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TEACHING ANATOMY

# Application of three-dimensional reconstruction and printing as an elective course for undergraduate medical students: an exploratory trial

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## Abstract

**Background** Medical three-dimensional (3D) digital reconstruction and printing have become common tools in medicine, but few undergraduate medical students understand its whole process and teaching and clinical application. Therefore, we designed an elective course of 3D reconstruction and printing for students and studied its significance and practicability.

**Methods** Thirty undergraduate medical students in their second-year of study volunteered to participate in the course. The course started with three lessons on the theory of 3D digital reconstruction and printing in medicine. The students were then randomly divided into ten groups. Each group randomly selected its own original data set, which could contain a series of 2D images including sectional anatomical images, histological images, CT and MRI. Amira software was used to segment the structures of interest, to 3D reconstruct them and to smooth and simplify the models. These models were 3D printed and post-processed. Finally, the 3D digital and printed models were scored, and the students produced brief reports of their work and knowledge acquisition and filled out an anonymous questionnaire about their study perceptions.

**Results** All the students finished this course. The average score of the 30 students was $83.1 \pm 2.7$. This course stimulated the students' learning interest and satisfied them. It was helpful for undergraduate students to understand anatomical structures and their spatial relationship more deeply. Students understood the whole process of 3D reconstruction and printing and its teaching and clinical applications through this course.

**Conclusion** It is significant and necessary to develop this course for undergraduate medical students.

**Keywords** Medical education · Medical image segmentation · Undergraduate education · 3D reconstruction · 3D printing

## Introduction

With the recently growing demand for personalized medicine, three-dimensional (3D) visualization and 3D printing technologies have become more and more applied and popular [11, 35, 36, 41], as these technologies can make human anatomical structures, even pathologically altered, visible. Currently, the application of 3D printing technology in medicine is mainly confined to surgery and medical education.

Three-dimensional printing has become a common tool in clinical practice to better understand the anatomical details of a disease condition preoperatively [29, 31, 42]. Before performing an operation, a surgeon can use 3D visualization technologies to delineate and visualize a tumor or a bone fracture and their adjacent structures based on the patient's computed tomography (CT) or magnetic resonance imaging (MRI) data. 3D-printed models can be used for preoperative assessment, surgical planning and rehearsal, which helps to improve the accuracy and success rate of surgery, shorten operation times, reduce operation risks and reduce the complications of surgery [3, 8, 16, 21, 46]. In orthopedics, 3D

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printing techniques can produce customized implants [7, 44].

In medical education, 3D printing technology could make anatomy teaching resources [15, 17, 43]. Three-dimensional prints of bones have been used to support anatomy education [1] and clinical teaching of orthopedic issues [27]. Randomized controlled trials have demonstrated that 3D-printed models facilitate and improve training in anatomy, especially with respect to structure recognition [9, 40]. Three-dimensional models of hepatic liver segments are shown to aid anatomical teaching [24]. Similarly, 3D-printed vascular models are used in simulation and for training purposes [18, 30]. Presenting patients with a 3D-printed model of their diseased organ also helps them to gain a better appreciation of their own pathology [4, 6, 10]. With advances in technology, 3D-printed models can, therefore, provide a low-cost, high-fidelity approach to surgical education and training compared with traditional methods [25].

In the above-mentioned investigations, most studies have simply used the end products, the 3D-printed models, as teaching tools. One study described the detailed process of 3D printing brains and skulls [37], but did not elaborate on the procedural elements of segmentation and 3D reconstruction. So far, there are few systematic and comprehensive courses on medical 3D reconstruction and 3D printing for undergraduates in medical schools. According to an oral survey conducted before class, most medical students only know very little about the process involved in developing 3D models.

The aim of this study is, therefore, to explore whether a course about medical 3D reconstruction and 3D printing is helpful for medical undergraduates in acquiring more detailed anatomy knowledge and understanding the teaching and clinical applications of 3D printing. The outcome of this study can help to determine whether or not developing such an elective course aids in medical students' anatomy learning. Thirty undergraduate medical students volunteered to participate in this study. Registered images of CT, MRI and thin-layer high-resolution tomographic images from Chinese visible human (CVH) data sets, as well as human histologically stained images, were used for creating 3D models and 3D printing. The learning process of the students and their anatomical knowledge acquisition were evaluated to analyze the significance, role and shortcomings of such an elective course.

## Materials and methods

Thirty second-year undergraduate students majoring in the 5-year medical program at the Army Medical University (Third Military Medical University) consented to participate in this study by voluntarily enrolling. Their characteristics are described in Table 1. These students had completed courses in systematic anatomy, topographic anatomy, histology and embryology and medical imaging before this study was conducted. Their performances in previous courses did not differ significantly.

An independent classroom was provided for the course. The following teaching equipment was available in the classroom: 12 graphic workstation computers with Amira software, version 5.2.2 (Mercury Computer System, Chelmsford, MA, USA), ACDSee software (official free edition; ACD Systems International Inc., Victoria, BC, Canada) and three 3D printers, including two fused deposition modeling (FDM) MakerBot® Replicator™ 2X printers (MarkerBot® Industries LLC., Brooklyn, NY, USA) and a commercial stereo lithography appearance (SLA) Form 2 printer (Formlabs Inc., Somerville, MA, USA). The medical data to be processed comprised ten groups of data (Table 2), including CT, MRI and histological section images from the University of Leiden and thin-layer high-resolution tomographic images from Chinese visible human data sets (Fig. 1).

A total of 11 lessons were conducted, requiring 33 class hours (each lesson contains 3 class hours). First, the students attended three lessons about basic theory. These lessons mainly comprised classroom teaching and case studies and aimed to provide students with a basic, preliminary understanding of advances in the application of digital medicine, medical imaging and 3D reconstruction and 3D printing technology. Then, the students were randomly divided into ten groups, with three students per group. Each group was randomly assigned one of the ten structures (Table 2). Under guidance of the teachers, each group was provided with supplemental information regarding their assigned data set; this included relevant anatomical structures, histology, imaging and pathological knowledge of their assigned structures. Finally, the teacher used Amira software to demonstrate how to use the tools, such as "Labelling", "SurfaceGen", "Smoothing" and so on, to segment, 3D reconstruct, smooth and simplify the model. According to the teacher' demo operation, students used Amira software to segment the

**Table 1** Participant characteristics

| Participant characteristics ($n=30$) | | |
|---|---|---|
| Male (number) | 28 | |
| Female (number) | 2 | |
| Age (years) | $21 \pm 2$ | |
| Stage of education (5-year medical program) | 2 | |
| Education status (pass/fail) | Systematic anatomy | Pass |
| | Topographic anatomy | Pass |
| | Histology and embryology | Pass |
| | Medical imaging | Pass |

**Table 2** Characteristics of the segmentation tasks of the different visualization methods (data type), topographical areas (region) and age and health of the specimens

| Data type | Region | Age of specimen | Health | Segmentation tasks |
|---|---|---|---|---|
| CVH2 | Pelvis | 22Y | Normal | Uterus, vagina, bladder, urethra, skin |
| CVH2 | Head and neck | 22Y | Normal | Brain, cerebellum, brain stem, skin |
| CVH5 | Knee | 25Y | Normal | Femur, tibia, patella, skin |
| MRI | Head and neck | 44Y | Normal | Cerebrum, cerebellum, brain stem, eyeball, optic nerve, skin |
| MRI | Pelvis | 26Y | Normal | Bladder, urethra, uterus, vagina, pelvis, skin |
| CT | Head and neck | 44Y | Normal | Bone, brain, cerebellum, brain stem, skin |
| CT | Upper abdomen | 48Y | Hepatic cancer | Liver, right kidney, liver tumor, bone, skin |
| CT | Thorax | 21Y | Aggressive fibroma | Thoracic bones, lung, chest tumor, skin |
| CT | Thorax | 56Y | Papillary adenocarcinoma | Ribs, costal cartilage, lungs, tumors, skin |
| Histological section | Male fetal pelvis | 24W | Normal | Bulbospongiosus muscle, Ischiocavernosus muscle, pubis, urethral cavernous, penis cavernous |

*CVH* Chinese visible human, *MRI* magnetic resonance imaging, *CT* computed tomography, *Y* year, *W* week

anatomical structure, reconstructed it in 3D, smoothed and simplified the reconstructed model, and applied 3D printing for the processed 3D digital model and post-processed the 3D-printed model. Examples of the segmentation and reconstruction process are shown in Fig. 2. At the end of the course, students submitted reports regarding their achievements and what they subjectively thought about the learning process. Teachers evaluated students based on their performance throughout this course. A Likert scale questionnaire was used to determine student perceptions post-course in the last class.

## Medical image segmentation

The CVH images were captured manually by camera and the histological section images were scanned with the Olympus BX51 and BX61 digital imaging systems at a 10× objective resolution. These images needed to be registered before segmentation. Due to the time limitations of the course, the images were registered in advance. The Amira software was used for image segmentation, and each group of students imported the registered images into the Amira software. According to the characteristics of the different groups of data, the instructor primarily selected the structures in the specimens that were relatively easy to segment (Table 2, segmentation tasks). The segmentation tasks of each group were evaluated by five experienced teachers to ensure that the workload and difficulty of the segmentation tasks were relatively similar. The bone and lung in the CT images could be automatically segmented through the threshold segmentation method, while the costal cartilage and tumor, digital human color photographs (CVH images) and histological images were manually segmented. The entire image segmentation process required four lessons. Examples of segmented images are shown in Fig. 3.

## Three-dimensional reconstruction and model preprocessing

Under the guidance of the instructors, the students used Amira software to 3D reconstruct the structures that they had segmented. They observed the 3D model, found errors and re-adjusted the 3D model until it was completely segmented in appearance such that no obvious errors were observed. Finally, the 3D model was smoothed and simplified to ensure that its surface was smooth. This process required three class hours.

## Three-dimensional printing

The 3D models established by each group of students were printed with photosensitive resin and PLA materials. Teachers first explained how a 3D printer functions and then demonstrated in a step-wise manner its operation to students. The students operated the 3D printer to print their own reconstructed models under the guidance of the teacher. The 3D printing class lasted for three class hours, but the printing required more time, so that teachers had to complete the unfinished printing works in class.

## Post-processing of 3D printing

Students used scissors and forceps to remove surface support material from the printed 3D reconstruction. A flat file, a round file and fine sandpaper were used to grind and smooth the surface of the model to eliminate surface irregularities. Then, a ventilated and dust-free place was given to students for painting the 3D-printed model with acrylic paint or BOTNY AEROSOL paint to emphasize

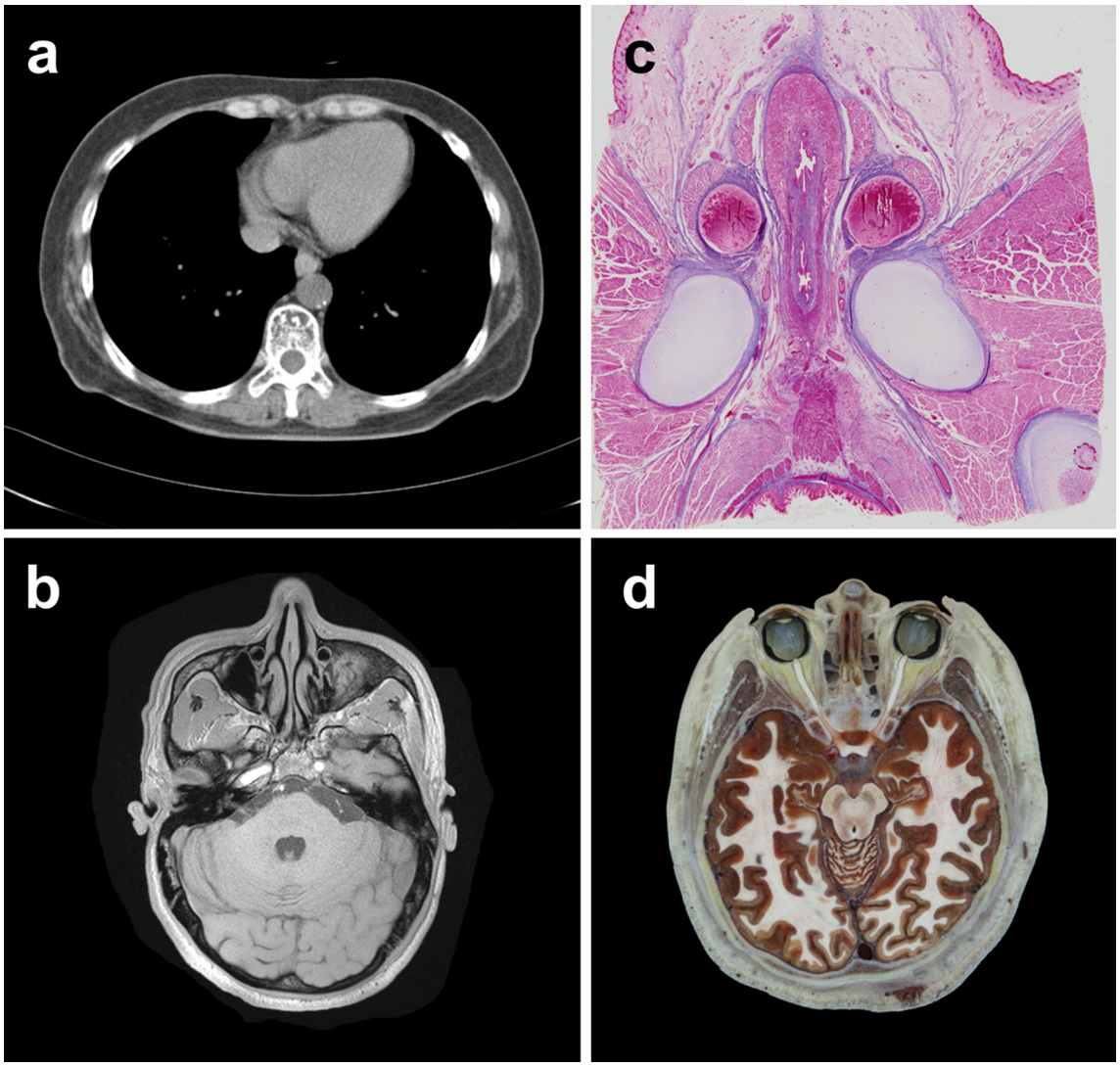



**Fig. 1** CT, MRI and histological images of human bodies and CVH anatomical section images. **a** CT cross-sectional image of the chest. **b** MRI cross-sectional image of the head. **c** Scanning image of histological staining of male embryo in the second trimester. **d** Cross-sectional image of the head from Chinese visible human data sets

the 3D effect of the 3D-printed model. This process lasted three class hours.

## Group report

In the last lesson, each group reported on their understanding of 3D reconstruction, the achievements of 3D printing and the group's learning, knowledge and experience with the course. The teachers scored the reports according to the students' ability to summarize their learning process and achievements in the course. This process lasted for three class hours.

## Evaluation score

The five experienced teachers scored the students according to their performance. The scores were mainly composed of three parts: 3D reconstruction which accounts for 40% of the total score, the final 3D-printed works which accounts for 30% and group report which accounts for 30%. The proportion of each part in the total score was discussed and decided by the five teachers according to the importance of each part. Among these, 3D reconstruction was evaluated to assess the students' knowledge about image segmentation and 3D reconstruction, and the corresponding score was based on the accuracy of the image segmentation and

smoothness of the 3D digital model. The final 3D-printed model score was based on four indicators: the accuracy and integrity of the printed model which accounted for 50% of the score, the quality of the supporting material removal which accounted for 20%, the degree of surface polishing which accounted for 10% and the model surface color which accounted for 20%. The group report helped to capture the students' understanding of the process of medical 3D reconstruction and 3D printing. The score for this part was based on the students' ability to summarize their learning process and achievements in the course.

### Student questionnaire

After the final course, the students in the class were asked to fill out an anonymous, researcher-designed questionnaire. The content validity of this questionnaire was assessed and checked by five experts. The questionnaire contained 27 items measured on a five-point Likert scale ranging from 1 to 5 as follows: 5—strongly agree; 4—agree; 3—no comment; 2—disagree; 1—strongly disagree. In addition, the students had the opportunity to comment on the content of the course. Detailed questionnaire information is available in Table 3. The complete survey questions and results in three periods are presented in this table, in which, items 1–3 are about students' cognition of 3D printing before the study, items 4–15 are about students' experience during the study and items 16–27 are about students' feelings and satisfaction after the study.

### Statistical analysis

The results of the questionnaire were computed and analyzed using IBM SPSS Statistics, version 24 (IBM Corp., Armonk, NY, USA). A Cronbach's alpha was calculated to analyze the reliability of this questionnaire. The mean rating of all students about each item was computed with IBM SPSS Statistics.

## Results

The five teachers scored the students on their performance. The scores in the following text are presented as mean values ± standard deviations for the 30 students, which were calculated using IBM SPSS Statistics software. The full score for each student was 100 points. The average score of the 30 students was 83.1 ± 2.7.

### Three-dimensional reconstruction

Students in each group completed their segmentation tasks and 3D reconstruction to obtain the relevant 3D visualization models in Amira software. Three examples of these digital models are shown in Fig. 4. In some cases, part of the structures was inaccurate or missing. The mean quality of the 3D reconstructed models was scored 78.2 ± 1.9.

### Three-dimensional printing and post-processing

The 3D reconstructed models were printed in three 3D printers. Students finished removing the supporting materials from the 3D-printed models, and polished and colored the finished products. Three examples of the final physical models are shown in Fig. 5. The mean quality of these 3D-printed post-processing models was scored 83.7 ± 3.8.

### Group report

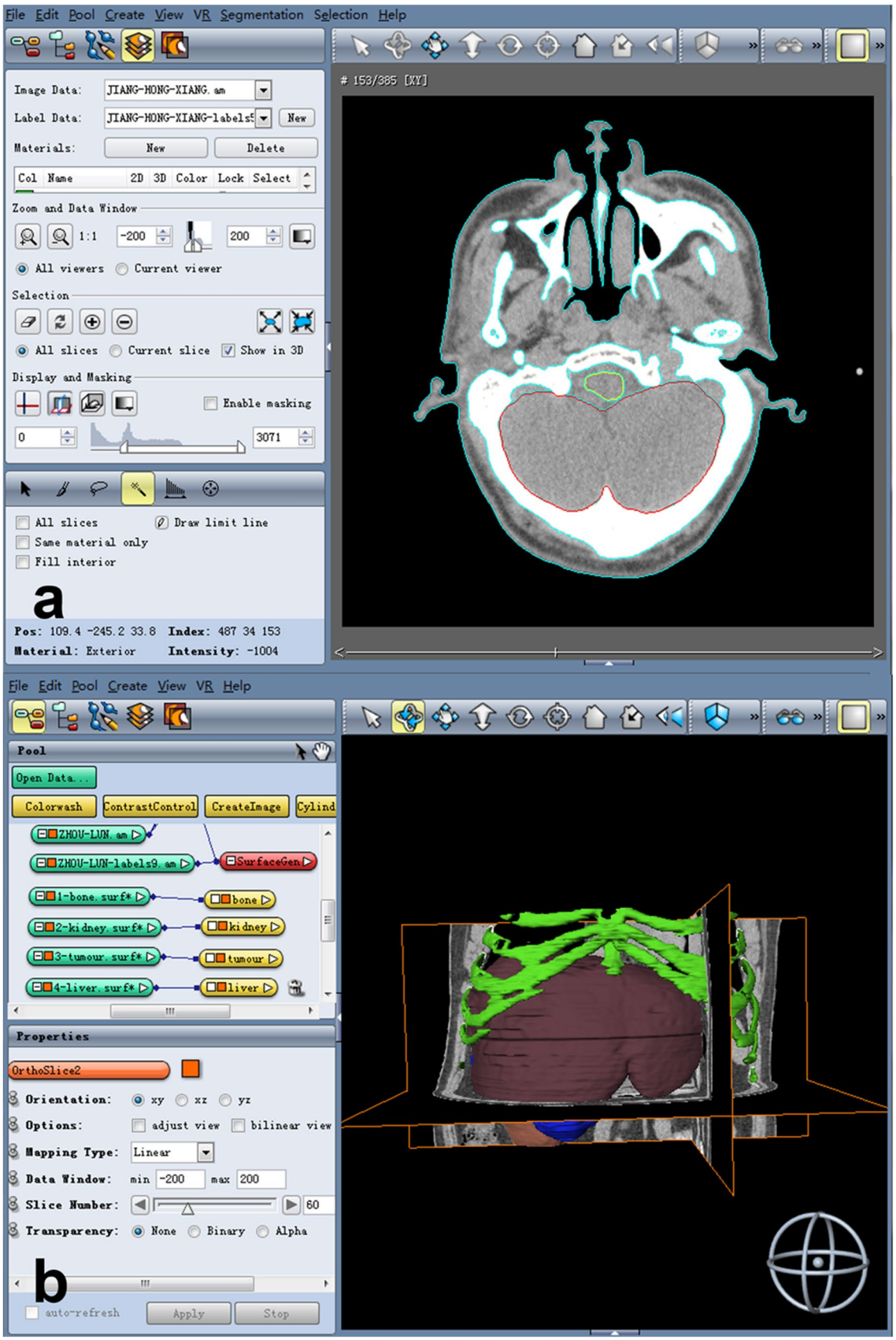
The reports showed that as a result of this elective course, most of the students were able to use Amira software for medical image segmentation, 3D reconstruction, model smoothing and simplification. They could also understand and fundamentally grasp the basic principles, development and the whole process of medical 3D printing. Furthermore, they could understand the role and application of medical 3D reconstruction and 3D printing in basic medicine and clinical medicine. The mean score for these reports was 89.2 ± 3.4.

However, students also reflected some problems, such as "The inclusion of excessively broad knowledge in medical image, including sectional anatomical images, CT, MRI and histological sectional images, brought great challenges for us". They also noted "Some of the structural boundaries were difficult to identify and learning the Amira software took us a great deal of time".

### Questionnaire analysis

Twenty students completed the survey. The results are shown in Table 3. The mean rating of each survey question is presented in Fig. 6.

The statistical analysis result showed that the reliability of this questionnaire was 0.86 (Cronbach's alpha), demonstrating its internal consistency. The survey results indicate that this course positively influenced the students' learning experience during the process of segmentation, 3D reconstruction and 3D printing (Table 3, item 19). The results also showed that 95% of the students either strongly agreed or agreed with the item "I am satisfied with the content of the course or the method of teaching" (Table 3, item 21–22). Ninety-five percent of the students either strongly agreed or agreed with the statement "I will recommend the course on medical 3D reconstruction and 3D printing to other students". Overall, the medical 3D reconstruction and 3D printing experience stimulated the students' interest and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3-tumour.surf*
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4-liver.surf*
liver
Properties
OrthoSlice2
Orientation: xy xz yz
Options: adjust view bilinear view
Mapping Type: Linear
Data Window: min -200 max 200
Slice Number: 60
Transparency: None Binary Alpha
b
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◂**Fig. 2** Examples of the segmentation and reconstruction process. **a** Data segmentation in Amira. Each color label represents an anatomical structure. **b** 3D reconstruction by volume rendering and surface rendering. Anatomical structures can be observed in three planes: *XY*, *YZ* and *XZ*

increased their motivation. Moreover, the mean rating of the questionnaire showed that the students had a significantly different understanding of 3D reconstruction and 3D printing before and after this course (Fig. 6, item 3 vs. item 14). The mean rating of all students about the experience during the study (Fig. 6, item 4–15) was $4.35 \pm 0.15$.

## Discussion

In this study, the students participated in the entire process of medical image segmentation, 3D reconstruction, 3D printing and post-processing of 3D-printed models, with the aim of acquiring more detailed anatomy knowledge and to enhance their understanding on teaching and clinical applications of 3D reconstruction and 3D printing. As shown in Table 3 and Fig. 6, through the course, the students came to understand the significance and effects of medical 3D reconstruction and 3D printing (Fig. 6, item 14, the mean rating is higher than 4.5). The average total score of the students in this course was 83.1, which is not bad. Moreover, 90% of the students were of the opinion that completing the segmentation of medical images was helpful for understanding anatomical structures and their spatial relationship more deeply (Table 3, item 8). All these information indicated that students have a high appreciation of this course.

Typically, anatomical spatial relationships are taught through dissection, living anatomy and medical imaging [33]. Students can receive tactile perception and appreciation of anatomical structures through cadaver studies. As the surgery proceeds through medical imaging, students can observe the changes of soft tissues in real time. However, there are some disadvantages for both methods. The use of cadavers exposes students to embalming fluid chemicals, and there are legal requirements for using cadavers [5, 32]. Additionally, increasing numbers of medical students and a reduction in the number of cadavers available for anatomical study remain practical problems [33]. Medical 2D images have the disadvantage of being unable to display complex and abstract anatomical spatial structures well. Three-dimensional reconstruction is useful for directly displaying 3D structures, especially multiple, spatially entwined, hollow, branching structures [26]. However, virtual (digital) models lack many of the haptic qualities of a physical specimen. So, 3D printing opened up a new way for researchers to present their data [22]. It has become a common tool in clinical practice to better understand the anatomical 3D appearance and spatial relationship of a disease preoperatively [29, 31, 42].

The 3D-printed anatomical models can help both the surgeon and the patient to develop a better understanding of the anatomy [19]. So, physical 3D objects that are based on actual image data of human bodies are more and more used to teach human anatomy [24, 34, 38]. Three-dimensional visualization and 3D printing technologies can make abstract structures easier to visualize, simplify complex structures and help with the teaching of morphology [13, 14, 45]. Three-dimensional visualization of a complex region improved students' anatomical knowledge and, in particular, it was most helpful for students with a relatively low spatial imaging ability [12]. For these reasons, 3D visualization technology provides better teaching and learning tools than 2D images, such as illustrations in textbooks [47]. Three-dimensional reconstruction of tumor and organs in patients is an effective method for studying anatomy as well as for surgical planning [20, 23]. Furthermore, 3D-printed models can be used as a hands-on teaching tool, which can improve the learning experience of students [2, 39].

In Kong et al.'s work, they printed hepatic structures which were reconstructed from CT images of fresh cadaver's liver and used them to teach medical freshmen [24]. They designed three types of 3D models including hepatic segments without parenchyma (type 1), with transparent parenchyma (type 2) and hepatic ducts with segmental partitions (type 3). But they only used these models to help in teaching anatomy and did not teach students how to create 3D digital models and 3D printed models. In Loke et al.'s study, they printed models of tetralogy of Fallot and used them in medical education for residents and improved learner satisfaction [28]. But they still did not teach students the whole process of creating 3D printed models and did not mention the connection between basic and clinical medicine. In our work, we provide a course which contains the detailed process of 3D reconstruction and 3D printing. This course provides a platform for undergraduate medical students to understand the clinical anatomy of disease and to better understand the teaching and clinical applications of 3D reconstruction and printing.

Medical simulation needs 3D reconstruction and 3D printing, so in our course we mention this point. The entire process of image segmentation, 3D reconstruction and printing enhanced students' motivation to learn, because 3D digital models are stereo perception and 3D-printed models are touchable, which make the normal and abnormal anatomy more intuitive. This, in turn, deepens students' interest and understanding of human anatomy, pathological anatomy and clinical anatomy. The elective course in this study provided images from a variety of sources, including digital tomographic

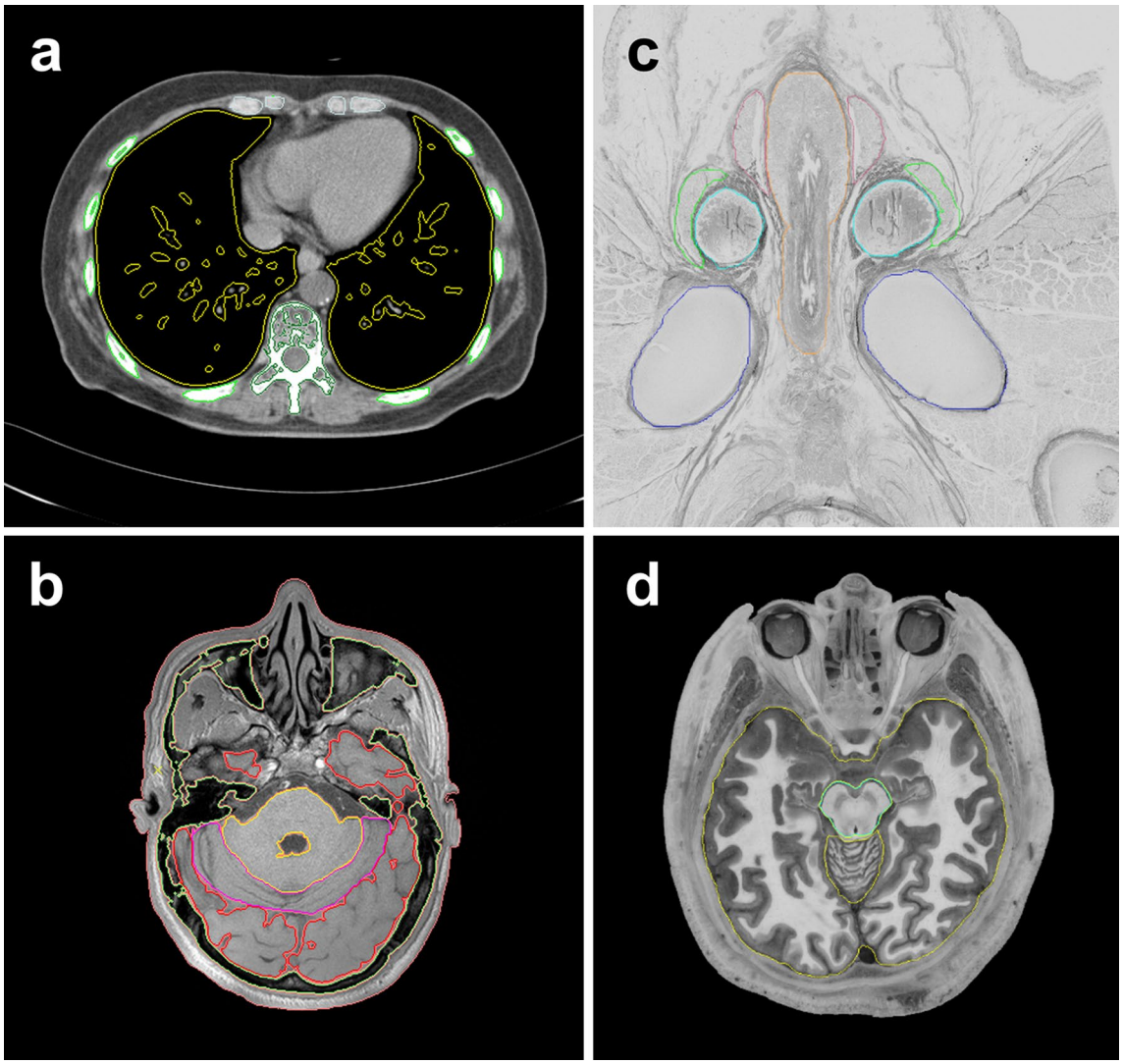


**Fig. 3** Segmented images. **a–d** Segmented images of Fig. 1a–d, respectively

images, CT, MRI and histology sections. This can help students understand how different data sets can be used to produce 3D visualizations and 3D reconstructions, and compare the differences in data segmentation and 3D reconstruction among these data. This elective course of 3D digital reconstruction and printing allows students to combine medicine (such as anatomy) with engineering technologies (3D printing). With rapid development and widespread application, 3D visualization and printing have become a cutting-edge technology that can meet an urgent need in modern medicine. It is necessary for medical schools to develop such a course, helping medical students to understand 3D visualization and printing technologies before they enter the clinic.

## Limitations

Thus far, there has been, to the best of our knowledge, no course to teach the processes of segmentation, 3D reconstruction and 3D printing for medical undergraduates. So this is a trial to apply a new elective course about 3D reconstruction and 3D printing in undergraduate students. For this reason, our study has some limitations. First, students need to be guided to recognize both normal and pathological structures, because they cannot identify the boundaries of the anatomical structures accurately in the early stages of their learning, which will take them a long time. Three groups of the CT data had diseases, which may affect students' "satisfaction", as it could either increase or decrease

**Table 3** Questionnaire and results

| Period | Item | Survey question | Mean ± SD |
|---|---|---|---|
| Cognition before study | 1 | I choose this course because I am interested in medical 3D reconstruction and 3D printing | 4.7 ± 0.5 |
| | 2 | This course is closely related to my major | 3.6 ± 1.2 |
| | 3 | Before the course, I knew less about medical 3D reconstruction and 3D printing | 3.9 ± 0.9 |
| Experience during the study | 4 | Through this course, I have improved my understanding on the advanced technology of digital medicine | 4.5 ± 0.5 |
| | 5 | After the theoretical part of this course, I have a basic understanding of the relevant theoretical knowledge of medical 3D reconstruction and simulation | 4.3 ± 0.6 |
| | 6 | During this course, I have acquired some knowledge related to the advanced technology of 3D printing | 4.4 ± 0.6 |
| | 7 | I find myself having some difficulty in completing the segmentation task because of the high level of ability required to recognize anatomical structures | 4.1 ± 0.7 |
| | 8 | I think completing the segmentation of medical images is helpful to understand anatomical structures more deeply | 4.5 ± 0.7 |
| | 9 | Medical image segmentation enhances my ability to summarize my experience in operation | 4.3 ± 0.8 |
| | 10 | Through the segmentation tasks, my communication skills with team members improved | 4.2 ± 0.9 |
| | 11 | The 3D reconstruction process has given me a clearer understanding of anatomy than ever before | 4.3 ± 0.6 |
| | 12 | The post-processing of 3D printing model improves my knowledge on complex spatial structure of the anatomical model | 4.5 ± 0.7 |
| | 13 | During the preparation of the summary report, my ability to summarize and refine knowledge was improved | 4.2 ± 0.7 |
| | 14 | Through this course, I realized the significance and effect of medical 3D reconstruction and 3D printing | 4.6 ± 0.6 |
| | 15 | I achieved my intended learning goals in medical image segmentation and 3D reconstruction | 4.3 ± 0.7 |
| Feelings and satisfaction after study | 16 | I think this course is of great help to my professional course of study | 4.0 ± 0.8 |
| | 17 | This course has enhanced my research ability and promoted my active learning in the class | 4.3 ± 0.6 |
| | 18 | This course enhanced my understanding of basic medicine and clinical medicine, and deepened my understanding of the intrinsic linkages between them | 4.4 ± 0.6 |
| | 19 | This course has positively influenced my learning experience by letting us experience the processes of segmentation, reconstruction and 3D printing | 4.5 ± 0.6 |
| | 20 | Through this course, I recognized my lack of knowledge in the past | 4.5 ± 0.5 |
| | 21 | I am satisfied with the content of the course | 4.6 ± 0.6 |
| | 22 | I am satisfied with the method of teaching used in this course | 4.6 ± 0.6 |
| | 23 | This course enhanced my interest in learning | 4.5 ± 0.5 |
| | 24 | I think the learning process of this course will have a positive impact on my future learning methods | 4.3 ± 0.7 |
| | 25 | I will share my learning outcomes with others | 4.4 ± 0.8 |
| | 26 | If there are other similar courses in the future, I will choose to participate | 4.7 ± 0.5 |
| | 27 | I will recommend the course on medical 3D reconstruction and 3D printing to other students | 4.6 ± 0.6 |

*3D* three dimensional, *SD* standard deviation

Surveys were rated using a five-point Likert-style scale with 1 = strongly disagree and 5 = strongly agree

the difficulty of 3D rendering. Second, the time for practice in this course is probably relatively short, because one student commented that "The class hours of this course should be longer". In agreement, teachers had to use extra time to complete the unfinished printing projects. Finally, due to the use of different data sets (CT, MRI, sectional anatomical images and histological images), it is difficult to equally distribute the workload and perform image segmentation and to comprehensively and accurately evaluate students' ability and efficiency. These limitations are topics for future studies.

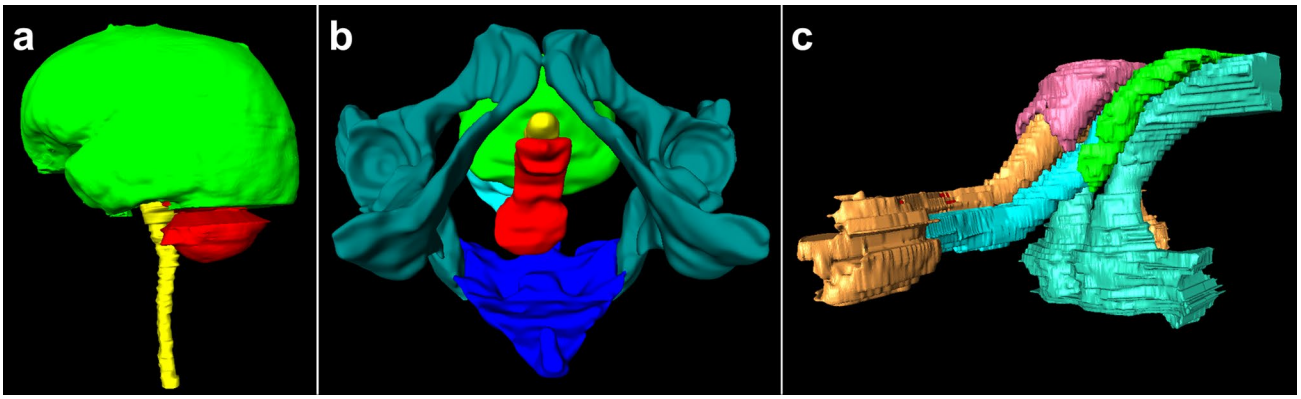


**Fig. 4** Examples of 3D digital models. **a** Cerebrum, cerebellum and brain stem from head and neck CT data. **b** Bladder, urethra, uterus, vagina and pelvic bone from pelvic MRI data. **c** Ischiocavernosus muscle, urethral sphincter, pubic bone and spongious and cavernous bodies of penis from a male fetal pelvis (histological slices)

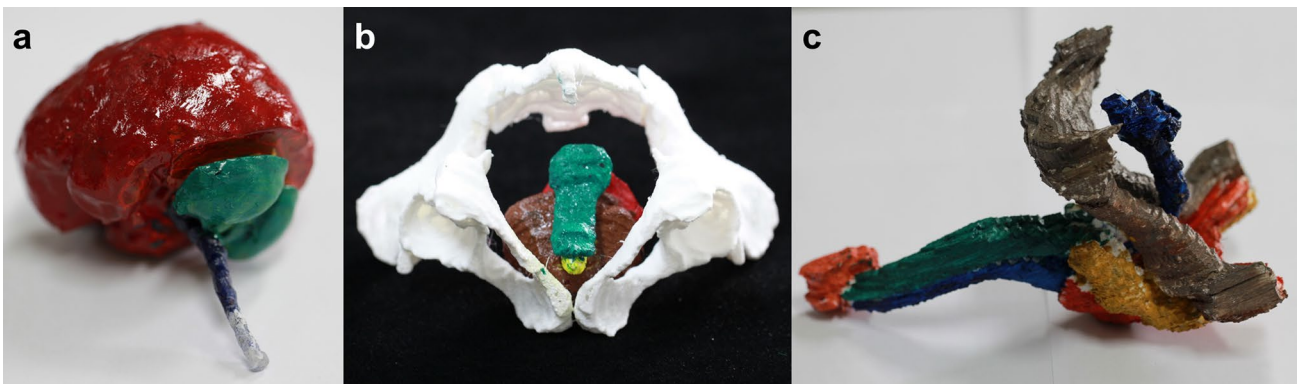


**Fig. 5** Examples of the 3D-printed post-processing model. **a–c** 3D-printed post-processing models of Fig 4a, b, respectively

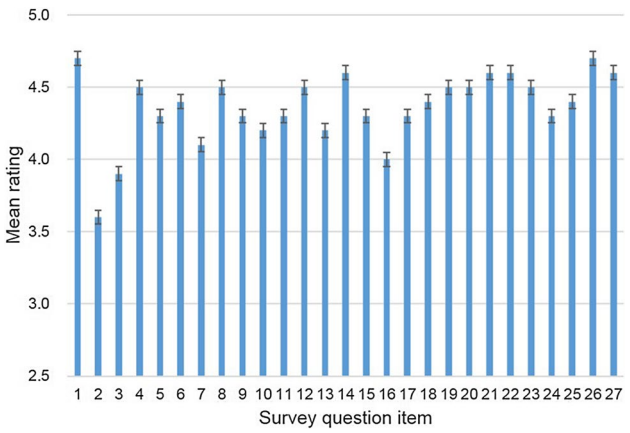


**Fig. 6** Mean rating of each survey question. The survey question item (*X*-axis) corresponds to the numbered item in Table 3. Surveys were rated using a five-point Likert-style scale with 1 = strongly disagree and 5 = strongly agree. *SD* standard deviation

## Conclusion

The elective course "medical 3D reconstruction and printing" stimulated the students' learning interest and satisfied the students. The entire process of this course developed the students' spatial ability. It is helpful for medical undergraduates to acquire more detailed anatomical knowledge including sectional, histological, pathological and medical imaging. In addition, this course provides an opportunity for students to understand the whole process of 3D reconstruction and printing and its teaching and clinical applications. 'There is a certain significance and necessity for medical schools to develop such a course for undergraduate medical students.

**Author contributions** XZ: data analysis; manuscript writing. ZX: data collection; teaching. LT: teaching guidance. YL: provision of materials and literature search. LL: statistical expertise. NC: data collection. SZ: teaching guidance. WL: conception and design. CW: provision of materials. YW: course design; teaching.

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## Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict of interest.

**Ethical approval** All CVH cadavers were enrolled in the body donation program of the CVH project, which follows the scientific and ethical rules of the Army Medical University (Third Military Medical University). The study was approved by the Ethics Committee of the Army Medical University (Third Military Medical University). Patient consent was provided for the use of their (anonymous) CT and MRI images. The histological section images were obtained in accordance with the Dutch regulations for the proper use of human and animal tissue for medical research purposes. The anonymous specimens, which belong to the historical collection of human embryos at the Department of Anatomy and Embryology, Leiden University Medical Center, Leiden, the Netherlands, had been donated for scientific research. The Leiden collection was established in the 1950–1970s. In the Netherlands, the study of historical collections is exempt from approval by a medical ethics committee.

**Informed consent** Informed consent was obtained from all individual participants included in the study.

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