, Field AS, Medow J, Lazar M, Salamat MS, Alexander AL. Diffusion tensor imaging of cerebral white matter: a pictorial review of physics, fiber tract anatomy, and tumor imaging patterns. *AJNR Am J Neuroradiol.* 2004;25:356-369.
15. Kovacs S, Peeters R, Smits M, De Ridder D, Van Hecke P, Sunaert S. Activation of cortical and subcortical auditory structures at 3T by means of a functional magnetic resonance imaging paradigm suitable for clinical use. *Invest Radiol.* 2006;41:87-96.
16. Feigl GC, Hiergeist W, Fellner C, et al. Magnetic resonance imaging diffusion tensor tractography: evaluation of anatomic accuracy of different fiber tracking software packages. *World Neurosurg.* 2014; 81:144-150.
17. Yeh FC, Wedeen VJ, Tseng WY. Generalized q-sampling imaging. *IEEE Trans Med Imaging.* 2010; 29:1626-1635.
18. Lerner A, Mogensen MA, Kim PE, Shiroishi MS, Hwang DH, Law M. Clinical applications of diffusion tensor imaging. *World Neurosurg.* 2014;82:96-109.
19. Bizzi A, Blasi V, Falini A, et al. Presurgical functional MR imaging of language and motor functions: validation with intraoperative electrocortical mapping. *Radiology.* 2008;248:579-589.
20. Galaburda AM, Pandya DN. The intrinsic architectonic and connective organization of the superior temporal region of the rhesus-monkey. *J Comp Neurol.* 1983;221:169-184.
21. Otto SR, Shannon RV, Wilkinson EP, et al. Audiologic outcomes with the penetrating electrode auditory brainstem implant. *Otol Neurotol.* 2008;29:1147-1154.
22. Campain R, Minckler J. A note on the gross configurations of the human auditory cortex. *Brain Lang.* 1976;3:318-323.
23. Code RA, Winer JA. Commissural neurons in layer III of cat primary auditory cortex (AI): pyramidal and non-pyramidal cell input. *J Comp Neurol.* 1985; 242:485-510.
24. Galaburda AM, Sanides F. Cytoarchitectonic organization of the human auditory cortex. *J Comp Neurol.* 1980;190:597-610.
25. Kondziolka D, Lunsford LD, Flickinger JC. Acoustic neuromas. *Curr Treat Options Neurol.* 2002; 4:157-165.
26. Neary WJ, Hillier VF, Flute T, et al. Use of a closed set questionnaire to measure primary and secondary effects of neurofibromatosis type 2. *J Laryngol Otol.* 2010;124:720-728.
27. Rueckriegel SM, Homola GA, Hummel M, Willner N, Ernestus RI, Matthies C. Probabilistic fiber-tracking reveals degeneration of the contralateral auditory pathway in patients with vestibular schwannoma. *AJNR Am J Neuroradiol.* 2016;37:1610-1616.
28. Hackett TA, Preuss TM, Kaas JH. Architectonic identification of the core region in auditory cortex of macaques, chimpanzees, and humans. *J Comp Neurol.* 2001;441:197-222.
29. Wallace MN, Johnson PW, Palmer AR. Histochemical identification of cortical areas in the auditory region of the human brain. *Exp Brain Res.* 2002;143:499-508.
30. Matthew LC, Joseph TB. Cochlear implantation in patients with neurofibromatosis type 2: variables affecting auditory performance. *Otol Neurotol.* 2005;33:853-862.
31. Lustig LR, Yeagle J, Driscoll CL, Blevins N, Francis H, Niparko JK. Cochlear implantation in patients with NF2 and bilateral vestibular schwannoma. *Otol Neurotol.* 2006;27:512-518.
32. Vermeire K, Van de Heyning P. Binaural hearing after cochlear implantation in subjects with unilateral sensorineural deafness and tinnitus. *Audiol Neurootol.* 2009;14:163-171.
33. Matsumoto R, Okada T, Mikuni N, et al. Hemispheric asymmetry of the arcuate fasciculus: a preliminary diffusion tensor tractography study in patients with unilateral language dominance defined by Wada test. *J Neurol.* 2008;255:1703-1711.

Conflict of interest statement: The authors declare that the article content was composed in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Received 13 September 2018; accepted 7 March 2019

*Citation: World Neurosurg. (2019) 130:e1-e8.
<https://doi.org/10.1016/j.wneu.2019.03.066>*

Journal homepage: www.journals.elsevier.com/world-neurosurgery

Available online: www.sciencedirect.com

1878-8750/\$ - see front matter © 2019 Published by Elsevier Inc.