The application of 3D printed models in the teaching of Tetralogy of Fallot to medical students: a randomized control trial

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Research

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Abstract

Background: Tetralogy of Fallot (TOF) is the most common cyanotic congenital heart disease. Its pathogenesis is complex and consists of different types of heart malformations. Whether for diagnosis or treatment, it is necessary to understand, in depth, the anatomical characteristics of this disease. With this, a full-colour model made by 3D printing technology is very suitable for helping users understand the complex configuration of organs and structures due to its high degree of simulation and homogeneity. The purpose of this study is to analyze the effect of 3D printing model on TOF teaching.

Methods: TOF image data were obtained from the medical image centre of the hospital and inputted into a colour 3D printer after software processing to print the full-colour model of TOF. Among the senior students of majoring in clinical medicine at our college, 30 students with equal male-to-female ratio were randomly divided into two groups: the 3D printing model group (n=15) and the traditional teaching group (n=15). At the end of the teaching session, theoretical examinations and a teaching effect questionnaire were distributed to evaluate the teaching effect.

Results: The overall score of the 3D model teaching group was higher than that of the traditional teaching group ($P<0.05$), with a higher number of students interested in the course compared to that of the control group. Additionally, the effect of the 3D printing model teaching group was better than that of the traditional teaching group ($P<0.05$), in terms of learning satisfaction.

Conclusion: The introduction of a 3D printed heart model into teaching can compensate for the deficiencies of the traditional teaching mode, improve the efficiency and effect of teaching, and is worth popularising and applying in the field of medical education.

Background

Tetralogy of Fallot (TOF) is the most common cyanotic congenital heart disease, with a prevalence rate of approximately 3%-5% of all infants born with a congenital heart disease[1]. It is one of the most serious congenital heart diseases. The pathogenesis of TOF is complex and consists of four types of heart malformations. Whether in diagnosis or treatment, it is necessary to understand, in depth, the anatomical characteristics of the four types of foetal heart malformations. In the undergraduate teaching of medicine, TOF is one of teaching emphases and difficulties in Paediatrics courses. It is difficult to form the spatial thinking of the TOF anatomy, but the understanding of the anatomical spatial structure during the teaching of TOF determines the degree of understanding of the disease and the teaching effect. With the development of medicine, students need to constantly increase and update their knowledge. Classroom teaching time is limited and precious. Faculty members in medical schools are always looking for ways to improve teaching effectiveness and efficiency.

With the development of science and technology, new instruments and technologies continue to emerge. In recent years, based on computed tomography (CT), magnetic resonance imaging (MRI), sectional anatomy, and other imaging data sets, three-dimensional (3D) reconstruction is performed to create 3D digital models that can be rotated, scaled, segmented, and fused, which improves the teaching effect. 3D printing can gradually accumulate 3D digital models into physical models with a variety of viscous materials[2]. In medical education, with a realistic, portable 3D printing model, we can easily take it to the classroom and show anatomical details, reproduce the 3D structure of human organs, and intuitively demonstrate the spatial structure. Its application in teaching and clinical practice has been reported in the past[3]. Materials for medical 3D printing include metals, polymers, ceramics, hydrogels, etc. [4]. With the progress of 3D printing technology, it is now possible to print full-colour, multi-material models, which can better show the pathological and anatomical changes of the disease. In this study, the latest full-colour multi-material 3D printer was used to print the heart model of TOF for teaching, and compared with traditional teaching methods, the teaching effect and efficiency were evaluated in the form of examination and questionnaire.

Methods

Research object

This study was conducted at the Clinical Medical School of Wannan Medical College.
Quota sampling was used to recruit thirty senior students majoring in clinical medicine. They were faced with the study of Paediatrics in a few months. We randomly divided them into two groups: (1) the traditional teaching group and (2) the 3D printing model group. The traditional teaching group consisted of seven males and eight females with an average age of 20.86±0.81, while the 3D printing model group consisted of 8 males and 7 females with an average age of 20.93±0.77. There were no significant differences in the age or sex ratios between the two groups ($P>0.05$).

TOF model printing

After CT scanning (SOMATOM Definition Flash, Siemens) and CT angiography, the imaging of a patient with TOF was obtained from the Medical Imaging Centre of the First Affiliate Hospital of Wannan Medical College. The obtained data sequence was processed by a 3D slicer software, and threshold segmentation was carried out using the functional modules of the segmentation editor (i.e., threshold, island, drawing tube, logical operator, and surface cutting). The 3D digital model was separated along the oblique coronal section, and the heart was divided into two parts. The angle of the section is the best view for observing the anatomical deformities of TOF[5]. The data were converted into a Standard Tessellation Language (STL) format that can be read by a 3D printer. We input it into a 3D printer (Sailner, J401Pro, Zhuhai Seine Technology Co.,Ltd. China) to create the model. The printer used was a full-colour multi-material mixing printer that can support seven types of materials. We chose two kinds of materials to print the coloured heart models and used them in equal proportions: FLX series flexible material and RGD series hard material. After setting the structure colour of each part, model I was printed with flexible material and model II was printed with hard material.

Teaching methods

According to the teaching schedule for the paediatric course, the classroom instruction time for TOF was 25 minutes. Both groups were taught at the same time. The traditional teaching group adopted textbooks and courseware, combined with clinical cases and imaging data. On the other hand, the 3D printing model group combined model teaching with traditional teaching methods, focusing on the demonstration of the four kinds of heart malformations using the 3D model. Afterwards, 5 minutes were set aside for the students in this group to watch the model in order to verify the anatomical changes of the heart.

Teaching effect evaluation

After the class, the two groups were given theoretical examinations and a questionnaire survey to evaluate the teaching effect. The theoretical exam contained 10 multiple-choice questions about TOF in order to evaluate their mastery of the topic. Three separate examinations were provided to account based on the Ebinghaus forgetting curve[6]. Ebbinghaus proved in the forgetting experiment that there is a fixed law of forgetting, the process of human forgetting is not balanced, there is the first fast and then slow law, the forgetting process is also affected by the memory materials. The first thing students forget is material that has no significance, no interest, or no need. A field test was conducted first, followed by a second test 24 hours later, and a third test seven days after. The contents of the three tests were identical. Additionally, the teaching effect was evaluated by the participants and suggestions were given through the satisfaction questionnaire.

Statistical processing

Statistical analyses were performed using GraphPad Prism9.0. The overall score data of the two teaching groups were expressed as the mean±standard deviation (x±s). The test scores between the two groups were analysed using student's *t-tests*. The questionnaire data were expressed as percentages and the chi-square (χ^2) test was used for the comparison between groups. The difference was found to be statistically significant ($P<0.05$).

Results

3D printed models

We obtained two sets of 3D printed cardiac models of the TOF. As shown in Fig. 1, we used a 3D slicer software to establish a digital model first (Fig. 1A-B), then we inputted it into a 3D printer and used GND hard material to create model I (Fig. 1C-D). The model weighed 54.74g, had a hard texture, rich glossiness, good transmittance, and its internal structure could clearly be seen. For model II, we used FLX soft material to create it (Fig. 1E-F). Model II weighed 76.72g, had a soft texture, and was easy to deform. The printing cost was $3 per gram, and the total cost of the two models was $390. The overall structures of the two models are shown in Fig. 1G. The four deformities of the TOF and structure of the heart were clearly discernible.

Results Of Theoretical Examinations

In the theoretical exams, the anatomical changes, clinical manifestations, diagnosis, and treatment of TOF were tested. The study found that the scores of the 3D printing model group were significantly higher than those in the traditional teaching group ($P < 0.05$) for all three tests. The results are shown in Table 1.

Table 1
Comparison of the theoretical exam results between the two groups

Group	Field test (10)	Test after 24h (10)	Test after 7d (10)
3D printing model teaching	9.20 ± 0.653	7.60 ± 1.02	6.20 ± 0.83
Traditional teaching	7.07 ± 1.44	6.07 ± 1.29	5.47 ± 1.02
t	5.060	3.490	2.079
P	< 0.05	< 0.05	< 0.05

Evaluation Of Teaching Effect

All the students completed the subjective questionnaire survey after the class. The contents of the questionnaire survey are shown in Table 2. The answers of the two groups were compared and analysed, in order to determine whether the 3D printing model teaching group satisfactorily mastered the 3D structure of the heart and the anatomical structure of the four malformations of TOF. Their understanding of the theoretical knowledge and the principle of surgical treatment were also evaluated. As shown in Table 3, the effect of the 3D printing model teaching group was better than that of the traditional teaching group ($P < 0.05$), in terms of learning satisfaction. However, there was no significant difference in the theoretical knowledge mastery satisfaction between the two groups ($P > 0.05$).

At the end of the questionnaire, the students were allowed to give their suggestions. Some students in the traditional teaching group said that they did not have a thorough understanding of the four anatomical deformities of TOF, and the case was not vivid enough, so they suggested incorporating after-school experiments or animations. For the 3D printing model teaching group, some students suggested increasing the number of models and gathering more disease data to promote the teaching of other topics. With this, support for the introduction of the application of 3D printing technology in learning medicine was given by the participants.

Table 2
Multiple choice items of the survey questionnaire

Question	Very satisfied	Satisfied	No idea	Dissatisfied	Very dissatisfied
Satisfaction with this teaching style	□	□	□	□	□
Master the 3D structure of TOF	□	□	□	□	□
Master the anatomical structures of four malformations	□	□	□	□	□
Increase interest in learning	□	□	□	□	□
Master theoretical knowledge	□	□	□	□	□
Master the principle of operation	□	□	□	□	□
Key: □=very satisfied, □=satisfied, □=no idea, □=dissatisfied, and □=very dissatisfied					

Table 3
Comparison of learning satisfaction between groups

Item	Traditional teaching		3D printing model teaching		χ^2	P
	Satisfied	Dissatisfied	Satisfied	Dissatisfied		
1	8(53.3)	7(46.7)	13(86.7)	2(13.3)	3.968	0.046
2	9(60.0)	6(40.0)	14(93.3)	1(6.7)	4.658	0.031
3	7(46.7)	8(53.3)	14(93.3)	1(6.7)	7.778	0.005
4	6(40.0)	9(60.0)	15(100.0)	0(0.0)	12.860	0.000
5	10(66.7)	5(33.3)	12(80.0)	3(20.0)	0.681	0.406
6	9(60.0)	6(40.0)	1493.3)	1(6.7)	4.658	0.0031

Discussion

TOF was the first complex heart disease to be palliated by surgery[7]. Before entering clinical practice, students should have a good background on anatomical concepts and clear surgical thinking. At present, most medical colleges in china still adopt the traditional mode of teaching—teaching based on textbooks, two-dimensional pictures, and courseware for classroom teaching, combined with imaging materials, autopsies, and other normal anatomy teaching models[8]. However, the heart is a hollow yet complex organ. Due to its anatomical structure, pathways of blood vessels, and the presence of some hidden cardiac anatomical marks, it may be difficult for students to fully understand and visualize the elaborate

3D anatomy of the heart using a simple two-dimensional atlas. Even 3D reconstructions based on imaging data have been difficult to present, and although some studies have tried to use virtual reality to present cardiac models, the equipment is expensive and thus not suitable for widespread use[9]. As for cadaver use, the connections between the structures in a cadaver specimen may be difficult to present clearly and the pungent specimens must be kept in the laboratory. Since the existing teaching models usually only present models of a normal heart, students may have a hard time forming a 3D structure in their minds of an abnormal condition such as TOF, making it difficult to fully understand the anatomical and hemodynamic changes involved.

Although we carefully prepared the teaching content for the traditional teaching group, given the 25-minute time limit, the study found that the teaching effect was not satisfactory and the students' interest in learning was low. Despite the fact that case-based learning was incorporated, students in the traditional teaching group still reflected that the case was not vivid enough and suggested adding after-class experiments or increasing animations. The feedback from the students showed that more time must be spent on strengthening the given materials. However, due to being limited by the teaching time, it is quite difficult to solve these problems with traditional teaching methods.

As for 3D printing, its advantages include the fact that a mould does not need to be designed, it has a short production cycle, and it is especially suitable for the rapid delivery of complex structured and customised medical products. The models have a high degree of simulation and homogeneity, which is very suitable for helping users understand the complex configuration of organs and structures[10]. The solid models printed by 3D reconstruction and 3D printing technology can be used as an anatomy teaching tool for preoperative communication, surgical rehearsal, and surgical planning. Since there have been cases of preoperative planning for TOF, the findings of our study are highly applicable in this context[11]. The 3D digital model was reconstructed based on patient imaging (CT, MRI) data, and the TOF model was printed using a 3D printer. The 3D model can accurately show the tissue structure, lesion location, and size of the organ to assist physicians in making management decisions. The 3D printing surgical planning model has three advantages. First, it visualises the tissue structure of the diseased site in complex cases, which is helpful in optimising the surgical design. Second, it helps facilitate the preoperative communication of surgical plans and surgical rehearsals. Third, it can help reduce the risk and time of operation, lessen the amount of blood loss, and improve the effect of surgical treatment[12–13].

In this study, the models were printed with equal proportions, in full-colour, and using multi-material to reflect the real structure and size of an infant heart with TOF. The advantages of 3D printing in classroom teaching is that it can create and scale real objects according to your needs, visually display a more complex structural relationship, is easy to carry, can be preserved long-term, and has no irritating smell[14]. When we revealed the 3D models in the classroom, the students immediately showed great interest, which created an active class atmosphere. In the survey questionnaire, all the students expressed satisfaction with this teaching tool and indicated that they had mastered the four anatomical deformities of TOF. They believed that 3D printing models could improve learning efficiency, allow for better mastery of knowledge, and improve understanding of the anatomical changes of TOF since this tool allows for more in-depth learning and the incorporation of clinical knowledge at the same time. However, our study has some limitations. First, we recruited only 15 people to teach because we only had two models. Small number of participants some of the results need to be interpreted with caution. Secondly, we only used 3D model for the teaching of TOF, the usefulness in other diseases teaching needs to be discussed.

Nowadays, with the continuous progress of medicine and the emergence of new diagnosis and treatment methods, students need to master increasingly more knowledge. Therefore, improving teaching efficiency within a specified period of time is one of the urgent goals that teachers should continue to pursue. We filled in the gap in TOF teaching using 3D printing models. After class, students expressed their hopes that more models can be provided in the future, and that other models can be popularised in the teaching of other topics as well. Although only two teaching models were created for this study, more models can be printed with increased financial support. Additionally, with the development of technology, the cost may be reduced in the future. The TOF models we created were made with hard and soft materials. For the hard material, the glossiness was good, it was not easy to deform, and it could print a completely transparent structure, which allows for the observation of the internal structures and is more conducive for teaching and viewing. In addition, the flexible material model can be cut at will, which allows for the simulation of an operation. With this, models can be designed for this purpose to help teach students about particular surgical techniques. This can greatly enhance students' sense of participation and interest in learning. The students also said that they wanted to know more about 3D printing technology and that they wanted to broaden their horizons. Hopefully, the application of 3D printing technology can be widely adopted in the clinical setting in the future. With the 3D models, medical students will be able to improve their understanding of certain diseases and improve their technical level regarding clinical work. This can promote the 3D printing technology into campus and expand the 3D printing market.

Conclusion

This study shows that with the development of 3D printing technology, the use of a full-colour 3D printing model can help compensate for the shortcomings of traditional teaching, as demonstrated in the teaching of students regarding TOF. The use of 3D models can help students quickly master the complex anatomical structures of lesions and can improve teaching efficiency and effect, given the limited teaching time. In the future research, we need to increase the sample size and popularize it in the teaching of other diseases, to obtain more realistic research results.

Abbreviations

TOF: tetralogy of Fallot; 3D: three-dimensional; CT: computed tomography; MRI: magnetic resonance imaging; STL: Standard Tessellation Language

Declarations

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Authors' contributions:

FWu conceived and designed this study. YHOu, LCChen, CYLing, ACao, and PJi processed the teaching program under the supervision of HCMiao. QYuan and HBLi collected and processed the data. HCMiao and YHOu analysed the data and wrote the manuscript. All authors read and approved the final version of the manuscript.

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Availability of data and materials

The datasets used and/or analysed during the current study are available from the Clinical Medical School, Wannan Medical College, upon reasonable request.

Ethics approval and consent to participate

The study was approved by the Medical Ethics Committee of the Clinical Medicine School, Wannan Medical College, and written informed consent was obtained from all participants. The authors assured in the signed consent form that the publication of the data will not indicate their names or identification information.

Competing interests

The authors declare no conflicts of interest. Anhui Jianying Technology Co., Ltd. declare that they have no competing interests.

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Figures

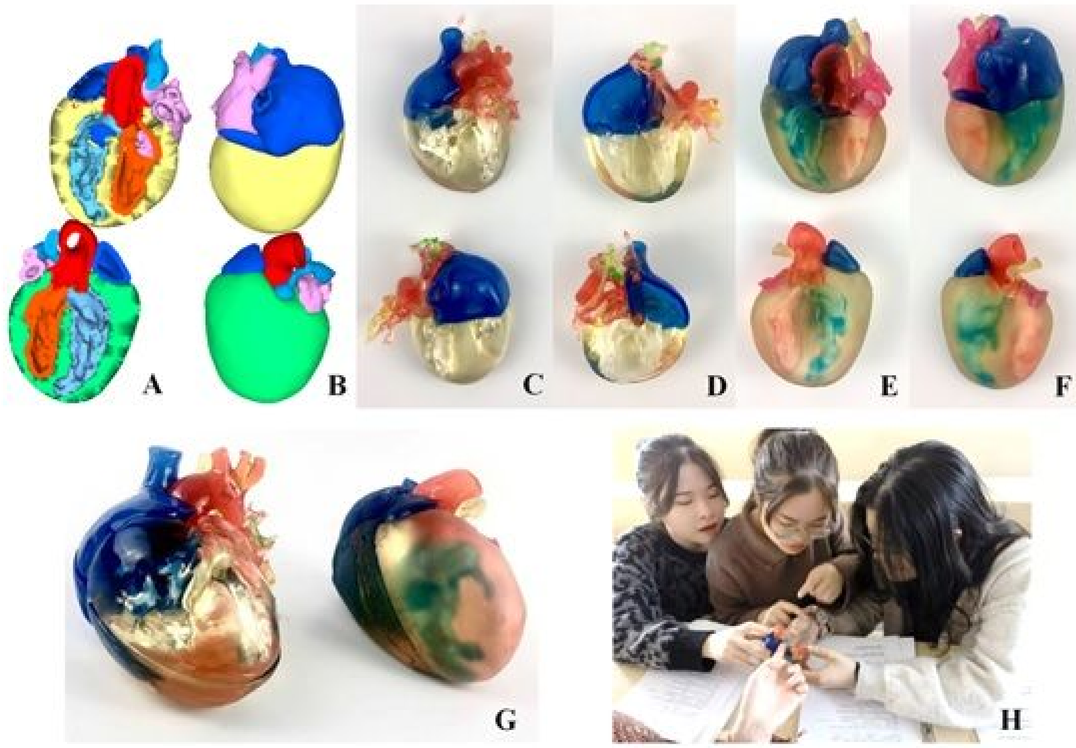

Figure 1

3D printed TOF model A-B: 3D digital model of TOF; C-D: Model I; E-F Model II; G: Overall structure of the two models; H: Application in teaching

Supplementary Files

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- SupplementaryMaterials.pdf