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Feng-Chou Cheng

Chun-Pin Chiang

Yi-Ping Wang

Wei-Cheng Lin

Julia Yu-Fong Chang

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# Integrating three-dimensional (3D)-printed teaching models to improve the learning effectiveness of oral pathology: A teaching practice research project

Feng-Chou Cheng [a,b†], Chun-Pin Chiang [c,d,e,f,g†], Yi-Ping Wang [c,d,e], Wei-Cheng Lin [c,d], Jer-An Guo [h], Julia Yu-Fong Chang [c,d,e*]

[a] *Chia-Te Dental Clinic, New Taipei City, Taiwan*
[b] *School of Life Science, College of Science, National Taiwan Normal University, Taipei, Taiwan*
[c] *Department of Dentistry, National Taiwan University Hospital, College of Medicine, National Taiwan University, Taipei, Taiwan*
[d] *Graduate Institute of Clinical Dentistry, School of Dentistry, National Taiwan University, Taipei, Taiwan*
[e] *Graduate Institute of Oral Biology, School of Dentistry, National Taiwan University, Taipei, Taiwan*
[f] *Department of Dentistry, Hualien Tzu Chi Hospital, Buddhist Tzu Chi Medical Foundation, Hualien, Taiwan*
[g] *Institute of Oral Medicine and Materials, College of Medicine, Tzu Chi University, Hualien, Taiwan*
[h] *Department of Biomedical Engineering, National Taiwan University Hospital, Taipei, Taiwan*

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**KEYWORDS**
3D-printed teaching models;
Tactile training;
Oral pathology;
Learning outcomes;
Objective structured clinical examination;

**Abstract** *Background/purpose:* In conventional oral pathology education, students often demonstrate limited engagement in histopathological learning and difficulty for conceptualizing the tactile characteristics of oral lesions due to reliance on two-dimensional images. This teaching practice research project aimed to evaluate whether integrating three-dimensional (3D)-printed teaching models into oral pathology instruction could enhance students' learning effectiveness, particularly in understanding lesion texture and clinical palpation.
*Materials and methods:* Thirty-two fourth-year dental students enrolled in a one-year oral pathology and diagnosis course at the School of Dentistry, National Taiwan University, during the 2024 academic year participated in this study. A 4-h curriculum-integrated workshop using 3D-

* Corresponding author. Department of Dentistry, National Taiwan University Hospital, College of Medicine, National Taiwan University, No. 1, Chang-Te Street, Taipei, 10048, Taiwan.
*E-mail address:* jyfchang@ntu.edu.tw (J.Y.-F. Chang).
† These two authors contributed equally to this work.

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Teaching practice research

printed models was implemented to facilitate tactile learning. Learning effectiveness was evaluated using student questionnaires, pre- and post-workshop tests, and objective structured clinical examination (OSCE) focusing on tactile description and diagnostic reasoning.
*Results:* Most students reported that direct tactile interaction with the 3D-printed models was more effective than viewing clinical images alone in improving their understanding of lesion characteristics and confidence in clinical palpation. Although some students suggested further refinement in simulating soft tissue consistency, overall feedback was positive. Written test scores improved significantly following the workshop, with mean scores increasing from 60.8 to 81.7 ($P < 0.0001$). In the OSCE assessment, 84.4 % (27/32) of students accurately described lesion tactile features, while 15.6 % (5/32) demonstrated partial accuracy.
*Conclusion:* Tactile training with 3D-printed models represents an effective teaching strategy for enhancing learning in oral pathology. Continued application and optimization of this approach may further improve student engagement, learning efficiency, and diagnostic proficiency.


## Introduction

As medical education increasingly adopts student-centered and integrated learning models, traditional unidirectional knowledge transmission is no longer sufficient to meet the demands of modern clinical practice, which requires interdisciplinary and comprehensive competencies. Oral pathology, a core discipline bridging basic medical sciences and clinical dentistry, encompasses a wide range of skills, including clinical observation, palpation, histological interpretation, and diagnostic reasoning. However, current teaching approaches remain largely dependent on static images, two-dimensional (2D) slide observation, and didactic lectures, which inadequately convey the three-dimensional (3D) morphology and tactile characteristics of oral lesions. As a result, dental students often demonstrate insufficient clinical responsiveness and may struggle to recognize even basic lesion types.[1–3]

From an oral medicine perspective, palpation is essential for detecting lesions within the oral and maxillofacial region and for forming preliminary clinical diagnoses. For example, cystic lesions typically exhibit elasticity on palpation, in contrast to the firm texture of fibrous lesions. However, such tactile sensations and 3D morphological features are difficult to teach due to the lack of appropriate instructional tools. Currently, no commercially available models are designed specifically to support palpation-based learning. Although various substitute materials have been used, most are standardized plastic products that fail to accurately simulate tissue elasticity or lesion variability. Consequently, students often struggle to integrate clinical tactile findings with visual clinical manifestations and histopathological changes, leading to a marked gap between theoretical knowledge and clinical application.[4,5]

The recent advancements in 3D-printing technology have provided a new opportunity to overcome the abovementioned limitations. Through medical image reconstruction and multi-material printing techniques, we can create simulated lesion models with tactile feedback and pathological features. Combined with clinical imaging and microscopic teaching design, this allows for the creation of a learning framework that integrates sensory experience and diagnostic logic.[6–9] This teaching practice research project aimed to systematically explore the application value and outcomes of using 3D-printed teaching models of multiple simulated oral pathological lesions in teaching, and to use statistical analysis to evaluate the impact of this teaching method on improving students' identification abilities, learning interest, palpation experience, and integrative clinical thinking.

## Materials and methods

### Research framework

This teaching research investigation compared the current modified teaching model with the past unmodified model. It analyzed whether using the modified teaching models could improve the students' acceptance and overall diagnostic ability compared to the traditional unmodified teaching models, as shown in Fig. 1. The modified teaching model referred to the instructional aids used in oral pathology education. First, as described in our previous publications, traditional glass slides have been progressively replaced with digital slides integrated with virtual microscopy to enhance students' self-directed learning (SDL).[10] Second, this study developed a three-dimensional (3D)-printed teaching model to assist students in understanding the tactile characteristics of various oral and maxillofacial lesions and to improve their diagnostic accuracy. This approach shifts instruction from reliance on clinical appearance and simulated tactile examination of oral lesions to an emphasis on authentic microscopic tissue changes. Consequently, conventional teaching of tactile alterations in pathological lesions is transformed into true tactile learning, enabling students to achieve a more integrated understanding of oral pathology.

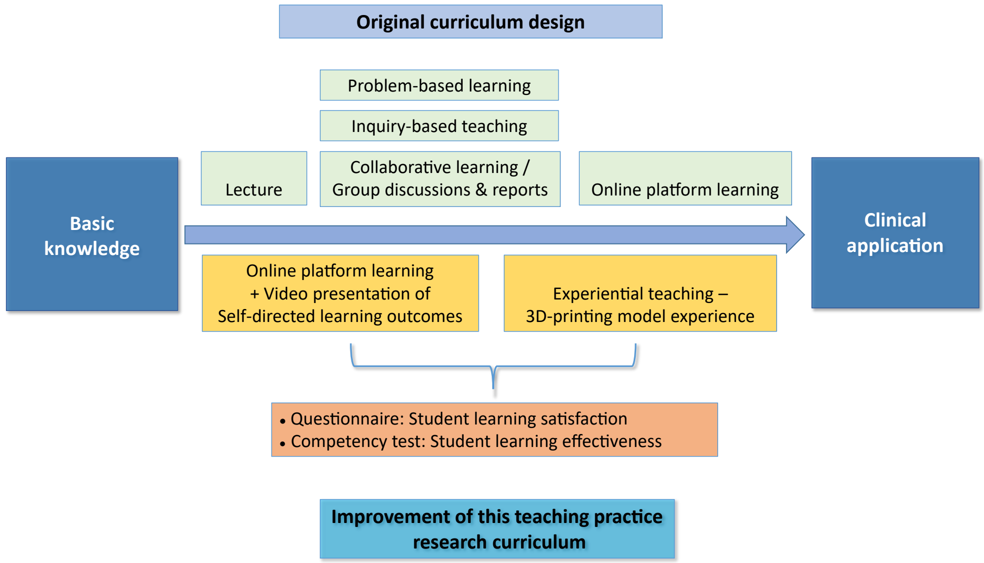


**Figure 1** Research framework of this study. This teaching research investigation compared the current modified teaching model with the past unmodified model.

## Participants

The study included 32 fourth-year dental students enrolled in a one-year course of oral pathology and diagnosis, during the 2024 academic year, at the School of Dentistry, National Taiwan University. In the second semester, a 4-h workshop was implemented for these dental students to learn about the tactile sensation of the oral and maxillofacial lesions using 3D-printed teaching models.

## Production of 3D-printed teaching models

This study applied patient-specific 3D-printed models to support the dental students' learning of the tactile sensation of the oral and maxillofacial lesions, dental surgical planning, clinical education, and doctor-patient communication. Representative mandibular pathology cases, such as odontogenic cysts, tumors, or osteonecrosis, were selected by the oral pathologists. Computed tomography (CT) or cone-beam computed tomography (CBCT) scans (in DICOM format) were obtained in accordance with institutional regulations and anonymized by the oral and maxillofacial radiology department.

Medical image segmentation and 3D reconstruction were performed using Materialise Mimics to isolate the bone structures and pathological areas. Further surface refinement and mesh editing were carried out using ZBrush to enhance printability and anatomical precision. The illustration of the process of dental CT segmentation and digital model reconstruction was shown in Fig. 2.

The final stereolithography (STL) files were printed using fused deposition modeling (FDM), with polylactic acid (PLA) used as the material for bony structures. Water-soluble polyvinyl alcohol (PVA) resin was selected for support structures to allow easy removal. Before printing full-scale models, small test sections were used to optimize key parameters such as layer thickness, infill density, and support design. Post-processing included removal of supporting material, surface polishing, and silicone curing. To simulate the soft tissue lesions, food-grade silicone (Shore 20A hardness) was manually applied to the printed mandibular structures. Throughout the process, oral pathologists were consulted repeatedly to ensure anatomical fidelity. The hand-applied silicone layer mimicking gingival and soft tissue morphology on the printed model was shown in Fig. 3.

Then, the final models were evaluated by the oral pathologists and oral surgeons to confirm their clinical utility in the preoperative planning. Additionally, these models were incorporated into training sessions for dental interns and used in patient education to improve understanding of the surgical process and associated risks.

## Teaching aid validation

To improve teaching effectiveness, the 3D-printed teaching models should undergo a tactile simulation validation process before being used for teaching. Therefore, the creation of 3D-printed teaching models considered the use of materials with different elastic coefficients in the internal filling design to achieve a tactile simulation effect. For example, the cysts were represented by the water-filled balloons filled under the silicone to create an undulating feel, tumors were simulated with a high-density material to mimic a tougher texture, and osteonecrosis was represented by PLA plastic directly exposed to simulate bone. After completion, we invited oral pathologists to test the products and provided tactile and diagnostic accuracy assessments to confirm that the simulation accuracy of these products met the requirements for use as the teaching aids.

## Teaching implementation and course design of tactile training

The 4-h workshop for tactile training emphasized the integration of hands-on practice and cross-sensory learning.

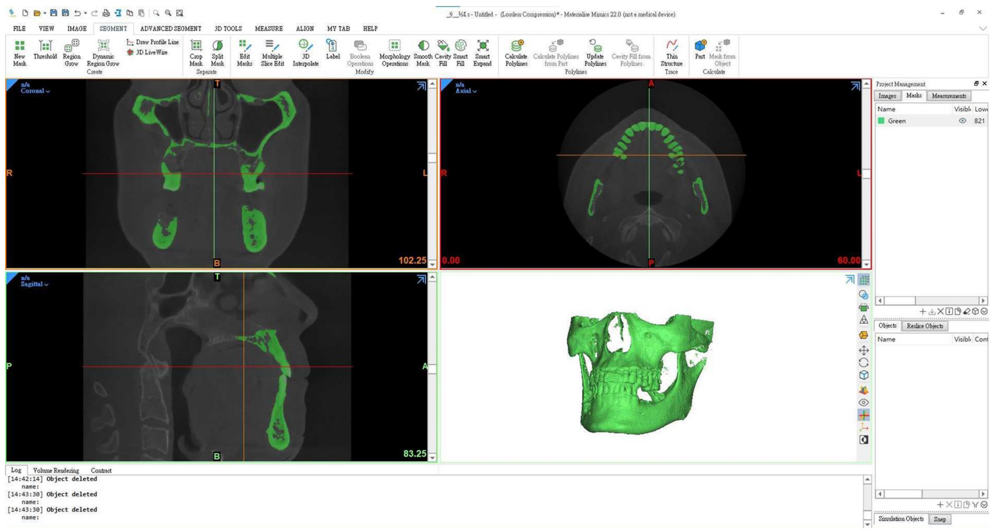

**Figure 2** Conversion of dental computed tomography (CT) images into 3D models. Axial CT images were segmented and reconstructed using image processing software (e.g., Mimics) to generate 3D models of the maxilla, mandible, and teeth. The models were then imported into ZBrush for surface trimming and smoothing.

**Figure 3** Soft tissue reconstruction on a 3D-printed mandibular model. Food-grade silicone (Shore 20A) was manually applied to the surface of the 3D-printed mandible model to simulate gingival and soft tissue morphology.

The course content included the following parts: (1) Pre-workshop test; (2) Model tactile practice and drawing: The students drew the lesion according to the tactile model to resemble the appearance of the panoramic radiographic image; (3) The students compared and interpreted the drawings with the 2D images (panoramic radiographic images) and 3D images (CBCT images and images presented by the 3D model software Slicer) of the original case; (4) The students compared the drawings with the microscopic pathology; (5) Actual specimen observation and explanation; and (6) Post-workshop test.

The main teaching implementation strategies were as follows: (1) Problem-based learning (PBL) to guide problem exploration based on the tactile models and actual cases; (2) Peer learning and group discussion to strengthen interactive learning and concept internalization; and (3) Multiple feedback through immediate guidance from the teachers and peer observation and evaluation.

## Survey tool

We conducted competency-based assessment and evaluating students based on their performance in the following ways: (1) Pre-workshop test: The students answered questions about the location, size, mobility, and consistency of the lesion presented by the test model; (2) Post-workshop test: The test method was the same as the pre-test; and (3) Objective structured clinical examination (OSCE) using several stations for testing: By using typical cases that had not yet been shown to the students, the students palpated the simulated lesion models and wrote the preliminary diagnoses, and then they further compared microscopic images to produce their complete diagnostic reports. Pre-workshop test and post-workshop test were evaluated using quantitative scores out of 100, while OSCE was evaluated using qualitative assessment, divided into three categories: completely correct, partially correct, and completely wrong.

In addition, after the workshop, we invited all dental students who took the course of oral pathology and diagnosis to fill out the questionnaires. All dental students were invited to join in this questionnaire survey at their free will to fill out the questionnaires without the pressure from the investigators. This study administered a semi-structured online questionnaire (Google forms) to assess students' perceptions of the effectiveness of 3D-printed teaching models. The questionnaire was designed to ensure the participants answered all questions to make sure that the returned electronic survey forms were all complete. These investigated questions included: (1) The learning objectives of this workshop were clearly stated; (2) The 3D-printed models helped me to visualize the oral pathological lesions; (3) This workshop improved my ability to sense and judge the tactile sensation (such as texture, consistency, and hardness) of the lesions; (4) The imaging learning unit helped me to better understand the characteristics of the radiological images; (5) The integration of clinical, imaging, and pathological aspects enhanced my understanding of the final diagnosis; (6) The workshop design encouraged active participation in the learning; (7) After this workshop, I was more confident in connecting the clinical presentations with the pathological tissue changes; and (8) The instructors provided clear and effective guidance and assistance throughout the activities.

The answer was designed to let the participants to raise a score ranging from 1 to 5. If the intensity or response for each question was extremely agreed, the score was 5. If the intensity or response for each question was neutral, the score was 3. In contrast, if the intensity or response for each question was extremely disagreed, the score was 1. The mean score was 3 or more meant that on average the answerers agreed the investigated questions, and the higher the score, the higher the degree of their agreement. The questionnaire was designed to allow the participants to express agreement, neutral or disagreement with each question.

At the end of the questionnaire, there were open questions about the participants' learning in this workshop. The participants could provide any suggestions and/or opinions (including advantages and disadvantages). They were suggested to fill the score or answer in fresh memory.

### Statistical analysis

All data collected were stored in excel files and used for statistical analysis. The differences in the mean scores of various investigated items were compared between groups by the independent sample *t*-test. The result was significant if the *P*-value was less than 0.05.

### Ethical consideration

This study was approved by the Research Ethics Committee of NTUH (No. 202407224RINB).

## Results

### Preparation of 3D-printed teaching models

The creation of 3D-printed teaching models was intended to facilitate students' learning of the tactile sensations of different oral and maxillofacial lesions and making the accurate diagnosis. We created the small 3D-printed models to simulate soft tissue lesions such as the surface-protruding papillomas and submucosal tumors and cysts of various textures and depth (Fig. 4). The larger models were also created using CBCT images to simulate disease manifestations of bone-involved lesions, such as squamous cell carcinoma and drug-induced osteonecrosis causing poorly-defined bone destruction, bone bulges caused by the normal variations such as exostosis, and bone expansion and well-defined bone resorption caused by ameloblastoma and odontogenic cysts (Fig. 5).

### Participants

Among 32 fourth-year dental students enrolled in this oral pathology and diagnosis course, 30 students participated in the workshop, while the other 2 students were absent due to personal reasons. Among the workshop participants, 27 participants completed the questionnaire with a valid response rate of 90 %. Since the OSCE was part of the final examination, all the 32 enrolled students participated in the OSCE.

### Teaching implementation of the tactile training course

We designed the tactile training course as a workshop, including activities such as experiencing the tactile sensation of 3D-printed models and drawing. The drawings were compared with the 2D images (panoramic radiographic images) and 3D images (CBCT images and images presented by the 3D model software Slicer) of the original case, allowing the students to experience the tactile sensation of actual clinical examination specimens and compare them with their radiographic images and histopathological findings. Pre-test and post-test were conducted blindly to assess the students' tactile abilities. The students discussed in groups and drew the tactile lesions as the possible panoramic radiographic images. The differences between the real case images and the model drawings were then reviewed using CBCT and Slicer software.

### Comparison in the learning performance of the tactile training course between pre-workshop test and post-workshop test

In the workshop where the students practiced tactile identification using the 3D-printed models, the students' feedback indicated that physically touching the models left a stronger impression than simply viewing the radiographic images. This tactile experience facilitated a better understanding of the key clinical palpation features and improved their ability to assess lesion texture and firmness, helping to bridge the clinical and pathological knowledge. Although some students suggested that the realism of soft tissue simulation could be improved, the majority of students found that the process of method engagement was helpful for enhancing learning motivation and competence.

Scoring was based on four criteria, including the description about the location, size, mobility, and consistency of the lesion presented by the test model. The students showed improvement in their correct answer rate for each criterion. Overall, students demonstrated a statistically significant increase in test performance, with mean scores improving from 60.8 on the pre-workshop test to 81.7 on the post-workshop test, representing a gain of 20.8 points ($P < 0.0001$) (Table 1).

### Correctness of the student answers based on the OSCE results

In an 8-min OSCE using a test model combined with ChatGPT to simulate the patient interview process, the students wrote dental records and made the preliminary diagnoses based on their findings obtained from the model palpation and the patients' interviews. The results demonstrated that 84.4 % (27/32) of the students

**Figure 4** The small 3D-printed teaching models simulating soft tissue lesions.

completed the dental records accurately, while 15.6 % (5/32) completed them partially correctly; none of the students produced completely incorrect records (Table 2).

## Students' perceptions of the effectiveness of 3D-printed teaching models

In the questionnaire survey, the students expressed a high degree of agreement on all investigated questions. The students' feedback indicated that actually touching the 3D-printed models left a deeper impression than simply looking at the pictures, helping to better understand the key points to pay attention to during the clinical palpation, improving the ability to judge the tactile sensation of lesions (such as texture, consistency, and hardness), and better connecting the clinical and pathological knowledge.

In addition, regarding the qualitative feedback from open questions on the learning experience of the 3D-printed model, the students' responses could be summarized into four main categories: (1) the advantages of tactile learning of the oral and maxillofacial pathological lesions; (2) the integration of vision and touch; (3) the cultivation of clinical thinking; and (4) the enhancement of learning motivation. Although some students felt that there was still space for improvement in the realism of soft tissue materials in the 3D-printed models, overall, the students generally believed that this was an interesting teaching and learning method that helped to improve learning willingness and ability (Table 3).

## Discussion

This research project aimed to enhance learning outcomes in oral pathology through the implementation of a SDL model utilizing 3D-printed teaching models to simulate the tactile sensation of oral and maxillofacial pathological lesions.[11] The project focused on addressing challenges in traditional teaching, such as the students' passive attitudes and limited dedication to microscopic pathology, and difficulties in developing tactile learning of the oral and maxillofacial pathological lesions. The students were tasked with their observations of radiographic images and digital slides, and interacting with 3D-printed models to experience the texture of the lesions firsthand, thereby improving their understanding, memory retention, and diagnostic skills. The results indicate that the tactile training with 3D-printed models are effective tools for promoting learning and improving oral pathology education. Continued implementation and enhancement of feedback mechanisms are recommended. In addition, this study also confirmed the potential of these advanced teaching strategies to transform dental education by increasing student engagement, learning efficiency, and diagnostic competence in oral pathology.

Dentistry is both an art and a science. Dentists need not only skillful hands and a keen aesthetic sense, but also ample knowledge to make accurate diagnoses of the oral and maxillofacial pathological lesions and provide appropriate treatment. Besides the teeth themselves, diseases of the oral mucosa, jawbone, and facial structures also fall within the scope of dentistry. Oral pathology and diagnosis specifically teach the pathogenesis, clinical and histopathological features, treatment, and prognosis of various oral mucosal, jawbone, and facial diseases, equipping the dental students with the ability to make a correct diagnose and develop the treatment plan for a specific oral and maxillofacial pathological lesion. The scope of oral pathology is incredibly broad, encompassing developmental defects in the oral cavity, jawbone, and facial regions; dental abnormalities; pulp and periapical diseases; periodontal diseases; bacterial, fungal, and viral infections; physical and chemical injuries; allergies and immune diseases; epithelial pathology; salivary gland pathology; soft tissue tumors; blood abnormalities; bone pathology; odontogenic cysts and tumors; skin diseases; and oral manifestations of systemic diseases.[12—15]

The dental students must study oral pathology and diagnosis to understand the pathogenesis, clinical and histopathological features, treatment, and prognosis of

**Figure 5** The large 3D-printed teaching models simulating disease manifestations with bone lesions.

**Table 1** Comparison in the learning performance of the tactile training course between pre- and post-workshop tests.

| | Pre-workshop test (n = 30) | Post-workshop test (n = 30) | Improvement | Independent sample *t*-test |
|---|---|---|---|---|
| **Correct answer rate (%) for each criterion** | | | | |
| Location | 73.3 ± 45.0 | 100 ± 0 | 26.7 | $P < 0.01$ |
| Size | 56.7 ± 50.4 | 73.3 ± 45.0 | 16.7 | $P < 0.01$ |
| Mobility | 60 ± 49.8 | 73.3 ± 45.0 | 13.3 | $P > 0.05$ |
| Consistency | 53.3 ± 50.7 | 80 ± 40.7 | 26.7 | $P < 0.01$ |
| **Overall learning performance** | | | | |
| Score | 60.8 ± 22.4 | 81.7 ± 20.7 | 20.8 | $P < 0.0001$ |

**Table 2** Correctness of the students' answers for dental record writing based on the objective structured clinical examination (OSCE) results (n = 32).

| | Number | Proportion |
|---|---|---|
| Completely correct | 27 | 84.4 % |
| Partially correct | 5 | 15.6 % |
| Completely wrong | 0 | 0 |

various oral mucosal, jawbone and facial diseases. They should also acquire the basic ability to diagnose and treat various oral mucosal, jawbone, and facial diseases. Accurate diagnosis requires a combination of knowledge including the clinical manifestations, characteristic features of the lesions, and histopathological findings of the biopsy specimens.[13—15] Therefore, learning this subject needs to integrate knowledge of the clinical manifestations, radiographic features, and histopathological findings of lesions.

However, the students often dislike learning about microscopic features in pathology or consider them unimportant.[16] Their participation in microscopic observation of the lesional tissue sections is low, and their test scores for the histopathological diagnosis laboratory course are relatively poor. In fact, the correspondence between clinical manifestations and microscopic features is an indispensable element for making an accurate clinical and histopathological diagnosis. Due to the students' negative attitude towards the microscopic examination of the lesional tissue sections and typical lecture-based teaching methods, this combination teaching of the oral pathology and diagnosis has limited effectiveness. Furthermore, each disease is primarily identified through a specific combination of results from clinical, radiographic, and laboratory examinations, including a comprehensive assessment of its clinical and radiographic features, pathogenesis, and laboratory and microscopic findings. Clinically, the location of the lesion, its tactile sensation, and its boundary with the surrounding tissues are crucial for the disease identification and diagnosis. However, if there is no practical clinical experience, an accurate diagnosis of the lesion is difficult. Therefore, the tactile sensation of the oral and maxillofacial lesion is crucial for students' ability to make a correct diagnose of the pathological lesion in the future.

The 3D printing can create a variety of concrete and practical teaching tools.[17—19] For example, the biological models make it easier for the students to understand the structure and function of biological organisms. The geographical terrain models create 3D-printed topographical representations of the Earth's surface, helping the students to understand topographical features and geographical concepts. The 3D-printed replicas of historical artifacts allow the students to experience and observe historical culture firsthand. The molecular structure models help the students to better understand molecular structure and reaction mechanisms. The 3D-printed mechanical parts showcase physical models of mechanical components, allowing the students to learn about design and structure.

**Table 3** Students' perceptions of the effectiveness of three-dimensional (3D)-printed teaching models (n = 27).

| Statements that the students agree with | Number | Proportion | Mean score |
|---|---|---|---|
| (1) The learning objectives of this workshop were clearly stated. | 27 | 100 % | $4.89 \pm 0.32$ |
| (2) The 3D-printed teaching models helped me to visualize oral pathological lesions. | 23 | 85.2 % | $4.44 \pm 0.85$ |
| (3) This workshop improved my ability to sense and judge the tactile sensation (such as texture and hardness) of the pathological lesions. | 23 | 85.2 % | $4.44 \pm 0.85$ |
| (4) The imaging learning unit helped me to better understand the characteristics of the radiological images. | 26 | 96.3 % | $4.70 \pm 0.54$ |
| (5) The integration of clinical manifestations, radiographic features, and pathological findings enhanced my understanding of the final diagnosis. | 27 | 100 % | $4.85 \pm 0.36$ |
| (6) The workshop design encouraged active participation in learning. | 27 | 100 % | $4.93 \pm 0.27$ |
| (7) After this workshop, I am more confident in connecting clinical presentations with pathological tissue changes. | 22 | 81.5 % | $4.44 \pm 0.80$ |
| (8) The instructors provided clear and effective guidance and assistance throughout the activities. | 27 | 100 % | $4.89 \pm 0.32$ |

Moreover, the Earth science 3D-printed models simulating volcanoes, earthquakes, or other earth science phenomena provide practical visualization teaching. These examples demonstrate the application of 3D printing in different disciplines and fields, providing the students with more concrete and interactive learning experiences.

To address the limitations of conventional oral pathology teaching and learning, this study employed 3D printing services to produce a variety of teaching models that simulated clinical lesions. These models enabled students to more effectively understand differences in lesion texture and tactile perception, including variations in softness, elasticity, firmness, and bony hardness, the presence of intralesional fluid that may produce a fluctuant sensation on palpation, and whether lesion margins are well-defined or ill-defined in relation to surrounding tissues. As a result, the effectiveness of students' tactile learning was enhanced.

In this study, the students showed improvement in their correct answer rate for the description about the location, size, mobility, and consistency of the lesion presented by the test model. A statistically significant improvement was observed in the students' post-test scores compared to the pre-test scores, rising from 60.8 to 81.7 with an improvement of 20.8 ($P < 0.0001$). Moreover, in the OSCE assessment, 84.4 % of students described the tactile characteristics of the lesions with complete accuracy, while the remaining 15.6 % provided partially accurate descriptions. No student gave a completely incorrect answer. All assessment methods including the students' pre-test and post-test, the questionnaire analysis, and the OSCE confirmed the effectiveness of these innovative teaching strategies in enhancing student interest and diagnostic capability.

In conclusion, this study explores that the application of 3D-printed pathology teaching models can enhance the dental students' clinical palpation experience, pathological diagnosis capabilities, and integrative thinking. This teaching strategy using the 3D-printed pathology teaching models overcomes the limitations of traditional oral pathology education in terms of spatial and tactile learning, offering more possibilities and innovative models for the medical education. It is recommended that these multimodal learning designs can be continuously promoted in the future, combining the clinical practice, technological applications, and students' learning motivation to cultivate future dentists with better logical reasoning and diagnostic skills.

## Declaration of competing interest

The authors have no conflicts of interest relevant to this article.

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