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ORIGINAL RESEARCH

Enhancing Neuroanatomy Teaching with DSI Studio's Fiber Reconstruction Technology

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Background: DSI Studio is an advanced imaging software specifically designed for the analysis of diffusion magnetic resonance imaging (dMRI). Its key features, which include fiber reconstruction, fiber tracking, and 3D visualization, have established its significant role in neuroscience research.

Objective: A solid understanding of spatial relationships is crucial for students studying anatomy. However, there has been limited research in Chinese medical education regarding the integration of 3D imaging technology into anatomical instruction. To address this gap, we conducted an innovative study utilizing DSI Studio to enhance neuroanatomy education.

Methods: An innovative study was conducted utilizing DSI Studio for fiber reconstruction and 3D visualization in neuroanatomy workshops. A total of 38 students participated in hands-on sessions, with 13 completing pre-training surveys and 19 completing post-training surveys. The students' understanding of neuroanatomy prior to training, as well as their performance and experiences during the neuroanatomy learning process, were systematically recorded. Additionally, the effectiveness of DSI Studio software in enhancing neuroanatomy learning was assessed in conjunction with the reconstruction capabilities of the software.

Results: The application of DSI Studio significantly improved students' visualization of neural structures, surpassing traditional teaching limitations. It enhanced their understanding of three-dimensional brain anatomy, boosted enthusiasm, and improved learning efficiency. The workshops supported the students' progression through the knowledge acquisition phases—understanding, mastery, and application.

Conclusion: DSI Studio demonstrates potential as an educational tool in neuroanatomy, offering a supportive and flexible learning environment conducive to achieving learning objectives. Our findings preliminarily support the adoption of DSI Studio's fiber reconstruction technology in undergraduate medical education.

Keywords: neuroanatomy, DSI studio, spatial understanding ability, fiber reconstruction

Introduction

Teaching the nervous system remains one of the most formidable challenges in systemic anatomy education due to its intricate knowledge base and the difficulty in visually representing its internal structures, like fiber bundles and nuclei, on gross specimens.[1–5] Unlike other anatomical systems with more readily identifiable features, the nervous system—particularly the central nervous system—often proves challenging for students to fully grasp.[6] Although the concept of fiber bundles is simple, distinguishing and classifying these pathways—which link brain regions or nuclei with poorly defined borders—is challenging in gross specimens.[7] Moreover, depicting pathological specimens and interpreting their functional consequences and clinical relevance presents additional challenges.[8] Increasingly, anatomy educators acknowledge that traditional learning tools may hamper the development of students' spatial abilities, which are crucial

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for their anatomical understanding and academic performance.[9,10] As demonstrated in contemporary anatomical research that a thorough grasp of neuroanatomy fundamentally depends on appreciating the intricate three-dimensional relationships between various neural structures.[11–13] In pursuit of enhanced teaching methodologies that foster students' spatial perception of these structures, educators have experimented with VR,[14] 3D printing,[15,16] and 3D digital imaging[13] technologies in anatomical instruction with some success. However, the substantial financial investments and specialized technical requirements involved have constrained the broad adoption of these advancements in mainstream Chinese medical education curricula.[17,18]

Diffusion magnetic resonance imaging (dMRI) offers a non-invasive approach to studying brain white matter, its primary principle being the measurement of water molecule diffusion, which reflects the microstructure and anisotropy of white matter.[19] Currently, various software programs can perform fiber tracking on both normal and pathological magnetic resonance images, effectively visualizing fiber bundles.[20] This capability aids doctors in more accurately diagnosing and treating neurological disorders such as Multiple sclerosis,[21] Stroke,[22] and Parkinson's disease,[23] among others. DSI Studio is a tractography fiber imaging software designed for dMRI image analysis, with its main functions including fiber reconstruction, fiber tracking, and three-dimensional visualization.[19,24,25] The traditional pedagogical tools - primarily printed atlases and textbooks - often fall short in demonstrating a fiber bundle's full trajectory and its spatial relationship with adjacent structures, leaving students to rely on imagination to understand these spatial connections.[26] Yeh's research demonstrated that leveraging advanced fiber tracking algorithms, DSI Studio can provide detailed three-dimensional reconstruction of neural tracts, its connection nervous area, and even fibers with abnormal orientations.[27] Applying fiber tracking technology to neuroanatomical teaching can greatly enhance students' understanding of complex structures, providing a more intuitive grasp of the brain's intricate pathways and compensating for the shortcomings of traditional teaching methods. The limited availability of three-dimensional neuroimaging technologies in educational settings has led to suboptimal student comprehension of neuroanatomical structures in China, resulting in a noticeable discrepancy between established curricular goals and actual learning achievements.[28,29] To address this gap, we implemented the current study employing DSI Studio's advanced visualization capabilities to revolutionize neuroanatomy instruction.

The project aims to facilitate student engagement with DSI Studio software for learning and training, using both normal and pathological nuclear magnetic resonance data for study. It involves tracking and reconstructing significant ascending and descending fiber bundles and associated functional nuclei within the nervous system. Students will examine normal fiber structures and delve into their pathological features and clinical symptoms post-damage, enhancing their comprehension, retention, mastery, and application of crucial fiber bundles and nuclei. The integration of fiber reconstruction through DSI Studio with established teaching methodologies could lead to improved educational outcomes.

Materials and Methods

Planning

The DSI Studio workshop was scheduled from December 2023 to February 2024. The team members initially prepared datasets compatible with the software. Normal human brain images were acquired from the Human Connectome Project (HCP), comprising 6 cases, with an equal gender distribution of 3 males and 3 females. Data on brain hemorrhage were obtained from a local hospital, with a total of 2 cases. Data for Parkinson's disease openly available from Parkinson's Progression Markers Initiative (PPMI), including 2 cases from a normal control group and 2 cases from Parkinson's patient group. The aforementioned raw MRI data were processed according to DSI Studio's guideline to generate fib files, which provided ready-to-use data for students' fiber tracking in DSI Studio. The university's student societies and online platforms were used to invite interested students to participate in the learning. The participants were primarily first- or second-year medical students who were neuroanatomy-naive but may retain foundational anatomy knowledge from pre-tertiary education. The workshop took place in a computer classroom and was structured and conducted by team members experienced in DSI Studio operations. As this was the inaugural use of the software in an undergraduate setting, the workshop was organized in small groups. A total of 38 students were divided into two training sessions with

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19 students each. These students were further randomly distributed into small groups, with 5 groups in one session and 6 groups in the other.

Content

Prior to the learning process, instructional videos of the software were made available for students to watch. It was only after viewing these tutorials that students were permitted to independently operate the software. An open and exploratory computer teaching environment was provided, allowing students to select images for analysis based on their personal interests. The learning session totaled 4 hours, divided into three stages: an introductory presentation, a period of independent learning, and a final stage for sharing experiences and summarizing outcomes, which included discussing both feelings and achievements.

The workflow of our workshop is as follows (Figure 1):

The first step is a 60-minute background introduction, which is subdivided into three parts. The initial part introduces the concept of magnetic resonance imaging to participants, the second part involves a review of brain anatomy conducted by the students themselves, and the third part covers the operation and application of DSI Studio software. This teaching approach helps students quickly integrate their existing knowledge with the new information presented.

The subsequent 120 minutes are allocated for student self-study. During this time, they become gradually acquainted with the software and then begin to perform fiber tracking and reconstruction based on their individual interests. Should they encounter difficulties, they are encouraged to seek assistance from their peers.

The concluding 60 minutes are reserved for students to share their achievements and experiences.

Data Collection

Feedback was gathered in the form of student responses and peer evaluations. Students were invited to complete pre- and post-learning questionnaires (see Supplementary Material 1). Prior to the study, questionnaires were distributed to collect data on students' experiences with traditional neuroanatomy learning. After the training, a different survey was administered to gather feedback on the assistance provided by DSI Studio in learning neuroanatomy and on the overall learning experience. Before training began, each student was provided with a piece of cardstock to independently document any problems encountered during the learning process and their solutions. The suggested topics for documentation included software operation, image analysis, results of fiber tracking, comprehension of the content, and the overall learning experience. Additionally, each instructor received a piece of cardstock to record the students' real-time reactions throughout the learning process, primarily noting facial expressions, verbal feedback, and learning behaviors. These situational records allowed for an authentic reconstruction of the students' learning processes, showcasing the true effect of the software training.

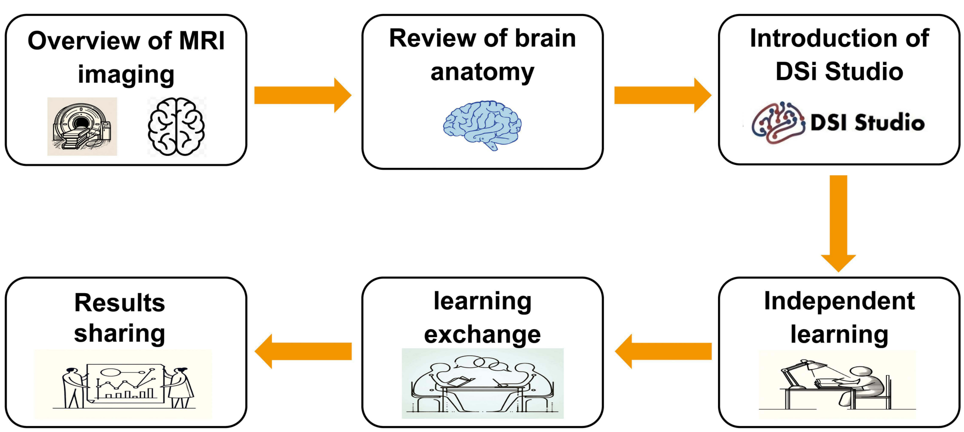

Figure 1 Structure and content covered in the workshop.

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Statistic Analysis

The survey employed a five-point Likert scale (1 = "very dissatisfied [very helpless]", 2 = "dissatisfied [helpless]", 3 = "neutral", 4 = "satisfied [helpful]", 5 = "very satisfied [very helpful]") to evaluate participant responses. This standardized interval measurement facilitated subsequent parametric statistical analysis. Data analysis was performed using SPSS version 19.0 (IBM Corporation, Armonk, NY, USA). Paired-samples *t*-tests were conducted to assess differences in three primary outcome variables—interest level, learning effectiveness, and clinical application competency—between pre-training and post-training evaluations. Statistical significance was established at $p \leq 0.05$. Continuous outcome measures are presented as mean ± SD (standard deviation) to indicate measurement precision.

Peer Evaluation

By presenting the workshop's design, demonstrating the operational process, and sharing the students' learning outcomes with peer educators, open-ended feedback was sought. Five main themes were explored:

The operation of the software.

The results of software reconstruction, including the advantages and disadvantages of the software.

Methods for incorporating the software into teaching.

The potential of the software to enhance teaching.

The target student that would benefit from this method of learning.

Results

Survey Results

Pre-Learning Survey Results

Three main phenomena were identified through the pre-learning survey (see Supplementary Material 2). First, regarding students' interest and attitude towards neuroanatomy, although all students expressed interest in learning about nervous fiber bundles prior to studying neuroanatomy, the traditional teaching model failed to effectively cater to their learning interests. A total of 23.68% of students had a negative attitude towards traditional teaching methods, and 50% felt that these methods only moderately satisfied their learning interests (Figure 2). Second, concerning the difficulty and learning effectiveness of neuroanatomy, all students reported finding the learning of fiber bundles challenging, with 81.57% considering it extremely difficult (Figure 3a). In terms of the effectiveness of displaying fiber bundles in gross specimens, 57.89% of students rated it as average, while 15.79% were dissatisfied with the results (Figure 3b). The high difficulty level and the lack of adequate learning aids led to less than ideal learning outcomes for students under the traditional teaching model; 57.89% rated their knowledge mastery as average and 31.58% as poor (Figure 3c). Third, regarding the

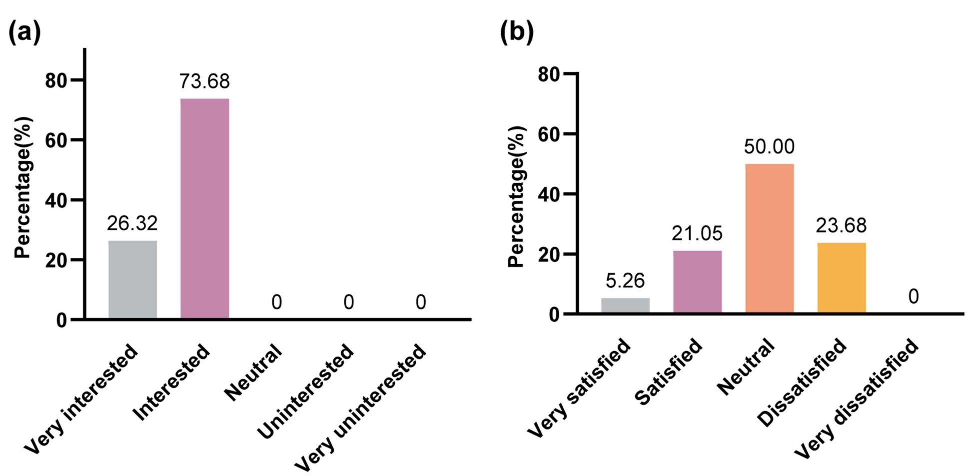

Figure 2 Phenomenon 1 identified through the pre-learning survey. (**a**) Students were interested in learning neuroanatomy, especially for nervous fiber bundles; (**b**) Student satisfaction levels with traditional anatomy pedagogy.

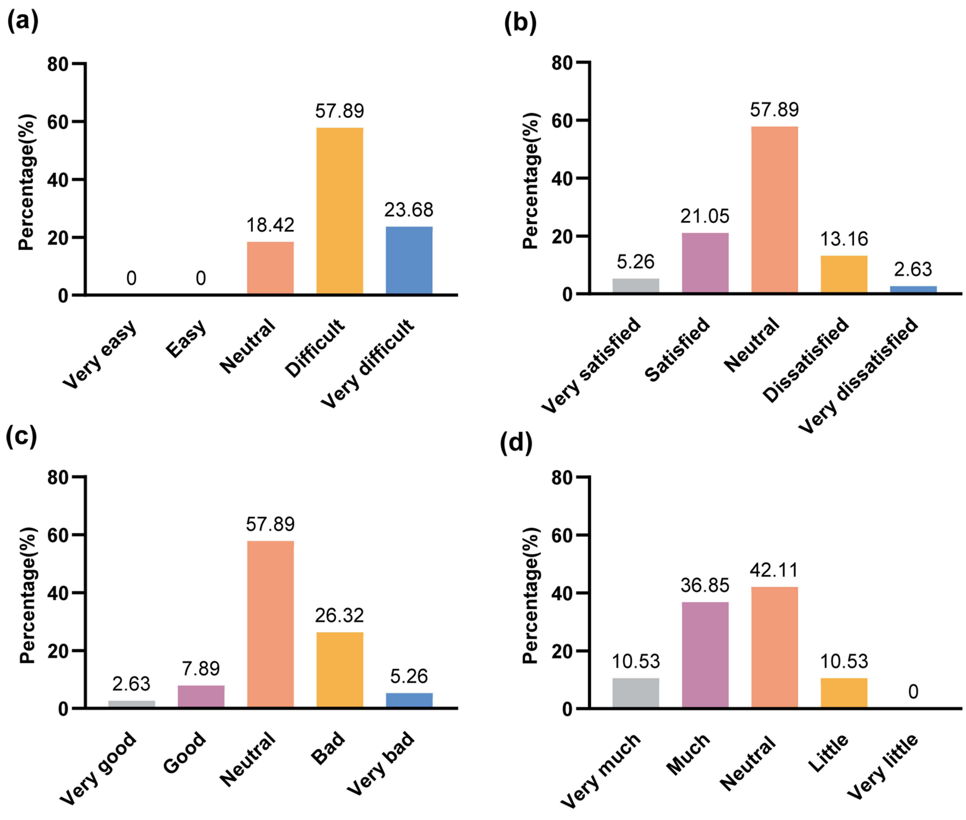

Figure 3 Phenomenon2 and 3 identified through the pre-learning survey. (**a**) Students found it difficult to learn the fiber bundles; (**b**) The effectiveness of the presentation of fiber bundles in cadaver specimen; (**c**) The extent of Students' neuroanatomical comprehension under traditional teaching model; (**d**) Contribution of the traditional teaching model to understanding clinically relevant diseases.

clinical relevance and application of traditional teaching methods, the traditional teaching of neuroanatomy did not effectively aid students in understanding clinically relevant diseases. While 42.11% of students believed it moderately helped them understand clinical diseases, 10.53% felt it provided no help in understanding clinical diseases (Figure 3d). In conclusion, the traditional teaching model exhibits significant shortcomings in teaching complex neuroanatomy, as it does not fully engage students' learning interests, leads to suboptimal knowledge mastery among students, and only moderately aids in their ability to link theory with clinical practice. Further investigation identified the main reasons for these results in traditional teaching as follows: ①Abstract concepts that are difficult to grasp; ② Challenges in observing fiber bundles in cadaver specimens; ③ Lack of ideal models; ④an insufficient connection to clinical practice (Figure 4). It was also discovered that students have a strong awareness and willingness to use advanced learning tools to help them overcome these learning challenges, with over 85% eager to explore innovative anatomy learning methods to enhance

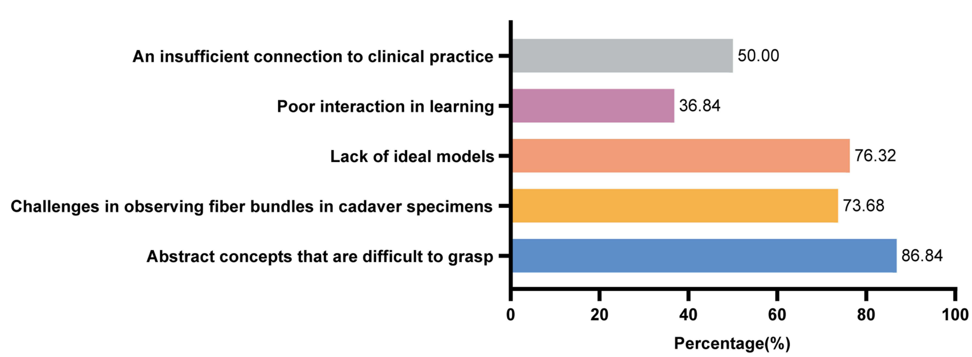

Figure 4 The main issues with the traditional teaching model.

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their interest, efficiency, confidence, and the ability to apply theory in clinical settings (see Pre-learning Survey Result in Supplementary Material 2).

Post-Learning Survey Results

The presentation of neuroanatomical structures by DSI Studio was met with high approval (see Post-learning Survey Result in Supplementary Material 2); First regarding software operation and learning outcomes, 94.74% of students were satisfied with the user interface, fiber reconstruction effects, and display effectiveness of the DSI Studio software (Figure 5a and b), with 65.79% regarding the presentation of complex neuroanatomical structures as extremely satisfying (Figure 5c). In terms of satisfaction with displaying fiber bundles and subtle structures such as nuclei that are difficult to depict on traditional gross specimens, no students expressed dissatisfaction, and over half (52.63%) thought it extremely satisfying (Figure 5d).

The impact of DSI Studio on student learning and engagement was positively assessed. Regarding Interest and Motivation, 94.74% of students believed that using the fiber reconstruction software for studying fiber bundles contributes to improved learning interest, efficiency, and self-confidence for 100%. Moreover, in terms of Clinical Relevance and Application, 55.26% found that training with DSI Studio was very helpful for interpreting magnetic resonance images. When asked about the software's assistance in understanding clinical symptoms of brain hemorrhage, 47.37% and 50% chose options indicating some and significant help, respectively. For understanding the clinical symptoms of Parkinson's disease, these figures were 34.21% and 60.53%. Furthermore, concerning Educational Value and Recommendation, 44.74% of students recognized significant advantages of DSI Studio training over traditional neuroanatomy teaching, and 57.89% would recommend the use of DSI Studio fiber reconstruction software for anatomy

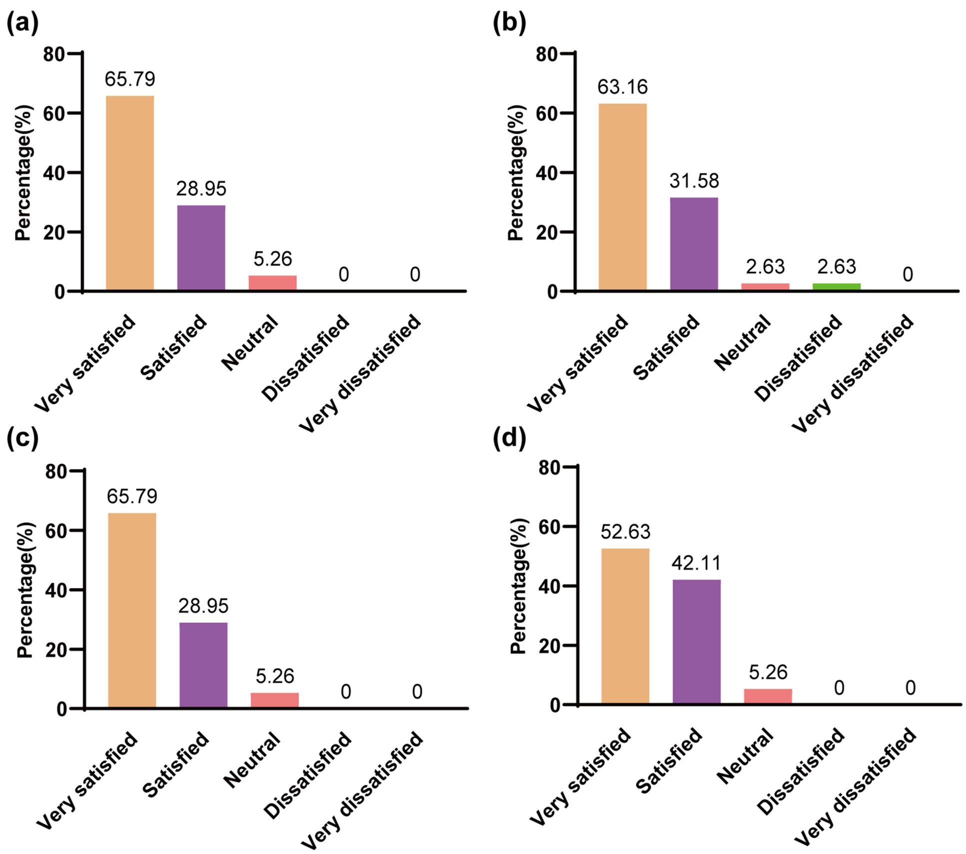

Figure 5 Student satisfaction with the presentation of neurological structures by DSI Studio. (**a**) Student satisfaction levels with the interface of DSI studio; (**b**) Student satisfaction levels with the fiber bundle reconstruction results of DSI studio; (**c**) Student satisfaction levels with the display of complex neuroanatomical structures by DSI studio; (**d**) DSI studio can display subtle structures such as fiber bundles and nuclei that are difficult to display on gross specimens satisfactorily.

learning without hesitation. The enhancement of the learning effect by DSI Studio abovementioned is detailed in Post-learning Survey Result.

A comparative statistical analysis was conducted across three measures: Interest/Motivation, Clinical Application Competency, and Learning Effectiveness, based on pre- and post-questionnaire assessments. The findings revealed that DSI Studio yielded statistically superior outcomes compared to the traditional teaching mode (Figure 6).

Learning Process Record

Initial Stage

At this stage, students gradually become familiar with the operation and functional options of the DSI Studio software, exploring the starting and ending points of fiber bundle tracking. They work in pairs or small groups, assisting each other. As they become more familiar with the software, they progressively master its usage and become more proficient at interpreting images. They begin to select data for fiber bundle reconstruction based on personal interests, gradually achieving a productive learning state. The teacher notes that initially, students appeared slightly puzzled, but as they became familiar with the user interface, a significant increase in learning confidence was observed.

Progression Stage

As the learning process advances, students identify fiber bundles and nuclei of interest and start fiber tracking and reconstruction. For example, Students W and L, who are interested in Parkinson's disease, attempted to compare the differences in fiber bundles within the basal ganglia between normal individuals and Parkinson's patients (Figures S1–S4 in Supplementary Material 3). Student Y focused on cerebral hemorrhage and conducted a comparative analysis of fiber counts between the affected and unaffected sides of patients. This analysis was linked to the traditional clinical concept of "triple hemiplegia syndrome", resulting in a comprehensive learning outcome. Student J had a similar experience, gaining a deep understanding of the impact of cerebral hemorrhage on limb movement by comparing corticospinal tracts on both sides of patients, significantly enhancing the link between nervous system structure and clinical diseases. Student L reconstructed the nigrostriatal fiber pathway in Parkinson's patients and shared the results with Student J (Figure S5 in Supplementary Material 3), finding that the software could clearly display the distribution of nerve nuclei in the brain.

Student A observed the fiber bundles between the putamen and caudate nucleus of a normal brain. Upon discovery, she was quite excited. She expressed that her understanding of the spatial structure between the basal ganglia nuclei in the brain had significantly improved. The teacher carefully documented her entire process from searching to confirmation to excitement, which drew the attention of nearby classmates, who gathered to observe.

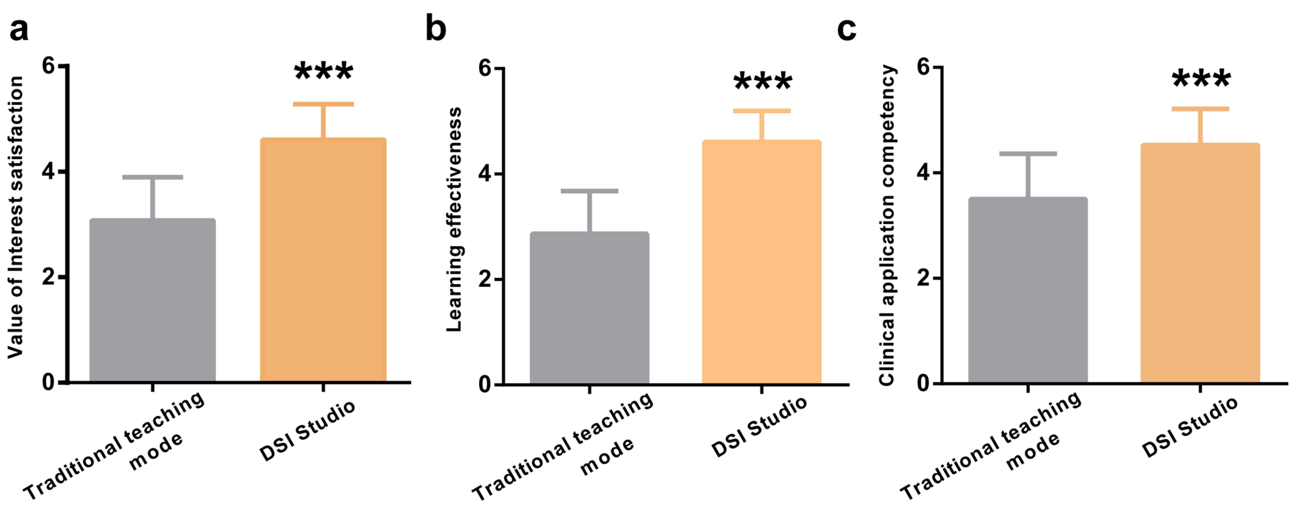

Figure 6 Graph displays the result of comparing student performance in three categories (Interest/Motivation, Clinical Application Competency, and Learning Effectiveness) between traditional teaching mode and DSI Studio's method. (**a**), (**b**), and (**c**) illustrate the differences in Interest/Motivation, Learning Effectiveness, and Clinical Application Competency, respectively, with *** denoting statistically significant results. The error bars represent the standard deviations.

Transition to Presentation and Discussion Phase After Self-Study

The session begins with the presentation of achievements. Student Y showcased the corticospinal tracts of patients with cerebral hemorrhage, rendering the complex fiber pathways more intuitive and vivid. The student showed a marked improvement in their understanding of the content; their joyful expression was a clear indication that the training had significantly bolstered their confidence in studying neuroanatomy. Student L, who had previously performed well, confidently demonstrated the fiber bundles within the basal ganglia, drawing the attention of several interested students through which created a harmonious learning environment. Additionally, many students engaged in small group discussions, freely sharing their findings and clearly benefiting from the experience.

This is followed by the sharing and exchange of learning experiences. Many students reported that DSI Studio greatly enhanced their understanding of the nervous system in three main ways. First, it provided a more intuitive comprehension of brain segmentation and fiber tract pathways, allowing for a clearer grasp of the connections between nuclei and fiber tracts compared to traditional teaching methods. Second, they were able to observe fiber trajectories under pathological conditions, identifying changes in fiber quantities by comparing healthy and diseased states. Third, DSI Studio effectively stimulated interest in self-directed learning.

Highlights of Achievements - DSI Image Display

Here, we highlight some of the students' accomplishments and compare them with cadaver specimens (Figure 7a). Observing the reconstructed corticospinal tract, one can clearly discern its origin in the precentral gyrus, its course through the internal capsule, and its spatial relationship with adjacent structures like the lentiform nucleus, thalamus, and caudate nucleus. In contrast, traditional specimen models can only show the location within the internal capsule and are unable to differentiate the corticospinal tract from other fiber tracts (Figure 7b). In a patient with right basal ganglia hemorrhage, the compression of the corticospinal tract on the right side resulted in paralysis of the left limb. The reconstruction illustrates different trajectories for the corticospinal tracts on each side, with 4772 fibers on the left and 1079 on the right (Figure 8). Clearly, the number of fibers on the impacted side is significantly lower than on the healthy side, providing a logical explanation for the limb paralysis due to reduced fiber count under compression.

The reconstruction of the substantia nigra fibers in both normal individuals and those with Parkinson's disease results in a vivid, three-dimensional representation that clarifies previously obscure positional relationships (Figure 9).

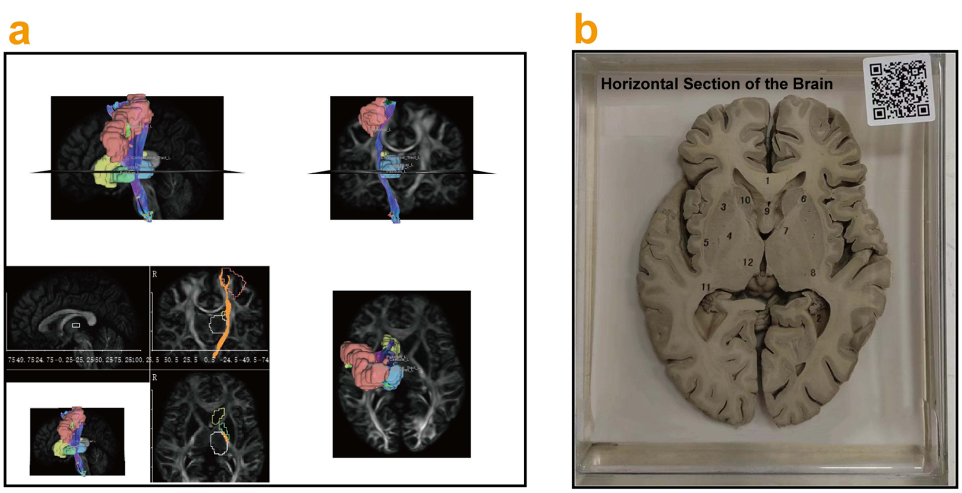

Figure 7 Comparative display of the corticospinal tract between DSI Studio imaging and cadaver specimen. (**a**) The corticospinal tract displayed by DSI Studio; (**b**) The corticospinal tract displayed in cadaver specimen.

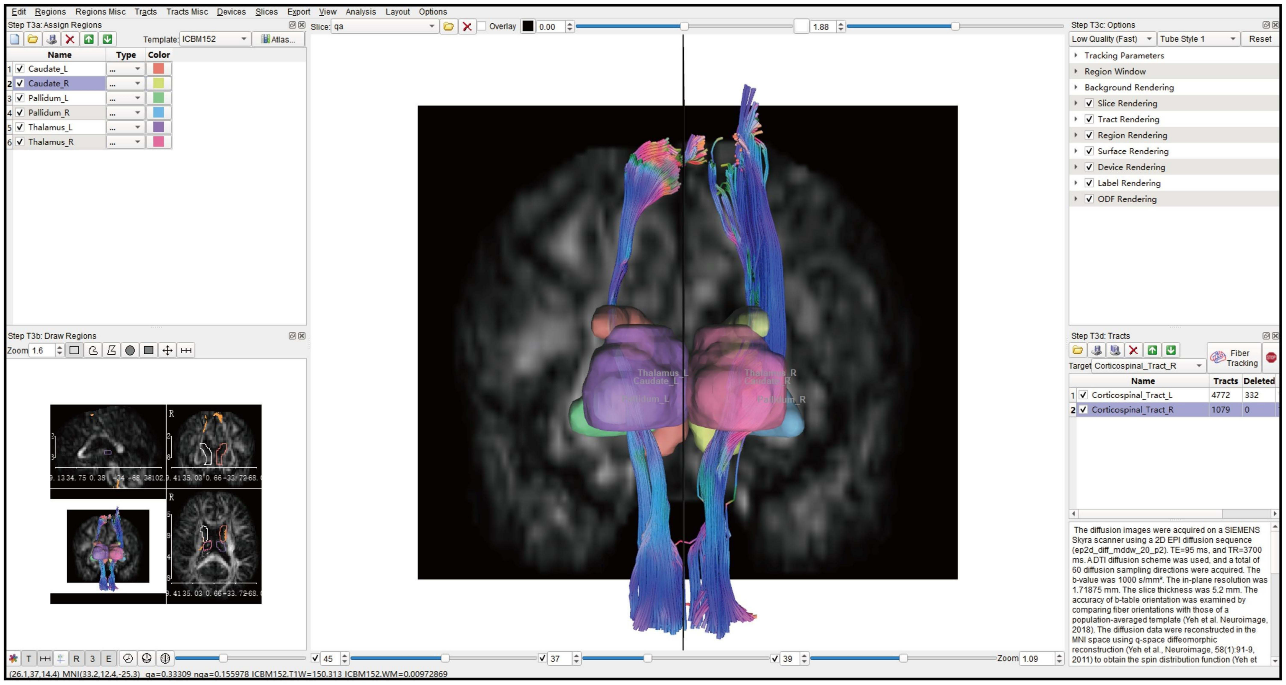

Figure 8 Comparison of the differences in the bilateral corticospinal tracts on a brain hemorrhage patient.

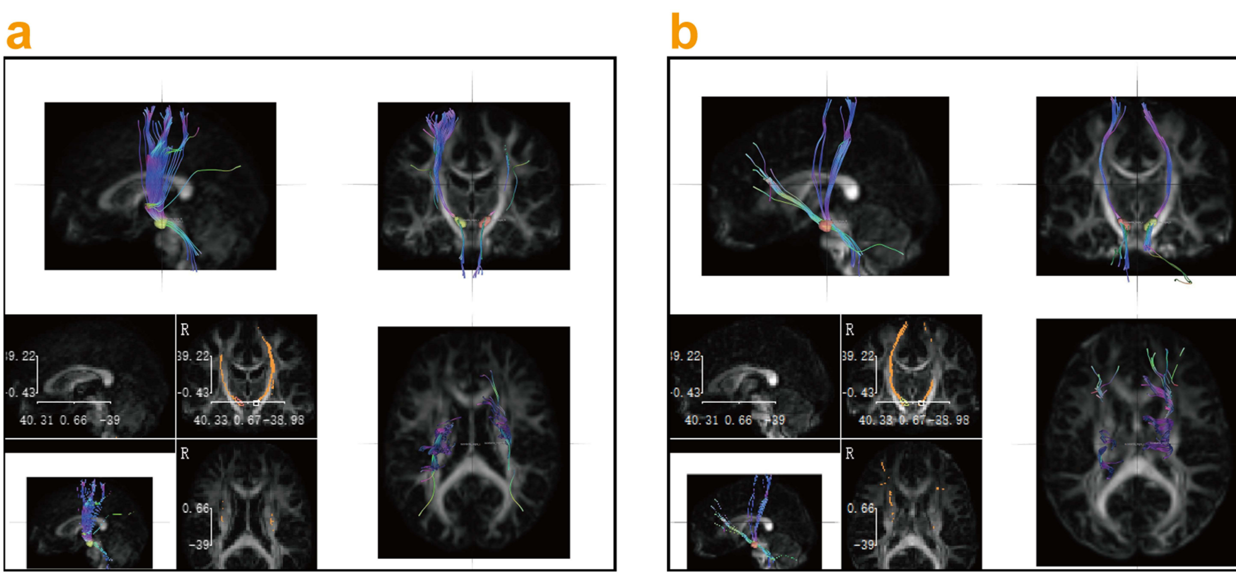

Figure 9 Comparative display of the substantia nigra fiber tracts in normal person and Parkinson's disease patient using DSI Studio. (**a**) The substantia nigra fiber tracts in normal person; (**b**) The substantia nigra fiber tracts in Parkinson's disease patient.

Peer Evaluation

During the discussions prior to the evaluation, it was noted that none of the peer teachers had previously used DSI Studio software or observed its use in teaching. They thus approached the project with curiosity. After the project's conclusion, we introduced five topics for the peer teachers' evaluation, garnering both positive and negative feedback.

Software Operation

The software interface could be more user-friendly. The fully English interface poses a challenge for students with limited English proficiency; it is recommended that they become acquainted with relevant professional English terminology beforehand to facilitate smooth operation.

Software Reconstruction Effect

The software offers distinct advantages. Fiber reconstruction is visually intuitive and features a strong three-dimensional effect. The distinction between normal and pathological fiber tracking is stark, helping students to better grasp the pathological aspects of diseases.

Application of the Software in Teaching

Different databases should be compiled for various disciplines, with data tailored to each. For undergraduates, who are new to clinical knowledge, the emphasis should be on normal fiber reconstruction, complemented by pathological examples. For clinical anatomy graduate students, a wider array of clinical data can be provided, allowing them to independently investigate and study areas of interest.

Impact on Teaching

The software is highly interactive and can capture student interest and enthusiasm. Teacher Zhao noted that visual aids can facilitate students' understanding of complex spatial structures. When students undertake the reconstruction of three-dimensional images themselves, it further stimulates their interest and solidifies their understanding.

Target Student for Learning Methods

Teaching in small groups, with a focus tailored to different audiences, is adopted. For general medical undergraduates, the priority should be on normal fiber tracking, with pathological fiber tracking as a secondary focus. For students with a foundational understanding of anatomy, elective courses could be offered to allow them to independently explore and study according to their interests.

Discussion

Pre- and Post-Project Questionnaire Analysis

In traditional teaching, instruction on fiber tracts is typically separated into theoretical and practical components. This approach allows students to gain a basic understanding of fiber tracts, but the simplicity of two-dimensional images falls short in fully demonstrating the spatial structure of fiber tracts, which can hinder student comprehension.[2,30]

In practical teaching, the reinforcement of theoretical knowledge is generally achieved by examining gross anatomical specimens. However, while these specimens are valuable for identifying the overall external morphology of the nervous system, they are less effective at illustrating the internal nuclei and fiber tract structures.[4] The pre-activity survey revealed similar student perceptions, with 57.89% rating the display of fiber tracts in gross specimens as average, and 15.79% finding it unsatisfactory. Additionally, the survey identified the main challenges of traditional teaching as the abstract nature of concepts, a lack of understanding, difficulty in observing fiber tracts in cadaver specimens, the absence of ideal models, and a disconnect from clinical relevance. Numerous studies have indicated that integrating anatomical structures with clinical contexts can lead to improved learning outcomes.[31] Educational research in anatomical sciences has consistently identified neuroanatomy as requiring instructional innovation, with student feedback regularly indicating demand for more effective teaching modalities.[32–34]

DSI Studio, in particular, has distinguished itself with its user-friendly operation, strong compatibility, clear imaging, and high resolution.[35] Consequently, we developed a neuroanatomy learning and training program utilizing DSI Studio. The training program yielded positive results; 63.16%, 68.42%, and 65.79% of students reported that the software considerably improved their learning efficiency, engagement, and confidence in anatomical studies, respectively. In the post-training evaluation questionnaire, 94.74% of students recognized the value in clearly visualizing fiber bundles, nuclei, and other internal neural structures, advocating for its widespread application. Additionally, 86.84% felt that the software helped them overcome the limitations of traditional teaching methods in reproducing the detailed structure of

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gross specimens. Moreover, 84.21% agreed that integrating this software with traditional teaching could be highly beneficial (Figure S6 in Supplementary Material 3).

Therefore, the teaching of neuroanatomy can be made more effective by integrating conventional methods with fiber reconstruction using DSI Studio software, as evidenced by the research conducted by Catena et al.[36] Cheung et al's research suggests that while anatomy education should continue to rely on cadaver specimens, it should be supplemented with techniques that elucidate otherwise "hidden" structures.[37]

Anatomy is inherently a morphological science, and illustrations often convey more information than textual descriptions alone. Forming a mental three-dimensional image of anatomical structures is crucial for mastering anatomy.[38] DSI Studio's advanced visualization technology renders two-dimensional anatomical diagrams as interactive 3D models, providing students with comprehensive spatial exploration of nervous system architecture across different planes and perspectives.[39,40] The insights gained from this approach surpass those provided by textbooks and standard models, rendering it particularly advantageous for anatomy courses.

Analysis of the Learning Process

Learning is a complex process that involves understanding, mastering, and applying knowledge at three levels. These levels are interconnected and collectively form a complete learning cycle.[2,41] In this classroom practice, students vividly demonstrated these three levels of learning.

Initially, students familiarized themselves with the software, interpreting nuclear magnetic data and exploring fiber orientations, which represents the understanding stage of learning. Some students experimented on their own, while others participated in collaborative discussions. Over time, many students gradually comprehended this knowledge, typically within half an hour. The classroom atmosphere evolved from quiet and formal to lively, joyful, and relaxed. The change in students' facial expressions from puzzled and serious to content reflected their joy after gaining understanding, mirroring findings in Pettersson et al 's research.[13]

As the learning process advanced, students began identifying fiber bundles of interest and engaged in fiber tracking and reconstruction. Some focused on Parkinson's disease data analysis and reconstruction, while others tracked brain hemorrhage patients or normal fiber bundles. This transition from understanding to mastery occurred naturally, as illustrated by Student A's excitement upon identifying the target structure. This excitement enhanced her understanding of the spatial structures between basal ganglia nuclei in the brain. We documented her journey from discovery to confirmation and excitement, which drew the attention of nearby students. This signifies that students were practicing and synthesizing newly learned knowledge, identifying intrinsic connections, and integrating it into their personal knowledge base, indicating the mastery stage.

Application is the advanced stage of learning, which involves the expansion and innovation of acquired knowledge.[42,43] The demonstration process exemplifies practical application of knowledge, internalizing it for output, which is indicative of the advanced stage of knowledge application. The presentation phase effectively connected the clinical pathological features of diseases with the corresponding abnormal fiber bundles, showcasing the students' ability to apply and transfer knowledge, significantly enhancing their learning effectiveness and capabilities.

Analysis of 3D Reconstruction Image Effects

Although cadaveric dissection provides anatomically accurate and intuitive visualization of neural fibers, the structural boundaries often appear indistinct and poorly delineated.[44] Furthermore, the preservation solution for specimens is typically formalin, which not only emits a strong odor but also poses long-term health hazards.[45] While plastinated specimens and wire-frame models can demonstrate the general course of fiber tracts and their spatial relationships with nuclei, these representations lack anatomical scale, often exhibit crude construction, and fail to reproduce the precise morphological characteristics of the actual neural pathways.[46] Both cadaver specimens and models encounter the same limitation—once they are structurally damaged during use, they lose their suitability for instructional applications.[47] With the advancements in imaging technology, modern imaging not only captures intricate human anatomical structures but may also better represents normal human anatomy or scenarios commonly seen in operating rooms than fixed cadaver tissues.[37,48] Our results showed: Multi-angle and multi-directional tracking of the corticospinal tract in DSI Studio effectively helped students develop spatial understanding; By using data on brain hemorrhage and Parkinson's disease, DSI Studio enabled students to grasp the pathological features of these conditions, interpret clinical symptoms, and facilitate the transfer of learning. In conclusion, DSI Studio vividly and accurately presented structures in three dimensions for anatomy teaching, compensating for the limitations of traditional specimens, enhancing students' spatial understanding of anatomy, improving their abilities to connect anatomy with clinical settings, and serving as an excellent tool in anatomy education.

Evaluation Analysis and Curriculum Development with DSI Studio

Post-course evaluations included teacher-student interviews and peer reviews. Feedback from students revealed that despite being new to this learning method, they quickly adapted to the software and enjoyed the approach. Students valued the ability to observe and manipulate the software repeatedly, which overcame the limitations of traditional methods in reproducing complex anatomical structures. The three-dimensional display of neural clusters and fiber bundles within the software improved their comprehension of challenging anatomical concepts and significantly increased their interest in the study of anatomy.

The evaluation was conducted by two professors, one associate professor, and two lecturers, who discussed five specific topics and provided overwhelmingly positive feedback. They recommended tailoring teaching strategies to the distinct needs of undergraduate and graduate students. For undergraduates, the focus should be on understanding and identifying normal anatomical structures, with an emphasis on normal structures in data presentations and diseases as additional context. Graduate education, in contrast, should prioritize the exploration of disease mechanisms, with data presentations highlighting pathological conditions over normal anatomy. Future plans should include collecting more normal and disease-related data to develop specialized DSI Studio nervous system learning datasets that cater to various professional needs. Gradually blending traditional teaching with DSI Studio's 3D reconstructions will encourage interactive learning between software, students, and teachers, fostering collaborative exploration in education.

Limitations

Despite the accomplishments of the training, there are some limitations and areas that could be enhanced. The study was conducted on a small scale with only 38 participants, limiting the generalizability of the findings to the broader medical community. The participants' selection did not fully represent the diversity of student grades and majors in the medical field, potentially introducing bias. The tight training schedule resulted in varying levels of understanding among students, with some finding the operations and software challenging. Approximately 18.42% of students did not find the software user-friendly and were hesitant to recommend it for broader use. Language barriers were also identified, as the software was in English, causing delays as students had to refer to translation dictionaries for medical terminology. The training was held in a computer lab with small screens, making it difficult to display comparative images effectively. This, coupled with a crowded software interface, hindered the observation process for some students. Around 21.05% of students expressed dissatisfaction with the clarity of fiber bundle displays and felt that their learning expectations were not met.

Conclusions

The fiber reconstruction technology offered by DSI Studio software provides a clear and intuitive display of fiber bundles, nuclei, and other internal neural structures. This overcomes the limitations associated with traditional teaching methods that use gross specimens and models. Students can visually and thoroughly understand the complexity of neuroanatomical structures, which increases their interest in and efficiency of learning anatomy. It also boosts their confidence in mastering knowledge and expands their ability to apply foundational anatomical knowledge to clinical practice.

Through interactive discussions and visual exploration using DSI Studio, students engage in a free-access interactive learning mechanism. This approach caters to their dual interests in normal anatomical structures and clinical diseases, while also introducing them to scientific research. This integrated teaching model, which combines knowledge of anatomical structures with clinical diseases and scientific research insights, provides a valuable educational practice. When combined with traditional learning methods, it can yield greater benefits.

Abbreviations

dMRI, diffusion magnetic resonance imaging; HCP, Human Connectome, PPMI, Project; Parkinson's Progression Markers Initiative.

Data Sharing Statement

The data supporting the findings herein are available from the corresponding author Li Lu upon reasonable request.

Ethics Approval and Informed Consent

We hereby affirm that our study adheres to the principles outlined in the Declaration of Helsinki. Informed consent was obtained from all study participants. Ethical approval (2023035) was obtained from the Research Ethics Committee of Shanxi Medical University. The study adhered to the ethical framework principles for research on learning. Patients with Cerebral Hemorrhage from Lu'an Hospital in Changzhi City provided informed consent. Parkinson's disease patient data are openly available from PPMI with approved informed consent.

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Author Contributions

All authors made a significant contribution to the work reported, whether that is in the conception, study design, execution, acquisition of data, analysis and interpretation, or in all these areas; took part in drafting, revising or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

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Disclosure

The authors report no conflicts of interest in this work.

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