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Original Article

Innovative 3D-printed dental teaching model for root canal treatment simulation

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Abstract *Background/purpose:* Effective endodontic education requires realistic models for simulating clinical procedures, particularly working length (WL) determination using electronic apex locators (EALs). Traditional training methods using extracted or plastic teeth lack standardization, realism, and compatibility with EALs. This study aimed to develop and evaluate a 3D-printed tooth model with conductive properties that allows realistic and standardized training in EAL-based WL determination.
Materials and methods: Custom 3D-printed teeth with two distinct working lengths (20.0 mm and 21.9 mm) were designed using cone-beam computed tomography (CBCT) and 3D scanning. Each tooth was embedded in two types of conductive media—tap water and saline. Thirty-six

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participants (students, trainees, and instructors) performed WL measurements using the Root ZX mini EAL. Accuracy was defined as measurements within ±0.5 mm of the true WL.
Results: The model demonstrated high reproducibility across user groups and media. Instructors achieved perfect accuracy (100 %), trainees ranged from 87.5 % to 100 %, and students demonstrated acceptable but more variable accuracy (86.7 %). No significant differences in measurement outcomes were observed between the two media ($P > 0.05$). Significant differences in accuracy were found among the three groups ($P < 0.05$), indicating the model's discriminative ability in assessing experience levels.
Conclusion: This novel 3D-printed model simulates realistic root canal anatomy and conductive conditions for effective EAL training. It distinguishes varying proficiency levels and provides a reproducible, standardized platform for preclinical education. The model bridges the gap between theoretical learning and clinical practice, making it a valuable tool for contemporary endodontic training.

Introduction

Endodontic treatment is an important portion in regular dental practice. Endodontic practice relied on comprehensive and effective training of dental students at the preclinical, as well as the clinical levels.[1] A well-training endodontic specialist could perform better and predict treatment outcomes. Due to the development of endodontic materials and techniques, both students and dentists require intensive practical exercises before performing new techniques on patients. Therefore, a simulation model to mimic the clinical practice is necessary.

A number of training systems have been introduced in educational settings.[2,3] For example, it is common practice to use extracted human teeth during pre-clinical endodontic education;[4–7] however, their use has several disadvantages and limitations such as availability is difficult, selection of suitable teeth is time-consuming, ethical considerations and they have a non-standardized anatomy for test situations.[8–12] A further development was introduced in form of an entire artificial tooth made of clear resin with multiple roots and colored root canals.[13] Recently, new models allowed multiple approaches for working length determination were introduced in the training procedure.[11,14] A teaching/training tooth model that allow the application of electronic apex locator (EAL) to practice endodontic techniques is available now.[8] EAL are widely used in endodontics to accurately determine the working length (WL) of root canals. Accurate WL determination is essential for successful endodontic treatment outcomes, as it ensures complete debridement while minimizing damage to periapical tissues. However, effective EAL training remains a challenge.

The manufacturing process of 3D printing has evolved over the last few decades.[15,16] They may be used as educational tools for training, especially to develop skills in negotiating these treatment obstacles in the laboratory and clinics. In dentistry, 3D printing technology has been used for treatment planning, surgical guidance, and fabrication of dental models for appliances in orthognathic surgery, implant surgery, oral and maxillofacial surgery, orthodontics, and prosthodontics.[17–19]

In endodontics, a physical tooth model fabricated by 3D printing has been used in various cases such as the diagnosis of atypical root morphology, the determination of locations of root resorption, and surgical planning for auto-transplantation.[20–22] Indeed, physical tooth models reproducing the internal root canal anatomy may be of clinical value especially in the endodontic treatment of anomalous teeth.

To address this, we developed a novel 3D-printed endodontic training model incorporating an EAL and designed to simulate clinical WL determination. The aim of this study was to create 3D printed artificial teeth that were realistic and represented an alternative to extracted human teeth and commercial replicas for endodontic training, which enables the use of EALs based on real patient situations for practice.

Materials and methods

Tooth scanning, designing, and printing

A three-dimensional (3D) shape of the original teeth in the model (Nissin, Kyoto, Japan) are acquired using a dental 3D scanner (Medit T710, Seoul, South Korea). Furthermore, to obtain the root canal 3D morphology, a three-dimensional radiograph of the selected teeth was taken using a cone-beam computed tomography (CBCT) with a small field-of-view (NewTom, Verona, Italy). The generated data were exported as single Digital Imaging and Communications in Medicine (DICOM) files and imported into the 3D slicer software. The segmentation was done by using 3D slicer software by selecting the region of interest (ROI) and then using the threshold tool to segment the root canal. All 3D models were stored as stereolithography (STL) files. The study protocol was approved by the institutional review board (Approval No.: B202405160).

Setup an electric signal conduction and embedding medium

To provide appropriate signal conduction, the surrounding the apex of printed tooth was embedding with a conducting medium. Electronic root canal length measurements were performed with Root ZX mini apex locator (J. Morita, Tokyo, Japan) using experimental models with different tooth embedding media. In this model, the tooth was soaked in the embedding medium wrapping at the apical area to make sure the EAL can work. The lip electrode was connected with a conducting wire that contact with the embedding medium. A size 15 K-file was inserted into the root canal and connected to the other EAL electrode for electronic measurement of root canal length. The EAL was operated according to the manufacturer's instructions. Readings were taken when the signal on the display of Root ZX mini device reached the "Apex" mark. When this mark was reached, the silicone stopper was positioned at the reference point (cusp), and the file was removed.

Model design and tooth preparation

Two custom-designed artificial teeth were 3D-printed, representing different working lengths (Tooth 1: 21.9 mm; Tooth 2: 20.0 mm). Each tooth was embedded in two types of conducting media: tap water and 0.9 % saline. The models were configured to be compatible with commonly used EAL devices. Conductive wiring allowed EAL probes to register electrical resistance and simulate real clinical conditions.

Working length assessed in participants

Three group participants were included in this study that included undergraduate student, trainee, and instructor. Among the three groups of participants, students are dental students who are undergraduate from the fourth year (endodontic laboratory) to sixth year (intern). The trainers are PGY (post-graduate two-year training) and specialist training residents. The instructors are visiting staff with endodontic specialists, having more than eight years of clinical experience. All participants had basic familiarity with EAL usage. Participants were instructed to measure WL for both teeth in each medium using the EAL device. Each participant performed working length (WL) measurements on the 3D printed teeth using an electronic apex locator. Each participant measured the working length three times per tooth. After completing three measurements, they recorded the confirmed value. The process was repeated for all assigned teeth, ensuring that each tooth was assessed by undergraduate student, trainee, and instructor.

Data collection and statistical analysis

Mean working lengths and standard deviations were calculated for each participant group under each condition. Accuracy was defined as measurements within $\pm$0.5 mm of the actual WL. Differences in measurements between groups were analyzed using Kruskal—Wallis test, followed by post hoc comparisons where applicable. Statistical significance was set at $P < 0.05$. All statistical analyses were performed using GraphPad Prism 9.5.0 (GraphPad Software, La Jolla, CA, USA).

Results

3D printed tooth

The original scanned tooth model was obtained (Fig. 1A) and a customized design of root portion were modified (Fig. 1B) to extend the root length with two different working length, 20.0 mm and 21.9 mm. We first print out the modify tooth (Fig. 1C) and make sure they can fit well in the dental model (Fig. 1D). Then the pulp and canal structure obtained from pulp/canal from CBCT (Fig. 1E) were added to the well-fitting tooth (Fig. 1F). In combination of above crown/root morphology, the finalized design is then digitally sliced and exported to a 3D printer for fabrication. The final printed teeth with pulp/canal system were showed in Fig. 1G.

Setup a simple 3D printing tooth model for application of EAL

The maxillary lateral incisor (#22, FDI notation) was removed from their sockets and replaced with 3D printed tooth in a plastic master model (Fig. 2A) and the apical 1/3-1/5 is socking into a conductive solution (Fig. 2B). After being installed into the model, a conductive wire is placed at the apex of the root tip where filled with conductive solution. At the other end, the connective wire extends to connect with the lip hook of the electronic apex locator to form a circuit that intimate the clinical situation (Fig. 2C). The canal lengths were determined electronically using size 15 K-files. Files were inserted slowly until the signal on the LCD screen display's bar reached the "Apex" mark, indicating the apical constriction. At this point, the silicone stopper was adjusted to the reference point, and the file was removed for length measurement. Finally, the model with apex locator was set up in the manikin (Fig. 2D) and illustrated in Fig. 3.

Working length measurement performance

The mean WL measurements for each group and condition are summarized in Table 1. For Tooth 1 (21.9 mm), mean values obtained using tap water as the conducting medium were as follows: students 21.4 $\pm$ 0.28 mm, trainees 21.4 $\pm$ 0.18 mm, and instructors 21.5 $\pm$ 0.00 mm. Similar values were observed when saline was used: students 21.4 $\pm$ 0.28 mm, trainees 21.4 $\pm$ 0.18 mm, and instructors 21.5 $\pm$ 0.00 mm. For Tooth 2 (20.0 mm), the tap water condition yielded the following results: students 19.8 $\pm$ 0.30 mm, trainees 20.0 $\pm$ 0.00 mm, and instructors 20.0 $\pm$ 0.00 mm. Under the saline condition, students measured 19.9 $\pm$ 0.36 mm, with trainees and instructors again achieving perfect accuracy (20.0 $\pm$ 0.00 mm). Notably, student measurements were slightly below the true working length but remained within an acceptable range, suggesting a learning curve in using the EAL model effectively. These results demonstrate high consistency

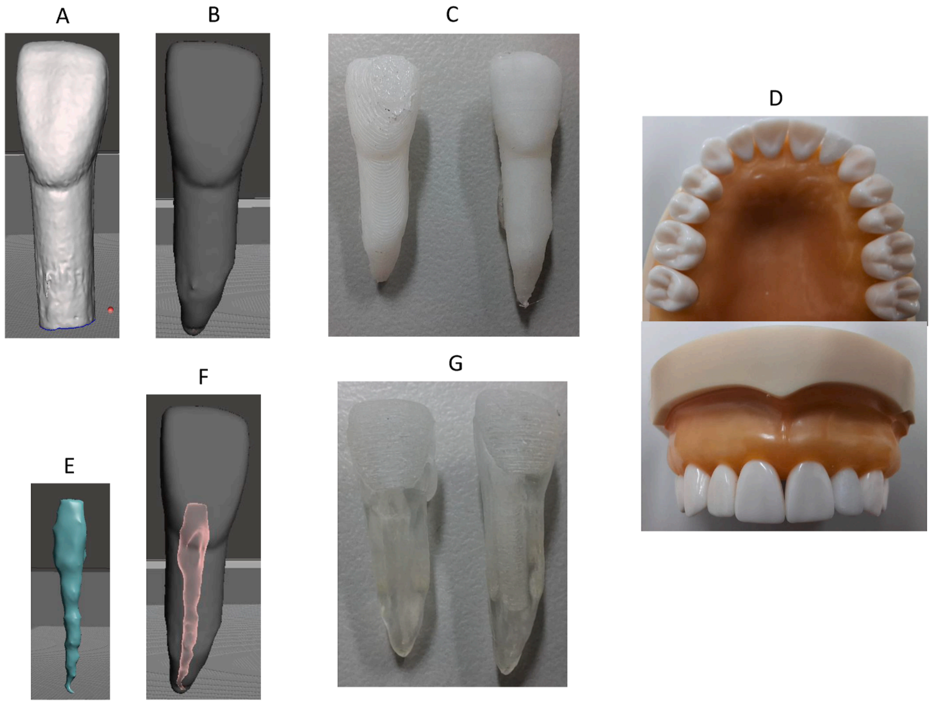

Figure 1 **3D scanned and printed tooth.** (A) Original tooth model using a dental 3D scanner. (B) Customized design of root. (C) 3D printed tooth model. (D) Printed tooth fit-well in the dental model. (E) Canal structure obtained from cone-beam computed tomography. (F) Pulp structure combined with tooth structure. (G) Final printed teeth with pulp system.

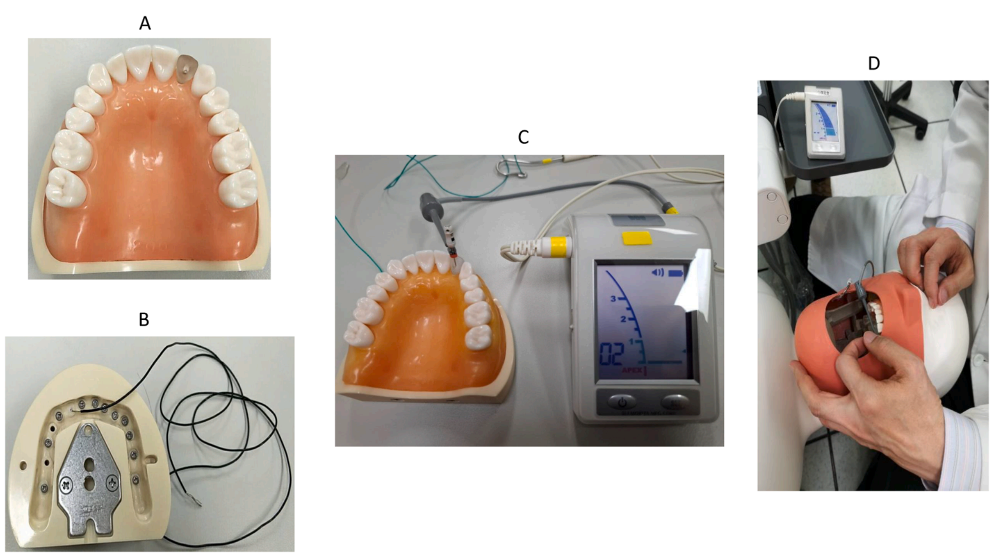

Figure 2 **Tooth model and design.** (A) 3D printed tooth set into dental model. (B) Conductive solution in the socket. (C) Setup tooth model with EAL for WL measurement. (D) Simulated the clinical endodontic treatment. EAL, electronic apex locator; WL, working length.

across both media, with minimal inter-group variability. Instructors achieved exact mean WL values, while students showed slightly greater variance.

Accuracy of working length determination

Next, we analyzed the accuracy of WL measurement in each group and condition. Accuracy, defined as a measurement within ± 0.5 mm of the actual working length, was presented in Table 2. For Tooth 1 in both media, 13 out of 15 students (86.7 %), 7 out of 8 trainees (87.5 %), and all 3 instructors (100 %) achieved accurate measurements. For Tooth 2, 13 students (86.7 %) again achieved accuracy in both media, while both trainees and instructors achieved 100 % accuracy. Statistical analysis using Kruskal–Wallis test revealed significant differences in accuracy among

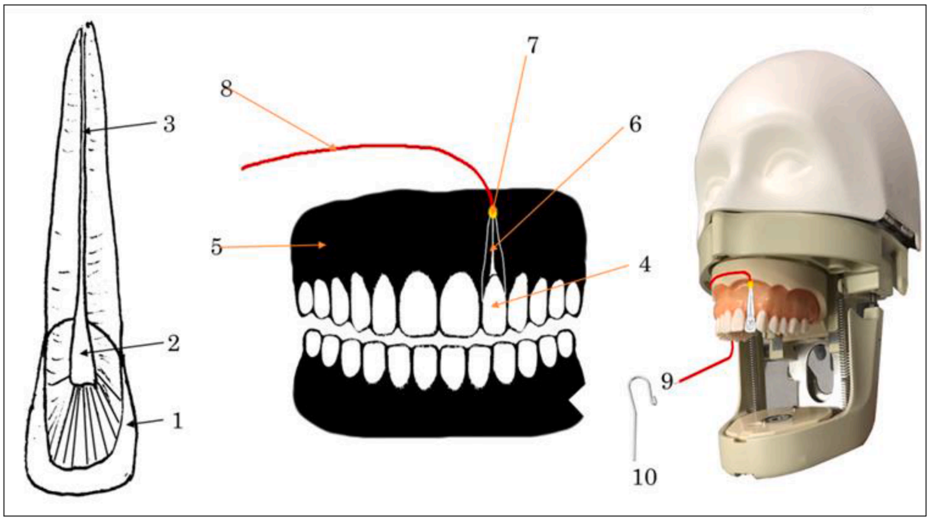

Figure 3 Schematic diagram illustrated the tooth and EAL setup. (1) Tooth Crown. (2) Pulp horn. (3) Root canal. (4) 3D printed lateral incisor. (5) Dental model on the plastic master model. (6) Pulp system printed by 3D model. (7) Conductive medium in the apical area of the printed tooth. (8) Conductive wire linked to apical area. (9) Conductive wire linked to lip hook. (10) Lip hook of the EAL. EAL, electronic apex locator.

Table 1 Mean working length (mm) measured by the participants.

Group	Tooth 1 (21.87 mm)		Tooth 2 (20.0 mm)	
	Tap water	Saline	Tap water	Saline
Students	21.4 ± 0.28	21.4 ± 0.28	19.8 ± 0.30	19.9 ± 0.36
Trainees	21.4 ± 0.18	21.4 ± 0.18	20.0 ± 0.00	20.0 ± 0.00
Instructors	21.5 ± 0.00	21.5 ± 0.00	20.0 ± 0.00	20.0 ± 0.00

Table 2 Accuracy of working length measurements (±0.5 mm of actual WL).

Group	Tooth 1 (21.87 mm)		Tooth 2 (20.0 mm)	
	Tap water	Saline	Tap water	Saline
Students	13/15 (86.7 %)	13/15 (86.7 %)	13/15 (86.7 %)	13/15 (86.7 %)
Trainees	7/8 (87.5 %)	7/8 (87.5 %)	8/8 (100 %)	8/8 (100 %)
Instructors	3/3 (100 %)	3/3 (100 %)	3/3 (100 %)	3/3 (100 %)
P value	0.0036	0.0036	0.0357	0.0357

WL, working length.

the groups for both teeth and both media types. For Tooth 1, $P = 0.0036$ in both tap water and saline; for Tooth 2, $P = 0.0357$ in both conditions. These results underscore the model's ability to discriminate between different training levels and highlight the higher precision achieved by more experienced practitioners. Overall, the model showed excellent reproducibility across different solutions and effectively distinguished between novice, intermediate, and expert users. The slightly lower accuracy and greater variability observed in student measurements may reflect their lesser clinical experience, further supporting the educational value of this training model in developing proficiency in electronic working length determination.

Discussion

In this report, we developed a novel simulation model that combined 3D printing technology and EALs for endodontic teaching and training purposes. Our primary goal was to create a preclinical setup that closely resembles real-world clinical conditions. Root canal models and artificial teeth, while useful, often fall short in this aspect as they are typically handheld during use. Teaching models that can be mounted in a phantom head offer a more realistic simulation. The results of our investigation indicate that this innovative model effectively simulates clinical scenarios and enables the application of EALs for endodontic training

Table 3 Comparison with traditional dental teaching models.

Feature	3D-printed conductive model	Traditional plastic teaching model	Extracted human teeth
Tooth structure	Anatomically accurate with pulp cavity and root canal	Solid plastic or resin; lacks realistic canal system	Realistic anatomy
Root apex conductivity	Conductive solution at apex for apex locator simulation	Non-conductive, requires manual working length estimation	Natural conductivity, but highly variable
Electronic apex locator training	Fully integrated; allows real-time audio feedback	Not compatible with apex locators	Can be used, but preparation is inconsistent
Standardization & reproducibility	High — can be mass-produced with identical properties	Moderate — varies by manufacturer	Low — no two natural teeth are identical
Compatibility	Fits various dental mannequins	Brand-specific models	Not compatible with mannequins
Ease of use	Easy to install and replace	Requires adjustments per brand	Handling and mounting can be difficult
Durability	Long-lasting and reusable	Can degrade over time	Fragile and may break during handling

and teaching purposes. In comparison to traditional models such as those made from natural or plastic teeth, our model offers distinct advantages, particularly in its applicability to preclinical training, young dentists, and endodontic specialists, meeting their specific educational needs and requirements (Table 3).

In our model, 3D designed and equipped with pulp cavity and root canal(s) which was obtained from CBCT and close in dimensions and shape to their natural counterparts. Our 3D printed teeth are suitable for endodontic training, designing variable levels of teeth according to the trainees's need. As compared to other models (Table 4), our model with key features included: 1. Realistic Tooth Anatomy that consists of a tooth body, pulp cavity, and root canal, mimicking the natural structure of human teeth. 2. Conductive Root Apex for EAL training. Furthermore, this model standardized the canal morphology that is especially important for preparing the National board Examination in Objective Structured Clinical Examination (OSCE) in our country. Although studies found artificial tooth models suitable for endodontic training,[23–27] the results of these studies suggest that complete replacement of natural teeth with artificial teeth for endodontic training should be regarded with caution. To be suitable for the desired learning experience, the models are expected to feature physical properties as similar as possible to those of a natural tooth.

EALs had demonstrated to be a useful device in determining WL as comparing to traditional radiography.[28,29] EALs offer numerous advantages over traditional radiography, including reducing the number of necessary radiographs, minimizing patient exposure to radiation, and enhancing the accuracy of working length determination. Several studies underscore the significance of using EALs in educational settings.[30–33] Most of them demonstrate a high-degree accuracy in measurement of the working length.[31,32,34] For example, Ravanshad et al. conducted a randomized clinical trial that highlights the efficacy of EALs compared to conventional radiographic methods, demonstrating that the integration of EALs optimizes working length determination.[34] This finding aligns with the conclusions of Bhaga et al. who conducted a clinical study finding that EALs is comparable to traditional radiographic measurements.[35] In terms of teaching methodologies, Tchorz et al. describe an improved model specifically designed for teaching the use of EALs.[8,33] By embedding extracted teeth in acrylic resin that mimics physiological conditions, dental students gain practical experience using EALs in a controlled environment, reinforcing theoretical knowledge and enhancing practical competency. In our model, we used the saline and tape water as conducting medium and the results of WL measured by EAL were similar. This allows the user to place the 3D printed tooth into the jaw model while connecting to an apex locator for working length determination. The results were compatible with previous report that the use of different embedding medium has shown to produce reliable measurement data.[36,37] Therefore, our model is feasible and simple for application in endodontic training. Base on this simple and novel design, our model had obtained the patent that can use pulp/canal pattern from real patients, design canal types with variable difficulty and application for different level of trainee.

Notably, our study evaluated the accuracy of working length measurements using an EAL in a 3D-printed tooth model under different conditions demonstrated the instructor group were the most accurate with consistently measuring and trainees performed better than students that matching the expected values in clinical practice. These results show clear differences in EAL accuracy based on operator experience. Although EALs have been used in several laboratory studies, this set-up has not been fully adopted to pre-clinical endodontic teaching models. Experienced clinicians recognize subtle signal changes (e.g., "APEX" or "0.0" fluctuations) that indicate the apical constriction. Our results showed students group had highest variability in WL measurement used EAL indicating the potential of this model to serve as a formative assessment tool that highlights skill gaps early in training.

Nevertheless, certain limitations warrant consideration. While the resin's mechanical properties ensure dimensional

Table 4 Comparison of endodontic training models with EAL.

Authors	Year	Model characteristics	Advantages	Disadvantages
Aurelio et al.[7]	1983	Extracted tooth embedded in agar—saline gel within a polystyrene tube; nail electrode; simulates in vitro resistance	Simple, affordable, effective for basic EAL practice	Lacks radiographic validation; limited realism
Donnelly[12]	1993	Tooth embedded in sugar-free gelatin with saline; metal lip clip for EAL circuit	Economical and easy to prepare; simulates apex readings	Limited durability and anatomical realism
Tchorz et al.[8]	2012	Extracted teeth embedded in acrylic resin with a conductive fluid reservoir for electronic apex locator (EAL) training.	1. Simulates clinical EAL use. 2. Allows radiographic verification. 3. Inexpensive and easy to fabricate.	1. Requires extracted teeth; infection control concerns 2. No direct root visualization.
Tchorz et al.[33]	2013	Artificial teeth in a model enabling EAL use and radiographic imaging, designed for repeated exercises.	1. Supports modern endodontic technique. 2. Mountable in a phantom head. 3. Replaceable artificial teeth.	1. Artificial teeth differ from natural tissue. 2. Radiopacity could be improved.
Hanafi et al.[27]	2020	Modular 3D-printed model with removable sextants, supporting EALs and radiographic working length determination.	1. Realistic clinical simulation 2. Customizable and reusable. 3. Reduces student stress in clinical practice.	1. Higher learning curve. 2. High complexity and cost; requires CBCT/STL setup
Berhanuddin et al.[13]	2021	Artificial teeth with continuous canal in a sealed model; phantom mountable	No biohazard; transparent for visual learning; affordable materials	Pilot study; limited sample size; validation pending
Our model	2025	3D-printed tooth with pulp/canal system, conductive apex, phantom head-compatible	Realistic, conductive apex for EAL, customizable canal anatomy	Still lacks full biomechanical properties

EAL, electronic apex locator; CBCT, cone-beam computed tomography; STL, stereolithographic data.

stability during instrumentation, they may alter tactile feedback compared to clinical scenarios. Ongoing material development focusing on dentin-mimetic composites shows promise in addressing this discrepancy. Additionally, the current single-root design necessitates expansion to multi-rooted teeth.

In conclusion, this 3D-printed conductive tooth model offers an improvement over traditional plastic models and extracted human teeth for endodontic training. It provides standardized, repeatable, and realistic root canal treatment simulations, making it an essential tool for modern dental education. The integration of electrical conductivity for apex locator training further bridges the gap between preclinical practice and real-world clinical experience.

Declaration of competing interest

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

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References

1. Qualtrough AJ, Whitworth JM, Dummer PM. Preclinical endodontology: an international comparison. *Int Endod J* 1999;32:406—14.
2. Pitts NB, Chow TW, Renson CE, Kirkwood J, Walker RT. Mounted human skulls as an aid to preclinical endodontic teaching. *Int Endod J* 1984;17:73—5.
3. Dummer PM, Alodeh MH, al-Omari MA. A method for the construction of simulated root canals in clear resin blocks. *Int Endod J* 1991;24:63—6.
4. DeWald JP. The use of extracted teeth for in vitro bonding studies: a review of infection control considerations. *Dent Mater* 1997;13:74—81.
5. Tchorz JP, Brandl M, Ganter PA, et al. Pre-clinical endodontic training with artificial instead of extracted human teeth: does the type of exercise have an influence on clinical endodontic outcomes? *Int Endod J* 2015;48:888—93.
6. Nattress BR, Manogue M, Carmichael F. A model for the teaching of clinical techniques in root canal treatment. *Int Endod J* 1997;30:343—6.

7. Aurelio JA, Nahmias Y, Gerstein H. A model for demonstrating an electronic canal length measuring device. *J Endod* 1983;9:568–9.
8. Tchorz JP, Hellwig E, Altenburger MJ. An improved model for teaching use of electronic apex locators. *Int Endod J* 2012;45:307–10.
9. Nassri MR, Carlik J, da Silva CR, Okagawa RE, Lin S. Critical analysis of artificial teeth for endodontic teaching. *J Appl Oral Sci* 2008;16:43–9.
10. Reymus M, Fotiadou C, Kessler A, Heck K, Hickel R, Diegritz C. 3D printed replicas for endodontic education. *Int Endod J* 2019;52:123–30.
11. Reymus M, Fotiadou C, Hickel R, Diegritz C. 3D-printed model for hands-on training in dental traumatology. *Int Endod J* 2018;51:1313–9.
12. Donnelly JC. Using a 1-ml syringe for the chloroform dip root canal filling technique. *J Endod* 1993;19:478.
13. Berhanuddin MA, Mohamad NF, Ayoub AA, Kamaruzaman M, Baharuddin IH, Ismail IH. Model to aid teaching of electronic apex locator use for endodontics in dental pre-clinical training – a uitm experience pilot study. *Compend Oral Sci* 2021;8:55–68.
14. Robberecht L, Chai F, Dehurtevent M, et al. A novel anatomical ceramic root canal simulator for endodontic training. *Eur J Dent Educ* 2017;21:e1–6.
15. Webb PA. A review of rapid prototyping (RP) techniques in the medical and biomedical sector. *J Med Eng Technol* 2000;24:149–53.
16. Esses SJ, Berman P, Bloom AI, Sosna J. Clinical applications of physical 3D models derived from MDCT data and created by rapid prototyping. *AJR Am J Roentgenol* 2011;196:W683–8.
17. Di Giacomo GA, Cury PR, de Araujo NS, Sendyk WR, Sendyk CL. Clinical application of stereolithographic surgical guides for implant placement: preliminary results. *J Periodontol* 2005;76:503–7.
18. Kessler A, Hickel R, Reymus M. 3D printing in dentistry-State of the art. *Operat Dent* 2020;45:30–40.
19. Moser N, Santander P, Quast A. From 3D imaging to 3D printing in dentistry - a practical guide. *Int J Comput Dent* 2018;21:345–56.
20. Lee SJ, Jang KH, Spangberg LS, et al. Three-dimensional visualization of a mandibular first molar with three distal roots using computer-aided rapid prototyping. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2006;101:668–74.
21. Kim E, Kim KD, Roh BD, Cho YS, Lee SJ. Computed tomography as a diagnostic aid for extracanal invasive resorption. *J Endod* 2003;29:463–5.
22. Lee SJ, Jung IY, Lee CY, Choi SY, Kum KY. Clinical application of computer-aided rapid prototyping for tooth transplantation. *Dent Traumatol* 2001;17:114–9.
23. Pouhaer M, Picart G, Baya D, et al. Design of 3D-printed macro-models for undergraduates' preclinical practice of endodontic access cavities. *Eur J Dent Educ* 2022;26:347–53.
24. Zhang R, Tang R, Spintzyk S, et al. Three-dimensional printed tooth model with root canal ledge: a novel educational tool for endodontic training. *Dent J (Basel)* 2023;11:213.
25. Razavian H, Hanjani K. A new teaching model with artificial teeth containing simulated pulpal tissue. *Dent Res J* 2021;18:19.
26. Peters O, Scott R, Arias A, et al. Evaluation of dental students' skills acquisition in endodontics using a 3D printed tooth model. *Eur Endod J* 2021;6:290–4.
27. Hanafi A, Donnermeyer D, Schafer E, Burklein S. Perception of a modular 3D print model in undergraduate endodontic education. *Int Endod J* 2020;53:1007–16.
28. Celebi Keskin IS, Yalcin TY. Evaluation of heated sodium hypochlorite's effect on the accuracy of contemporary electronic apex locators: an in vitro study. *BMC Oral Health* 2025;25:634.
29. Saha D, Mazumdar D, Biswas M, Chanani A, Das S. Comparative evaluation of efficacy in working length determination: radiography versus electronic apex locators using in vivo and ex vivo methods with stereomicroscope validation. *J Conserv Dent Endod* 2024;27:790–4.
30. Gordon MP, Chandler NP. Electronic apex locators. *Int Endod J* 2004;37:425–37.
31. Plotino G, Grande NM, Brigante L, Lesti B, Somma F. Ex vivo accuracy of three electronic apex locators: Root ZX, elements diagnostic unit and apex locator and propex. *Int Endod J* 2006;39:408–14.
32. Guise GM, Goodell GG, Imamura GM. In vitro comparison of three electronic apex locators. *J Endod* 2010;36:279–81.
33. Tchorz JP, Hellwig E, Altenburger MJ. Teaching model for artificial teeth and endodontic apex locators. *J Dent Educ* 2013;77:626–9.
34. Ravanshad S, Adl A, Anvar J. Effect of working length measurement by electronic apex locator or radiography on the adequacy of final working length: a randomized clinical trial. *J Endod* 2010;36:1753–6.
35. Bhagat E, Agnihotri Y, Das A, Das S, Panda S, Hota S. Accuracy of an electronic apex locator (EAL) in measuring the working length of root canals in comparison with radiographs: an in vivo study. *Cureus* 2024;16:e60283.
36. AlShwaimi E, Narayanaraopeta U. Effect of time on electronic working length determination with a novel endodontic module in preclinical endodontic training. *Saudi J Med Med Sci* 2014;2:37–42.
37. Wolf TG, Krauss-Mironjuk A, Wierichs RJ, Briseno-Marroquin B. Influence of embedding media on the accuracy of working length determination by means of apex locator: an ex vivo study. *Sci Rep* 2021;11:3340.