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Original Article

3D-printed craniocerebral model promotes the interests and education efficiency for the medical interns in neurosurgery department

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Abstract: Objective: Three-dimension (3D)-printing facilitates the understanding of the complex structures with an isometric and high simulation model. Here we aimed to discuss the efficiency using 3D-printing craniocerebral models in clinical education for the interns. Method: We randomly divided 124 clinical interns into two groups: the traditional education group (n = 62) and the 3D-printed model group (n = 62). The interns in the traditional education group were taught with oral teaching and imaging data, such as computed tomography (CT) and magnetic resonance imaging (MRI) scans. The interns in the 3D-printed model group received the education via the 3D-printed model from the 4 selected clinical samples. Self-designed questionnaires for the subjective assessment of education styles and examinations for teaching contents were conducted to investigate the education efficiency between the 2 groups. Results: The interns in the 3D-printed model group had higher scores in the favor for the course contents, the concentration during clinical study, the degree of interest, the acquisition of the knowledge, and the memorable degree in comparison with that in the traditional education group. Furthermore, the test scores for the interns in the 3D-printed model groups were significantly higher than that in the traditional education group. Conclusion: Clinical education with the assistance of 3D-printed model significantly improved the learning efficiency for the clinical interns, acquiring more detailed knowledge about the anatomy or diseases in neurosurgery.

Keywords: Clinical education, 3D-printing, neurosurgery, medical student

Introduction

The application of three-dimension (3D) printed technology has been widely used in the fields of clinical, nursing, pharmaceutical, medical imaging, teaching and scientific research [1]. The clinical applications of 3D-printed technology-based physiological/pathological models could simulate surgery, and will help the operator to locate the accurate position of the lesions. The highly simulated human hard tissues manufactured by 3D-printed technology could be also used as temporary and permanent implants [2-5]. Generally, it has an extensive prospect for the 3D-printed model in clinical applications.

Neurosurgery is a typically professionalized clinical specialty, which contains numerous complicated terminologies on anatomic structures and neurological functions [6], such as brain structures, functional regions, cerebrovascular system, cranial nerves, and innervation of the never fibers. In the theoretical education, the majority of medical undergraduates might feel curious but confused about the brain, because the complicated theories about the brain won't lead to a solid imagination about the brain structures, in spite of the plenty of two-dimension (2D) data, such as the computed tomography (CT), magnetic resonance imaging (MRI) or other image data. These would lead to a blockade of the interests for the clinical interns. Given the complex and elusive characteristics of brain and neurosurgery, we would like to explore the motivation methods for improving both the interests and education efficiencies.

The application of the 3D-printed technology for cerebral structures could alter the 2D image data into an isometric 3D model. It could visually reflect the intracerebral complexities, the lesion localizations and the relationships of the lesion with the surrounding nerves as well as the blood vessels. Additionally, 3D-printed technology could also selectively print the contents which might be extracted from the interesting areas on the image data. Traditionally, cadaver head specimens were used for promoting the teaching efficiency. However, as the donors of the specimens are limited, and the approval procedures for both the legislation and the ethics are tedious, consequently, interns usually could just receive clinical interpretations during their noviciate stage, which was similar to their theoretical educations. The 3D-printed model substitute for the cadaver head specimens was more acceptable and meanwhile could arouse the interests for the interns [7, 8].

In this study, we applied 3D-printed model in the clinical education for the interns, and compared the subjective assessments and education efficiencies with the traditional education group. We hypothesized that the 3D-printed model would provide a vivid sense for the understanding of the interns in brain and neurosurgical diseases.

Materials and methods

Subjects

Total of 124 clinical interns were recruited from Anhui Medical University. All the students were at their fifth grade, having received theoretical educations from the college. The neurosurgery part in the theoretical education was taught by the same teacher. We randomly divided the interns into 2 groups according to the clinical teaching methods: the traditional education group and the 3D-printed model group. All the interns received 2-month clinical education in the department of neurosurgery. Informed consents were obtained from all individual participants (included 124 clinical interns and 4 teaching volunteers) in the study. This study was approved by the Clinical Research Ethics Committee of Anhui Medical University of China. All procedures performed in the study involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards.

Investigation method

In the clinical education, three patients in the department of neurosurgery and a healthy volunteer were recruited for the example presentation. Clinical education was conducted by a senior neurosurgeon, who was also titled with associate professor. The education contents included the anatomical structures of nerves, related bones and representative neurosurgical diseases (details in **Table 1**). The interns in the traditional education group mainly received oral teaching, combined with imaging data (CT and MRI scan) and clinical pictures presentation. For another, the interns in the 3D-printed model group received the education via the 3D-printed model from the 4 samples, except for the oral teaching.

3D-printed for cerebral model

Four volunteers from the neurosurgery hospitalization were selected, including three patients with anterior skull base meningiomas, basilar aneurysms and skull defects, respectively, as well as normal volunteers. First, based on the volunteer's 3.0T MRI (layer thickness 1 mm) and/or high-resolution thin-layer CT scan (layer thickness 0.5 mm) imaging DICOM data, 3D reconstruction was performed via mimics 17.0 and 3-MATIC 9.0 software. The specific principle was to use the gray value of the tissue to extract the tissue structure separately. The software automatically calculated and reconstructed it into a three-dimensional image. If you needed to distinguish the tissue within the same gray value range, you should manually select layers to separate. The extracted tissues such as skulls, blood vessels, tumors, optic nerves, brainstem and other structures output STL format files to a 3D printer (J750, Stratasys, USA), and different modules used different hardness, color and transparency of materials, using light-curing principle to print 1:1 ratio with photosensitive resin material, and used high-pressure water gun to remove supporting material after completion. The model preparation was provided by Guangzhou Medprin Regenerative Medicine Technology Co., Ltd. with technical support and 3D printing. After the completion of the 3D printing model, two neurosurgery professors judged that the printed models were highly consistent with the actual image data of the patient and used for clinical teaching.

Table 1. Clinical teaching of 4 representative cases

Patient	Age (year-old)	Gender	Diagnosis	Location	On-site inspection for the interns (random 4 questions)
Case 1	53	Male	Meningioma	Anterior and middle cranial fossa	Anterior basis cranii, olfactory sulcus, cribriform plate, optic nerve, olfactory nerve, middle basis cranii, greater and lesser wing of the sphenoid bone, sphenoid ridge, anterior clinoid process, optic canal, foramen lacerum, tumor, sella turcica, pituitary fossa, posterior cranial fossa, petroclival, anterior cerebral artery, anterior communicating artery, middle cerebral artery, internal carotid, anterior middle cranial fossa
Case 2	47	Female	Intracranial aneurysm	Apex of basilar artery	anterior skull base, anterior clinoid process, posterior clinoid process, dorsum sellae, sella turcica, posterior cranial fossa, upper clivus, middle clivus, lower clivus, frontal bone, temporal bone, pterion, petrosal bone, apical petrous, oval foramen, spinous foramen, basilar artery, intracranial aneurysm superior cerebellar artery, posterior cerebral artery, middle cerebral artery, anterior cerebral artery, anterior communicating artery, posterior communicating artery, Willis circle
Case 3	28	Male	Cranial defect	Left frontal temporal parietal skull	Frontal bone, temporal bone, sphenoid bone, parietal bone, occipital bone, arcus superciliaris superciliary arch, glabella, tubera frontale, key hole, zygomatic arch, supratemporal line, temporal squama, sphenoid ridge, external auditory canal, pterion, sagittal suture, coronal suture, lambdoidal suture
Case 4	36	Male	Healthy volunteer	Brain	Frontal lobe, temporal lobe, parietal lobe, occipital lobe, lateral ventricles (frontal horns, occipital horns, body of lateral ventricle), corpus callosum, brainstem (midbrain, pons, medulla oblongata), foramen magnum, frontal pole, temporal pole, lateral fissure, interhemispheric fissure, cerebral falx, cerebella tentorium, central sulcus, anterior central gyrus, posterior central gyrus, sagittal sinus, transverse sinus, straight sinus, torcular herophili

Table 2. Comparisons of the basic data between the two groups

Variables	3D-printed model group (n = 62)	Traditional education group (n = 62)	*P*	OR	95% CI
Age (x ± s)	22.34±0.98	22.35±0.88	0.92		
Gender (n)			0.58	0.81	0.39-1.68
Male	37	40			
Female	25	22			
Score of the theory course	76.32±5.49	76.26±6.05	0.95		

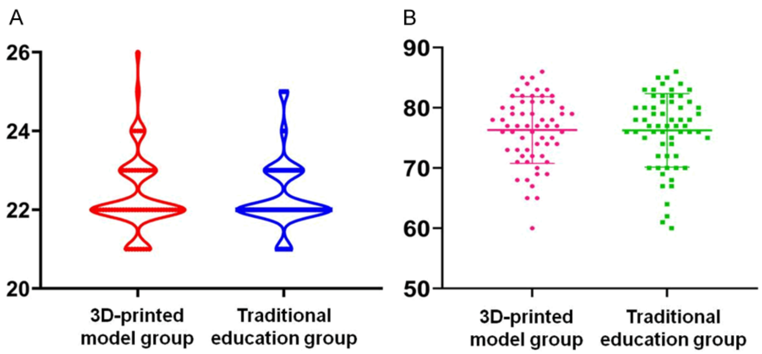

Figure 1. Basic information of the participants in 3D-printed model group and traditional education group. A: Age; B: Score of the theory course.

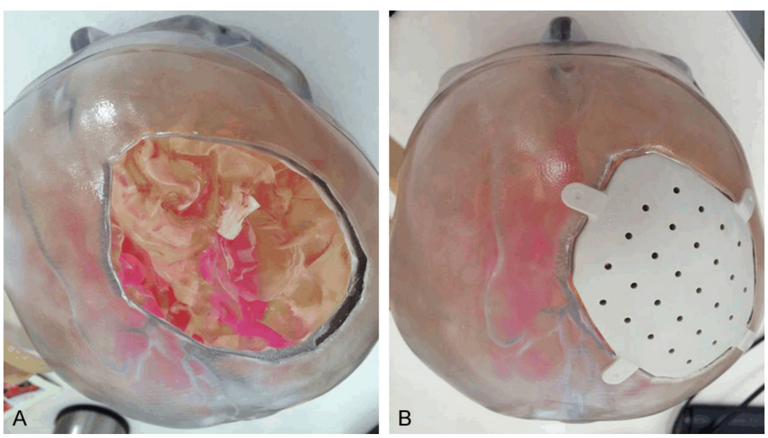

Figure 2. 3D-printed model for (A) decompressive craniectomy and (B) cranioplasty (PEEK for the material).

Observation indicators

The education efficiencies were judged according to 2 aspects: subjective and objective assessments. In the subjective assessment, we designed a questionnaire to analyze the degree of interest for all the interns, including the favor for the course contents, the concentration during clinical study, the degree of interest, the acquisition of the knowledge and the memorable degree. Each item was self-evaluated with a scoring from 0-100. At the end of the clinical education, every interns should finish the paper examination in which 10 questions contained according to the education syllabus.

Statistical analysis

Photograph prism (Version 8.0.1) software was applied for the data analysis. Data were calculated and expressed as the mean ± standard deviation (SD). The statistical comparisons for measurement data between two groups were evaluated using Student's t tests. Binary data were analyzed by Chi-squared test. A value of $P<0.05$ was considered to be of statistical significance.

Results

Comparison of basis information between the two groups

The basic information of the two groups was summarized in **Table 2** and **Figure 1**. The mean age of the clinical interns was 22.35±0.88 for the traditional education group and 22.34±0.98 for the 3D-printed model group, respectively. No statistical differences were found in both age (P = 0.92) and gender (P = 0.58) between the two groups. Additionally, as established theoretic knowledge might influence the results in the clinical internship, we also retrospectively compared the scores of the theory courses, and the results indicated no differences in the theoretical scores between the two groups (P = 0.95).

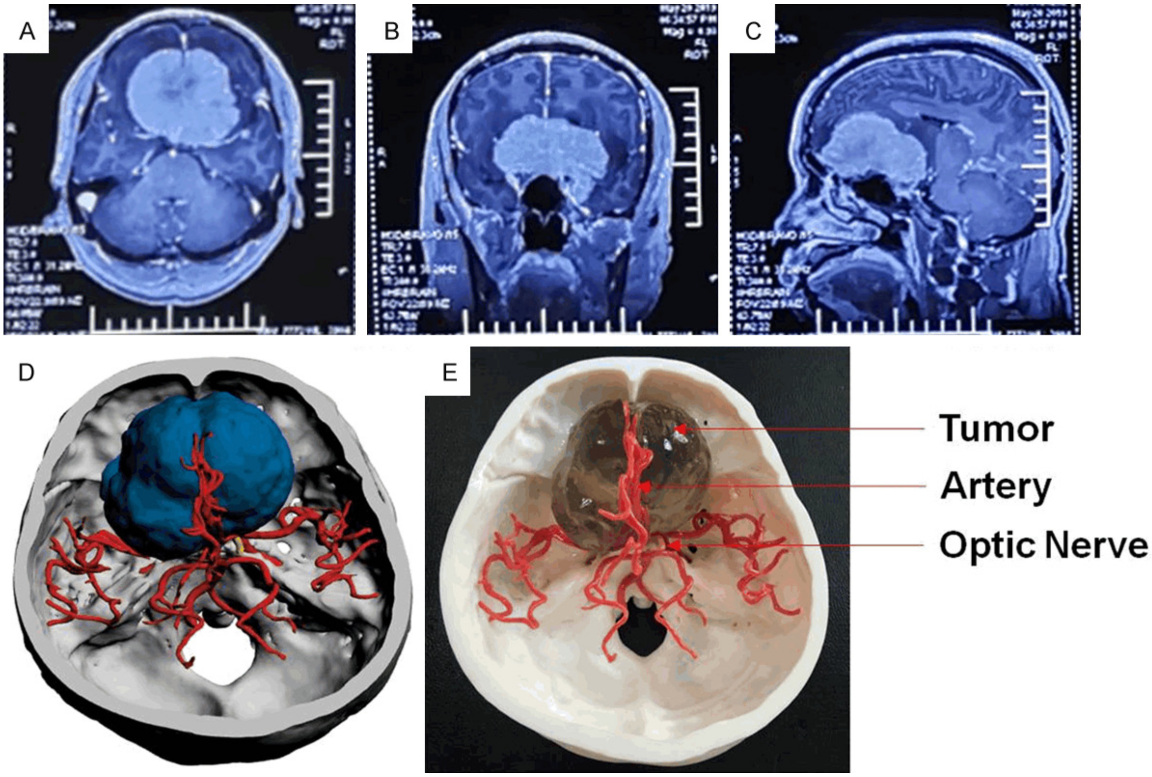

Figure 3. 3D-printed model for the huge meningiomas. T1-weighted MRI scan (A: Axial scanning; B: Coronal scanning; C: Sagittal scanning), 3D digital reconstruction (D) and 3D-printed model (E).

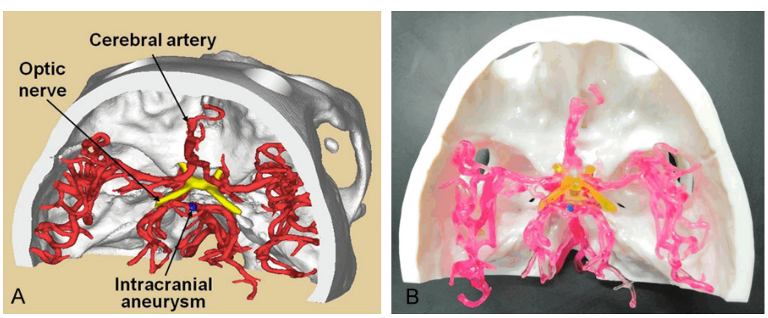

Figure 4. 3D-printed model for the intracranial aneurysm. A: 3D digital reconstruction; B: 3D-printed model.

Establishment of 3D-printed models

The 3D-printed models of the 4 cerebral structures of high simulation were constructed according to the data extracted from the MRI or CT scans.

As showed in **Figure 2**, the first patient was diagnosed with cranial defect due to decompressive craniectomy after traumatic brain injury. The 3D-printed cranial model was conducted by the data of high solution thin layer CT scan. We mainly introduced to the interns the structure of skull, the anatomy of basis cranii, the marking points of body surface projection, the pathogenesis of cerebral hernia and the operation essentials for the decompressive craniectomy as well as cranioplasty.

As for the case 2 (**Figure 3**), T1-weighted MRI scan showed a huge meningiomas in the anterior middle skull base. With the application of the 3D-printed model, we explained the clinical manifestation, the imaging characteristics, diagnosis, differential diagnosis and surgical options. With regard to the patient, the vision and visual field were damaged. However, the occurrence of the symptom could not be clearly explained by the imaging data exclusively. The 3D-printed model could illustrate the relationship of the tumor with the optic nerve, and therefore explained the causality.

The third patient suffered a basilar artery aneurysm (**Figure 4**). As the complexity of the

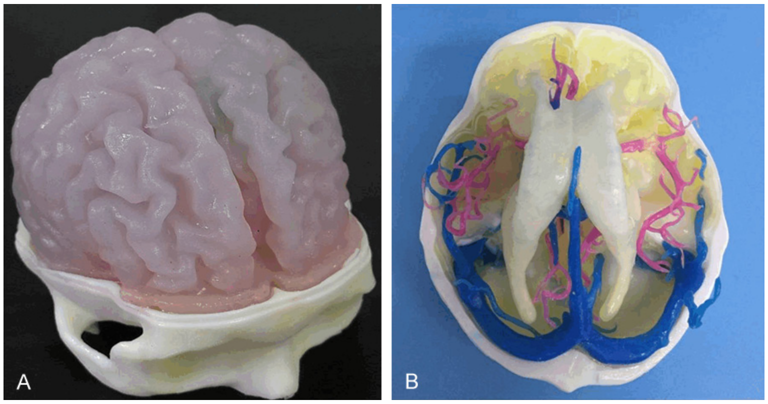

Figure 5. 3D-printed model for the normal craniocerebrum. A: Skull and brain tissue; B: Intracranial artery (red), venous (blue) and ventricle (white) system.

cerebrovascular anatomy, the 3D-printed model could vividly exhibit the intracranial artery system, including basilar artery, middle cerebral artery, anterior cerebral artery, anterior communication artery, posterior communication artery, and Willis circle. Moreover, it could help illustrate the pathogenesis of intracranial aneurysms and hemodynamics changes.

Additionally, a normal MRI scan-derived 3D-printed model was obtained from a healthy volunteer to elaborate the physiological structure of brain. We could observe the structure, morphology, softness, color, sulci and gyri of the brain as well as the skull, explaining the functional brain areas (**Figure 5A**). On the other hand, through the cerebrovascular bioprinting, we also introduced the artery branching system, venous reflux system, lateral ventricle and third ventricle systems (**Figure 5B**).

Self assessment with the education

We designed a questionnaire for the interns to assess the acceptability of the education styles. Five contents were included in the questionnaire. In the results (**Table 3** and **Figure 7**), we found the interns in the 3D-printed model group had higher scores in the favor for the course contents (93.57±5.38 vs. 62.44±7.40, P<0.001), the concentration during clinical study (93.44±6.13 vs. 72.28±9.49, P<0.001), the degree of interest (86.67±8.76 vs. 64.51±7.18, P<0.001), the acquisition of the knowledge (87.15±5.67 vs. 67.25±7.13, P<0.001), and the memorable degree (94.75±4.51 vs. 64.75±4.60, P<0.001) in comparison with that in the traditional education group. The results indicated that the education style with the 3D-printed model group might capture the interests for the clinical interns.

Objective assessment with the education efficiency

The interns had the examination for 10 random questions for each case which we had taught them during the intern period. The results showed that the test scores for the interns in the 3D-printed model groups were significantly higher than that in the traditional education group (**Table 4** and **Figure 6**). It indicated that the teaching methods with assistance of 3D-printed model might have better learning effects.

Discussion

The 3D-printed cerebral model had a great significance for the clinical education, altering the abstract theories and 2D imaging to a vivid object for the interns [9]. The model provided solid details of the brain structures and the relationship between the lesions with the surrounding tissues. Meanwhile, it could also stretch the interns' mind for more clinical questions which might exist in the theoretical education period [10].

In the traditional education for the neurosurgical interns, the cadaver head specimens were used for the interpretation of the details of cranial structures. However, the feasibility of the cadaver head specimen in the clinical education was poor. Several reasons were listed. 1) The acquisition of the cadaver head specimens was limited. 2) The clinical internship was usually performed in the clinical department, but it was improper or forbidden to exhibit the specimens in the presence of patients. 3) The interns had relatively little understanding about the brain structures, but the cadaver head specimen was filled with brain tissues. Therefore the interns could not observe the details of the brain comprehensively. 4) Legislation- and ethics-related problems in frequent usee of the cadaver head specimens for

Table 3. Self assessment with the education between the two groups

Variables	3D-printed model group (n = 62)	Traditional education group (n = 62)	t	*P*	*R*	*95% CI*
Favor for the course contents	93.57±5.38	62.44±7.40	37.07	<0.001	0.96	29.45-32.81
Concentration during clinical study	93.44±6.13	72.28±9.49	25.13	<0.001	0.91	19.48-22.85
Degree of interest	86.67±8.76	64.51±7.18	26.25	<0.001	0.92	20.48-23.85
Acquisition of the knowledge	87.15±5.67	67.25±7.13	27.80	<0.001	0.93	18.47-21.33
Memorable degree	94.75±4.51	64.75±4.60	77.39	<0.001	0.99	29.22-30.78

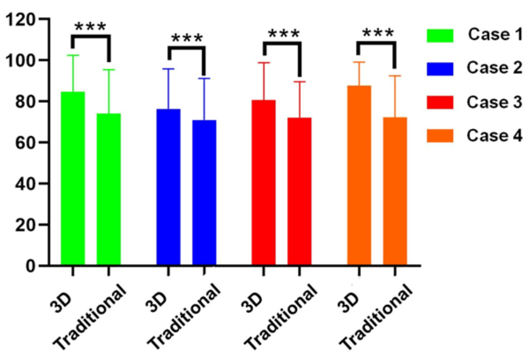

Figure 6. Comparisons of the scores for the 4 subjects between the 3D-printed model group and traditional education group. ***P<0.001.

clinical internship. The 3D-printed model might be an ideal substitute overcoming the disadvantages which were discussed above. First, the fabrication of 3D-printed was based on the extracted data from CT or MRI scans, and the characteristics of high simulation and repeatability allowed the visualization of the exposed targets. The advantage facilitated the observation and better understanding for the interns. Second, the application of the model was conducive for the communication of doctors with patients at the bedside, enhancing the trust from the patients and the relatives. More importantly, the model could relieve the limitations of both legislation and ethics which the application of the cadaver head specimen might have [10-12].

Additionally, the 3D-printed technology could also be applied to assist clinical treatment and scientific research. The doctors could directly communicate with the patients via the model of high simulation, interpreting the surgical methods and relieving the patients' fear. Additionally, the general surgeon, who conducted the neurosurgery, could optimize the surgical approach to the lesion and distinguish the relationship between the lesion and the surrounding parenchyma, thus emaking the surgery more scientific and successful [8, 13-15].

Some limitation of the 3D-printed model should be aware. First, the 3D-printed technology was not time-effective. The processing time usually takes 3 to 7 days from the data extraction of CT or MRI scans to the model accomplishment. It was not suitable for the clinical studies about the emergency or confined operations. Thus, there was an urgent need for shortening the processing time in clinical practice. Second, the costs of specialized printing machine and the bioinks were still too high to be affordable, especially for the underdeveloped areas. Distinguishing printing styles and applications of different bioinks according to the diverse diseases could reduce the manufacturing costs. Fortunately, the cost of 3D-printing for pathological models has been included in the health insurance in some provinces of China. It will help ease the burden for the patients and promote the popularization and the application of 3D-printed technology [16-18].

In conclusion, clinical education with the assistance of 3D-printed technology significantly improved the learning efficiency for the clinical interns, acquiring detailed knowledge about the neurosurgery anatomy or related diseases.

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Disclosure of conflict of interest

None.

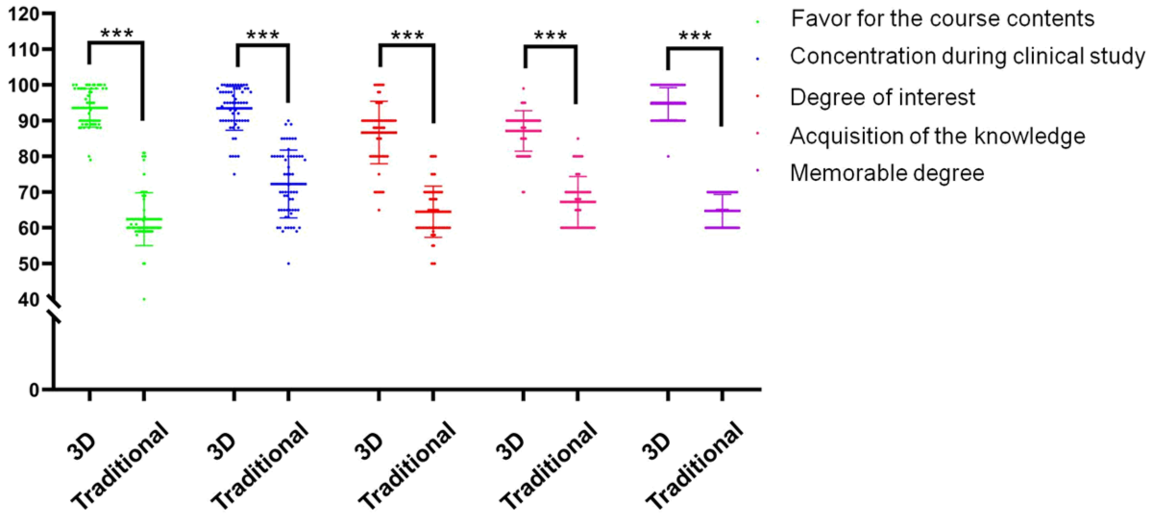

Figure 7. Self assessment with the different education styles between the 3D-printed model group and traditional education group. ***P<0.001.

Table 4. Paper examination results of the 4 sample presentation

Variables	3D-printed model group (n = 62)	Traditional education group (n = 62)	t	*P*	*R*	*95% CI*
Case 1	84.75±17.66	74.10±21.32	5.80	<0.001	0.36	6.98-14.33
Case 2	76.39±19.50	70.98±20.14	3.99	<0.001	0.21	2.70-8.12
Case 3	80.66±18.15	72.13±17.43	4.94	<0.001	0.22	4.41-10.36
Case 4	87.70±11.46	72.30±20.12	5.95	<0.001	0.29	8.24-16.53
Total score (100%)	82.38±17.41	72.38±19.71	9.96	<0.001	0.29	8.03-11.97

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