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MEDIHEALTH ACADEMY

Dear Colleagues,

It is with great pleasure that I welcome you to the first issue of the new year. In this issue, reviews of new developments in the field of dentistry and original researchs are included. One of our most important goals is to mediate appropriately the sharing of knowledge and experience among dental professionals, researchers and academicians. In this issue, we share with you five articles covering various topics in dentistry.

The first article of our journal, " Comparing haptic enhanced virtual reality simulation to plastic manikin local anesthesia training: an in-situ evaluation" is an original article and the authors aimed to evaluate a custom haptic-enhanced VR system (H-VRLA). The second article " Development of a new teaching tool for visualizing invisible tips by adjusting full dentures" is an original article. This study investigated the training effects of using pressure sensors on force magnitude control during the dental procedure. The third article is a study titled "Comparative evaluation of the performance of artificial intelligence-supported chatbots in answering basic science questions on the dental specialty exam." The study examines whether the chatbots' knowledge level is consistent with the exam standards according to the years the exams were held and the subjects covered by comparing the accuracy rates of the answers given by different chatbot models,. The fourth article '' Alkasite restorative materials in dentistry: a bibliometric analysis from 2020 to 2025" is a original article. According to the authors, this study provides the first bibliometric overview of alkasite research in dentistry, highlighting emerging research trends, geographical distribution, and scientific impact, and provides a valuable reference for future research. Finally, the fifth article '' Oral pigmentations" is a review. It is aimed to contribute to the clinical diagnosis and differential diagnosis processes of various oral and particularly gingival pigmentations encountered by clinicians.

I would like to thank the authors, reviewers, editorial team and publisher for their hard work and dedication in bringing this issue to fruition. We look forward to providing you with the latest insights and developments in dentistry, and we welcome your feedback and suggestions.

Sincerely,

Assoc. Prof. Elif Pınar BAKIR, PhD

Editor-in-Chief

Journal of
Dental Sciences
and Education

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ORIGINAL ARTICLES

REVIEWS

Journal of Dental Sciences and Education

Original Article

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Comparing haptic enhanced virtual reality simulation to plastic manikin local anesthesia training: an in-situ evaluation

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ABSTRACT

Aims: The inferior alveolar nerve block (IANB) is a common injection in dentistry and requires precise motor and anatomical skills. Traditional local anesthesia training methods, plastic manikins (PMLA), often fall short, particularly in visualizing hidden anatomy, which can hinder student confidence and performance during live procedures. Virtual reality local anesthesia (VRLA) simulations offer visual advantages but typically lack realistic tactile feedback. This study evaluated a custom haptic-enhanced VR system (H-VRLA) designed to address this gap.

Methods: A mixed-method, two-group, pre and post simulation design assessed the usability and effectiveness of the H-VRLA (n=31) versus PMLA (n=30) in preparing students (n=61) for peer-to-peer IANB injections. Participants completed a pre and post simulation survey and knowledge assessment, rotated simulation methods, delivered peer-to-peer injections and took a survey. Data was analyzed using descriptive and inferential statistics.

Results: Prior to simulation training, students exhibited low baseline knowledge with no significant differences between groups. Post-intervention, both groups showed a statistically significant increase in knowledge test scores and confidence ratings, but only H-VRLA achieved a statistically reliable gain in Final Scores. In a comparison of training realism, PMLA method was rated significantly higher for procedural features (e.g., holding the syringe, retracting the cheek), while the H-VRLA method was rated higher for visually locating anatomy. H-VRLA rated "Anatomy Helped" significantly higher. This high perceived helpfulness was a strong predictor of their final performance (R2=0.26). In contrast, for PMLA, the final score was not predicted by the helpfulness rating; instead, initial confidence was the sole strong predictor of final confidence.

Conclusion: Both simulation methods effectively supported learning. H-VRLA excelled in anatomical visualization, while PMLA was superior for realistic tactile experience. A hybrid approach is recommended, and future H-VRLA development should focus on enhancing bimanual haptics and tactile realism to better support skill transfer to live practice.

Keywords: Local anesthesia training, virtual reality, haptic technology, manikin training, simulation

INTRODUCTION

The inferior alveolar nerve block (IANB) is a routinely taught local anesthesia injection technique used to anesthetize the lower jaw, including the teeth, lip, and chin. Traditional dental and dental hygiene training in local anesthesia typically involves a layered approach with didactic instruction (lectures and textbooks), preclinical practice on plastic manikins with real instruments, demonstration and observation on patients, and, in some cases, student-to-student injection practice (peer-to-peer training) using a learner-expert model.

In Spring 2024, a survey was conducted among dental hygiene students (n=50) enrolled in a pain management course to obtain their feedback on plastic manikin local anesthesia (PMLA) training designed to ultimately prepare them for peer-to-peer injections. Responses identified several challenges: desire for more hands-on opportunities to build their confidence and competence, issues identifying anatomical landmarks, needle placement, and insertion depth, and the need for individualized feedback. Some students felt that anatomical landmarks were easier to identify during patient care than on a plastic manikin.

Although training with a traditional metal syringe on a plastic manikin head serves as an important bridge between foundational knowledge and the transition to clinical practice, this method has significant limitations. The inability to visualize underlying anatomical structures (such as patients' bones, nerves, blood vessels) requires students to perform

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procedural steps without confirmation of spatial accuracy. Palpating plastic surfaces is not the same as feeling the anatomy of live patients and this gap makes students anxious before approaching patients for treatment.

Time and resource constraints further limit the effectiveness of preclinical training. Lab sessions for manikin training require significant faculty resources to oversee all students and offer introductory exposures rather than repeated practice. Transitioning from limited practice to live patient injections-even under supervision-can be intimidating for students. As a result, dental education programs continue to face challenges in teaching complex psychomotor skills effectively.[1]

Virtual reality (VR) simulations may help bridge the learning gaps inherent in PMLA training by showing rich three-dimensional hidden anatomical structures and providing additional repeated practice opportunities.[1,2] However, commercially available VR systems that use handheld controllers lack precision that's needed for realistic fine motor skill development. Customized haptic technology can more authentically replicate instrumentation and provide more realistic tactile feedback.[3-5] This in-situ pilot study evaluated the usability and effectiveness of a customized haptic syringe integrated within a virtual reality local anesthesia simulation (H-VRLA), and compared its impact to traditional PMLA training in preparing students for peer-to-peer local anesthesia injections.

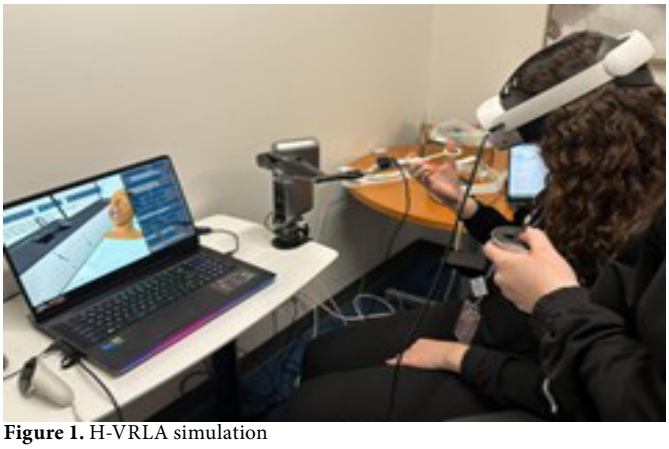


Figure 1. H-VRLA simulation

Figure 2. H-VRLA simulation (close up)

METHODS

Ethics

This feasibility in situ study evaluated two distinct simulation training methods for teaching and learning. Since the outcome data is specific to the institution and design of the simulation methods, the findings are not generalizable beyond this setting. Only aggregate data, such as averages, percentages, and counts were reported, ensuring the study did not involve human subject research. All data were de-identified, and participation had no impact on students' course grades or academic outcomes.

Students completed the evaluation protocol as part of their course curricular activities with no impact on their grades and a researcher facilitating the data collection had no role in their curricular activities. Given the minimal risk, lack of generalizability, de-identified data, and exclusive use of aggregate reporting, the Institutional Review Board determined that this project did not qualify as human subjects research thus did not require a formal application.

Photographs of a teaching assistant using the technology (Figure 1 and 2) were not part of this evaluation and a signed media release form for usage of the images in this publication was obtained.

Study Design

The evaluation method employed a mixed-method two-group pre-and-post simulation training survey and knowledge test to assess student perceptions and learning differences between traditional PMLA (Columbia Dentoform Local Anesthesia Teaching Simulator; Columbia Dentoform, Lancaster, PA USA) and H-VRLA training methods for the IANB injection technique. The study occurred within a pain management course for teaching and learning purposes at.[2] Using data collected from online Qualtrics surveys and knowledge tests, the study compared students who practiced with the H-VRLA or the PMLA simulation training method. After completing their respective simulation training, they alternated methods to ensure that all students received the same experiences.

The evaluation aimed to address the following questions:

- How do students who practiced using the H-VRLA or the PMLA simulation perceive its learning effectiveness, realism (fidelity), confidence, and usability to prepare them for live peer-to-peer live training?
- How do students who practiced using the H-VRLA or the PMLA simulation perform on knowledge tests to demonstrate their learning?

Participants

A total of 61 undergraduate dental hygiene students were enrolled in the Spring 2025 pain management course. The average age was 27.36 (SD=5.8) with 58 female and 3 male students. At the start, an alphabetical list of the students was divided in half and assigned to either the Group H-VRLA (n=31) and the other half Group PMLA (n=30).

Evaluation Procedure

To assess the educational value and effectiveness of a new simulation method that addressed PMLA training limitations, the study ensured that all students had equal opportunities to practice with both methods while still allowing for a thorough evaluation. The structure of the evaluation is as follows (Table 1).

Instruments

Pain management course: The Pain Management course prepares dental hygiene students to safely and successfully

Table 1. Evaluation procedure

n=61	1. Live lecture & pre-survey/quiz	2. PMLA & post-survey/ quiz	3. H-VRLA & post-survey/ quiz	4. PMLA	5. H-VRLA	6. Peer-to-peer live & post survey
H-VRLA (n=31)	1 Hour lecture+20 min. pre-survey/quiz		30 min. individual sim+20 min. post-survey/quiz	1.5 Hour small group sim lab on IANB		1.5 Hour peer practice+15 min post survey
PMLA (n=30)	1 Hour lecture+20 min. pre-survey/quiz	1.5 Hour Small Group Sim Lab on IANB+20 min. post-survey/quiz			30 min. individual sim	1.5 Hour peer practice+15 min post survey

H-VRLA: haptic-enhanced VR system, PMLA: Plastic manikins

administer local dental anesthesia in accordance with multiple state practice acts. The course covers topics including: anatomy, physiology, pharmacology, instrumentation, technique and complications related to local anesthesia. The 14-week course includes lecture, laboratory and clinical components. In the past, the laboratory component provided hands-on instruction on various local anesthetic injection techniques using a plastic manikin and real instruments. After exhibiting competency on a manikin (Figure 3), students qualified to inject each other. In some US states, hygienists are not credentialed to give block injections. In an effort to best prepare students for eventual practice, this course included this skill. In Spring 2025 the H-VRLA simulation with custom haptics was added to the curriculum.

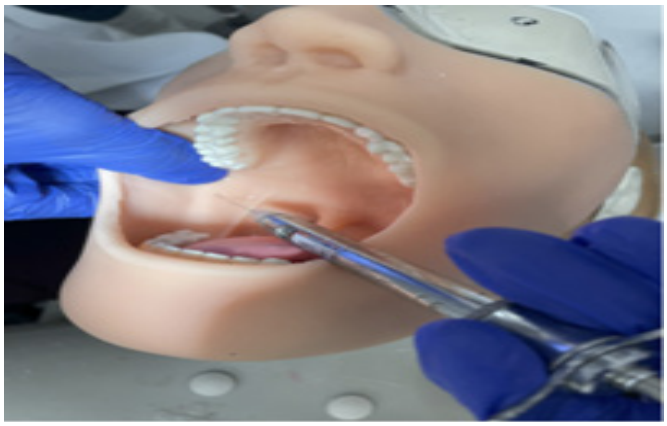


Figure 3. IANB PMLA training

The Haptic Enhanced Virtual Reality Local Anesthesia Simulation Training (H-VRLA) system is a custom-designed prototype intended to overcome the visualization and tactile limitations of traditional training methods. The core system integrates commercial virtual reality hardware, specifically the Oculus Quest 3 VR headset, with the HaplyTM Inverse 3 haptic system. This setup features custom syringe modules with integrated tracking, powered by a high-performance computer. The custom VR software is built on Unity 2022.3.33f1 and utilizes HaplyTM Inverse Components (v2.1.1) and Python programming for haptic feedback refinement. Key haptic features distinguish between soft tissue and bone, providing a realistic touch sensation. The system also includes user-friendly features such as an iPad-based control interface for teaching assistants and supports left- and right-handed users through a side-switching feature, with the goal of improving the overall usability experience. This prototype was evaluated to see if it could close the performance gap between VRLA and PMLA training (Figure 1 and 2).

The main feature differences between the PMLA and the H-VRLA are outlined in Table 2.

Table 2. Current feature differences

Feature	PMLA	H-VLRA
Hands	Bimanual: Supports dominant and non-dominant hands	Unimanual: currently supports dominant hand only
Syringe	Real instrumentation: Uses real metal syringe loaded with real anesthetic carpule	Simulated instrumentation: uses 3D-printed syringe
Visual anatomy	Realistic head/cavity size. Visualization is limited to external landmarks (alveolar ridge, pterygomandibular raphe) for IANB	Realistic head/cavity size. Full 3D internal anatomy visualization is provided. Cannot palpate structures
Haptic anat-omy	Allows palpation of mandibular foramen and coronoid notch using the non-dominant hand. Provides basic resistance mimicking tissue penetration. Allows manual cheek retraction.	Provides basic resistance mimicking tissue penetration with syringe
Accuracy	Requires subjective observation by an expert. No sensors.	Provides objective accuracy metrics: distance to nerve and site of injection. Can provide log file analytics.
Individualization	Limited ability for personalized/ individualized instruction due to small group sessions.	Offers complete individualized instruction over multiple sessions scheduled with a Teaching Assistant (TA).
Repeat practice	Limited to one scheduled lab period with faculty	Offers repeat practice with multiple sessions scheduled with a TA

H-VRLA: haptic-enhanced VR system, PMLA: Plastic manikins, IANB: Alveolar nerve block

Measurements & data collection: Data collection utilized four instruments administered via online Qualtrics surveys: a 7-item Pre-Simulation survey, a 15-item Post-Simulation survey, a 20-item multiple choice Pre-and-Post Knowledge Assessment, and an 11-item Post Peer-to-Peer IANB Training Survey. The surveys primarily used five-point Likert scales, with the Post-Simulation and Peer-to-Peer survey also incorporating open-ended questions. All three surveys demonstrated strong reliability, with Chronbach's alpha values of 0.850 for the Pre-Simulation survey, 0.845 for the Post-Simulation survey, and 0.848 for the Post Peer-to-Peer survey.[6] The Pre-Simulation survey measured prior experience, initial confidence, and a knowledge test while the Post-Simulation Survey measured changes in perceived confidence, learning effectiveness, usability, and knowledge test related to the assigned simulation method. The final survey assessed feedback on how both simulation methods impacted the live peer-to-peer training experience. For a detailed list of all survey items, Likert scales, open-ended questions, and reliability data, please refer to the Appendix (Table 3 and 4).

Table 3. Pre and post simulation survey (n=61)

Item	Question/topic (category)	Response type
Items (n=7)	Pre-sim	
1.	Have you previously assembled a syringe in a general clinic setting? (Prior experience)	L5-A
2.	How would you rate your experience/ability to perform the IANB (inferior alveolar nerve block) on a plastic manikin? (Prior experience)	L5-B
3.	How many times have you performed an IANB on a plastic manikin? (Prior experience)	L5-C
4.	How would you rate your experience/ability to perform the IANB on a live person? (Prior experience)	L5-B
5.	How many times have you performed an IANB on a live person? (Prior experience)	L5-C
6. *	How confident do you feel in your ability to perform an IANB on a live person? (Confidence)	L5-D
7.	How confident do you feel that the training methods provided in this course can help prepare me for performing IANB (inferior alveolar nerve block) on a live patient? (Confidence)	L5-D
Items (n=15)	Post-Sim	
1	How was your overall experience practicing IANB local anesthesia injection with the (H-VRLA/PMLA) simulation? Please use three words (adjectives) to describe the experience. (Experience)	Open ended
2	Overall, how well do you think you achieved the IANB local anesthesia injection tasks using the (H-VRLA/PMLA) simulation? (Learning)	L5-E
3	What did you find easiest to use or do with the (H-VRLA/PMLA) simulation? (Usability)	Open ended
4	What did you find most challenging to use or do with the (H-VRLA/PMLA) simulation? (Usability)	Open ended
5	What would improve with the (H-VRLA/PMLA) simulation? What features would you add or remove? (Usability)	Open ended
6 *	Now that you have practiced the IANB procedure using the (H-VRLA/PMLA) simulation, how confident do you feel in your ability to perform an IANB on a live person? (Confidence)	L5-D
7	The anatomy in the (H-VRLA/PMLA) simulation helped me to locate important anatomical landmarks effectively (e.g., inferior alveolar nerve and alveolar artery) (Learning)	L5-F
8	I found practicing the IANB procedure with the syringe and (H-VRLA/PMLA) simulation helped me to learn the IANB procedural steps effectively. (Learning)	L5-F
9	I found performing the IANB with the syringe and (H-VRLA/PMLA) simulation to be similar to real-life sensations such as performing the injection on a live patient? (Fidelity)	L5-F
10	I found the syringe easy to use while performing the injection on the (H-VRLA/PMLA) simulation. (Usability)	L5-F
11	The quality of the experience using the syringe with the (H-VRLA/PMLA) simulation interfered or distracted me from performing the IANB steps. (Usability)	L5-F
12	Overall, I found the syringe with (H-VRLA/PMLA) simulation set up easy to use. (Usability)	L5-F
13	I needed assistance/guidance/training to be able to use the (H-VRLA/PMLA) simulation set up. (Usability)	L5-F
14	If this practice was readily available at the College, I would practice with IANB with the (H-VRLA/PMLA) simulation set up frequently (before working on a live patient). (Learning)	L5-F
15	I found the (H-VRLA/PMLA) simulation training set up could help prepare me for performing IANB (Inferior Alveolar Nerve Block) on a live patient. (Learning)	L5-F

* Comparable questions, H-VRLA: haptic-enhanced VR system, PMLA: Plastic manikins, IANB: Alveolar nerve block
Table 3 Key Likert scales (L5) (pre-post simulation survey)
- L5-A (frequency): 1=never... 5=more than three times
- L5-B (ability): 1=novice... 5=expert
- L5-C (count): 1=0 times... 5=more than 3 times

Analysis

To assess group differences and changes over time across the two treatment groups two primary forms of the t-test were employed:

- **Paired samples t-test:** This was used to evaluate within-group change between pre- and post-measurements for both Pre and Post Knowledge Test Scores and Confidence Ratings. The analysis determined if the mean difference (gain) between the time points was statistically different from zero for each group individually. The 95% Confidence Intervals (CIs) were calculated for all mean gain scores.
- **Independent samples t-test:** This was used to compare the mean scores between the two groups on key outcome variables, including the self-reported usefulness of anatomy "Anatomy helped" rating. The 95% CI was calculated for the mean difference between the groups.
- **Repeated measures ANOVA/ANCOVA:** This test was used to analyze between main effects on post simulation knowledge tests.

Predictive relationships: Simple Linear Regression was utilized to assess the predictive relationship between key independent variables and post-intervention outcomes. These analyses were conducted separately within each of the two groups to identify potential differential predictive structures. The coefficient of determination (R2) and the standardized beta coefficient (B) were reported for all regression models.

Sample size and power: The adequacy of the sample size was assessed by conducting a post-hoc evaluation of statistical power against Cohen's standard for a medium effect size (Cohen's d=0.50 and Cohen's f2=0.15). The discussion of the results includes consideration of the calculated power to interpret non-significant findings and potential for Type II error.

To further contextualize the quantitative results, text analysis was used to explore responses to open-ended follow-up questions. Using an established coding method, responses were manually analyzed by reviewing raw data, identifying frequently used words and phrases, categorizing them into meaningful codes, and organizing them into a table.[7] Given

Table 4. Post live peer-to-peer training survey (n=61)

Item	Question	Response type
1	How was your overall experience practicing IANB local anesthesia injection on a live person (peer)? Please use three words (adjectives) to describe the experience. (Experience)	Open ended
2 & 2B	Overall, how well do you think you achieved the IANB local anesthesia injection tasks on a live person? If you answered 1, 2, or 3 to the question above, what specifically do you need to improve? (Learning)	L5-E+open ended
3	How will you improve your learning outside of class? (order in rank from top to bottom the resources you would like to use) (Learning)	Rank order (6 options)
4 & 4B	Which type of manikin do you prefer for practice of the IANB procedure before practice on a live person? (select one) Based on your choice, please let us know why: (Learning)	SC4-A+open ended
5 & 5B	Which type of manikin training helps you to learn anatomy better? Based on your choice, please let us know why: (Learning)	SC4-A+open ended
6 & 6B	Which type of manikin training helps you to learn the IANB procedural steps better? Based on your choice, please let us know why: (Learning)	SC4-A+open ended
7 & 7B	Which type of manikin training felt most realistic or like performing on a live person? Based on your choice, please let us know why: (Fidelity)	SC4-A+Open ended
8 & 9	Reflecting, which features of the (H-VRLA/PMLA) simulation training were most realistic or like performing the IANB on a live person? (Fidelity)	L100-G (9 features)
10 & 11	How easy do you feel practicing the IANB local anesthesia injections on the (H-VRLA/PMLA) simulation transferred to practicing on a live person? (Learning)	L5-H
10 B & 11B	If you answered 1 or 2 to the question above, what do you think made it difficult to transfer to a live person?	Open ended
10 C & 11C	If you answered 3 or 4 to the question above, what do you think made it easy to transfer to a live person?	Open ended

H-VRLA: haptic-enhanced VR system, PMLA: Plastic manikins, IANB: Alveolar nerve block
Table 4 Key Scale Definitions (Post Peer-to-Peer Survey)
• SC4-A (Single Choice, 4 Options): 1=PMLA, 2=H-VRLA, 3=Both, 4=Neither
• L100-G (Fidelity Scale): 0=Strongly disagree... 100=Strongly agree (25-point increments)
• L5-H (Difficulty/Ease): 1=Extremely Difficult... 5=Extremely Easy

the brevity of responses, manual coding was conducted, and to ensure semantic validity, multiple researchers reviewed and confirmed the categorization of words and phrases.

RESULTS

Pre-Simulation Survey & Knowledge Test

Prior experience: On average, all students reported low prior experience with local anesthesia manikin training and live patient experience related questions with no statistically significant differences between the two groups (Figure 4).

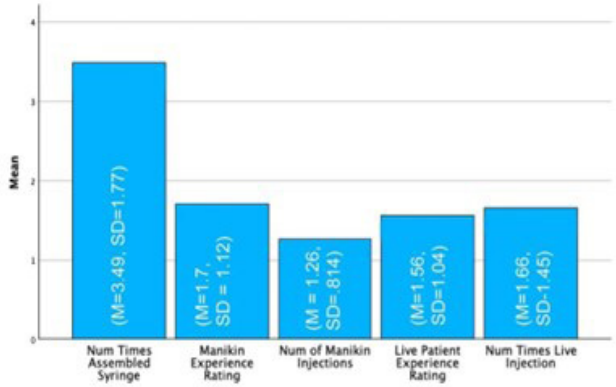


Figure 4. Overall mean prior experience

Confidence: Both groups reported low to moderate confidence in performing the IANB on a live person (Figure 5) and moderate confidence that the training methods provided in the course would adequately prepare them for live IANB injections. No statistically significant differences were observed between groups.

Knowledge test: Both groups scored similarly on the pre-simulation knowledge test with no statistically significant differences observed between groups (Figure 6).

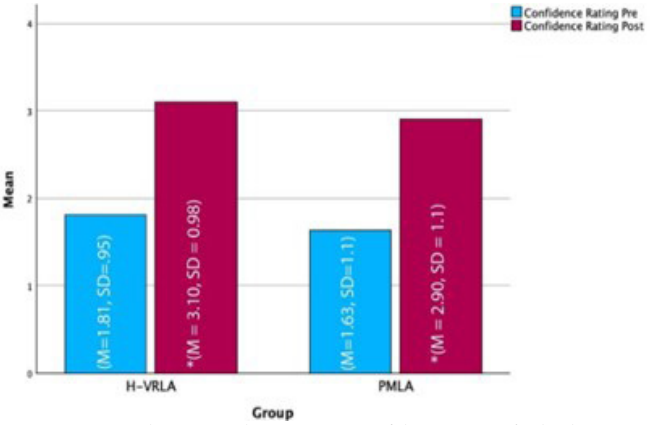


Figure 5. Pre and post simulation mean confidence rating for both groups

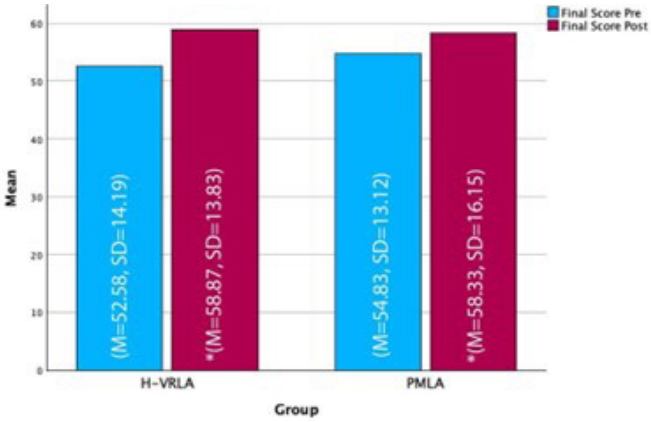


Figure 6. Pre and post simulation mean knowledge test scores for both groups

Overall, on average, all students had low prior experience, low confidence levels, and low prior knowledge before engaging with their respective IANB simulation training.

Post Simulation Survey and Knowledge Test

Overall experience: The majority of students in both groups reported positive learning experiences: 80% for H-VRLA,

emphasizing engagement and educational value, and 86% for PMLA. A few PMLA users, however, noted issues with realism, confusion, or the need for more demonstrations.

Perceived learning: Average results showed similar ratings for both groups except for the usefulness of anatomy (Figure 7). An independent sample t-test on the learning usefulness of anatomy rating "Anatomy helped" for each group found a statistically significant difference between groups, t (59)=3.225, p=0.002. H-VRLA reported a significantly higher mean rating. The 95% CI for the mean difference (G1-G2) was [0.40, 1.71], excluding zero.

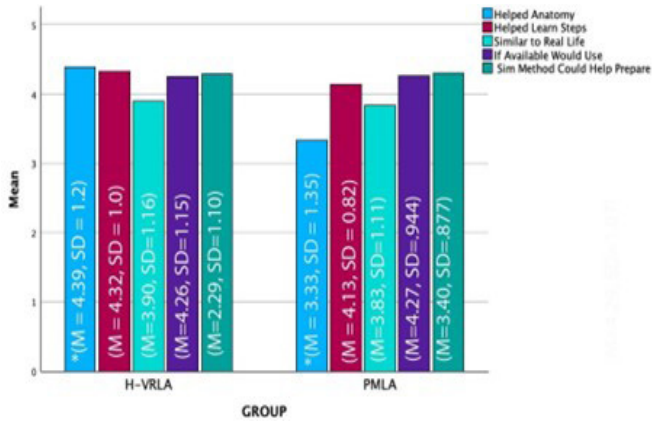


Figure 7. Mean learning perceptions for H-VRLA & PMLA training methods

In H-VRLA, the "Anatomy Helped" rating was a significant positive predictor of the post score (B=5.848, p=0.003), accounting for 25.9% of the variance (R2=0.259). For PMLA, the rating was not a significant predictor (B=-2.057, p=0.365, R2=0.029). All other features comparing the use of the 3D printed syringe with the H-VRLA to the traditional metal syringe on the PMLA did not show any statistically significant differences on the post-survey.

Usability: Results indicated similar usability feature average ratings for both groups showing strong agreement for ease of use for their respective simulation methods (Figure 8).

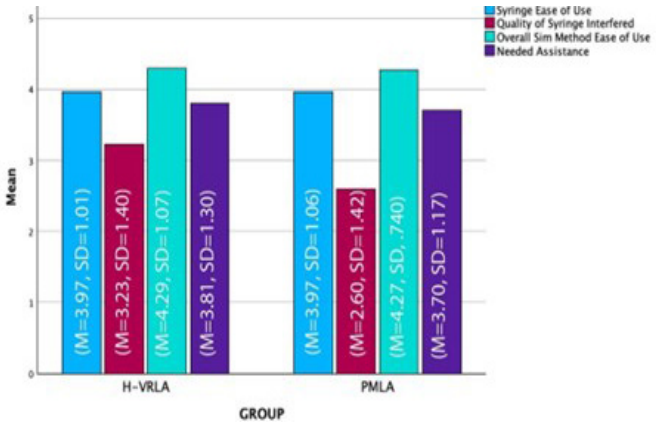


Figure 8. Mean usability ratings for the H-VRLA and PMLA training methods

Easiest aspect: H-VRLA users primarily reported in the open-ended question that identifying hidden anatomical landmarks (bone, nerves, vessels) easiest (35% of responses). PMLA users focused on procedural elements, with 20% finding dispensing anesthetic easiest and 16% identifying external landmarks (coronoid notch) as easiest.

Most challenging aspect: This open-ended question clearly delineated the limitations of each system. Hand stabilization (due to inability to establish a fulcrum, 22%) and injection accuracy (16%) were the main difficulties for H-VRLA. Identifying anatomical landmarks (43%) was the primary challenge, followed by injection technique (30%) and limitations of the plastic manikin (hard mucosa, poor bone feedback, 30%) for PMLA.

Suggested improvements: Students provided open-ended feedback for enhancing realism and learning. H-VRLA users suggested enhancements to realism included a more lifelike syringe, the ability to fulcrum, visible anesthetic flow, and non-dominant hand tactile feedback (20% of responses). Additional practice sessions were also recommended. PMLA users requested more realistic manikins with anatomical variations and less rigid materials (26%) and greater instructional support, including personalized guidance and faculty feedback (30%).

Pre and post simulation confidence ratings: Both groups showed an increase from pre-to post-simulation confidence levels (Figure 5).

Pre and post simulation knowledge test scores: Both groups showed increased mean knowledge test scores from pre and post simulation methods (Figure 6).

Pre-and-Post Simulation Inferential Test Comparisons

Within-group paired t-tests (confidence): Both groups demonstrated a highly significant increase in Confidence Ratings from pre to post. H-VLRA increased from M=1.81 to M=3.10, t(30)=-5.150, $p < 0.001$, and PMLA increased from M=1.63 to M=2.90, t(29)=-6.836, $p < 0.001$. Both 95% CI's for the mean gain excluded zero (H-VRLA: [0.78, 1.80]; PMLA: [0.89, 1.65]).

Regression on confidence scores: The model suggested that only 0.3% of the variability in H-VRLA's post confidence scores is explained by their pre confidence scores. The relationship was not statistically significant (p=0.785). For H-VRLA, a person's initial confidence rating does not reliably predict their final confidence rating. The model suggested that 29.7% of the variability in PMLA's post confidence scores is explained by their pre confidence scores. The relationship was statistically significant (p=0.002). For PMLA, a person's initial confidence rating is a reliable predictor of their final confidence rating. For every one-point increase in pre confidence, the post confidence is predicted to increase by 0.543 points.

Within-group paired t-tests (knowledge test scores): Examining within-group change, H-VRLA showed a statistically significant increase in scores from pre (M=52.58, SD=14.19) to post (M=58.87, SD=13.83), t(30)=-2.285, p=0.030. The 95% CI for the mean gain was [0.67, 11.91]. In contrast, the gain for PMLA (MGain=3.50, 95% CI=[-1.87, 8.87] was not statistically significant, t(29)=-1.332, p=0.193.

Regression on knowledge test scores: This analysis indicates the strength and nature of the linear relationship between the initial and final scores within each treatment condition. For H-VRLA, the model suggests that 16.1% of the variability in the treatment post-test scores is explained by their pre-test scores. The relationship is statistically significant (p=0.025). For every one-point increase in the pre-test score, the post-test

score is predicted to increase by 0.391 points. For PMLA, the model suggests that 28.4% of the variability in the treatment post-test scores is explained by their pre-test scores. The relationship is statistically significant (p=0.002). For every one-point increase in the pre-test score, the post-test score is predicted to increase by 0.657 points.

Repeated measures ANOVA/ANCOVA findings (knowledge test scores): A mixed-design analysis on knowledge scores revealed a statistically significant main effect of Time, indicating an overall improvement from pre to post simulation test across both groups, t(60)=-2.592, p=0.012. However, there was no significant Treatment Group x Time interaction, F(1.59)=0.536, p=0.467, suggesting the degree of improvement was comparable between groups. Furthermore, the ANCOVA revealed no significant main effect of the Treatment Group on the post test scores after adjusting for pre scores, F(1.58)=0.240, p=0.626 (Adjusted MH-VRLA=59.44; Adjusted MPMLA=57.75).

Post Peer-to-Peer Live IANB Training Survey

The Post Peer-to-Peer Training Survey collected feedback after all students experienced both simulation methods and performed a live injection.

Live training experience: Students widely viewed the live peer-to-peer injection as a valuable experience: 49% described it positively (informative, educational, effective), and 32% found it exciting and fun. However, a smaller percentage found it challenging, difficult, or stressful (10%). Students who reported not achieving tasks "very well" cited the need to improve needle depth and location, build confidence, and gain more practice.

Perceived learning: Results showed students rated their perceived achievement to perform IANB tasks on a peer as very well (Figure 9). Students, 16 out of 61, who answered that they did not feel they achieved the tasks very well provided open-ended responses explained that they need to improve needle insertion depth and location (count=3), build more confidence and nervousness (count=4), more practice (count=4), and still do not understand or have difficulty finding landmarks (count=3).

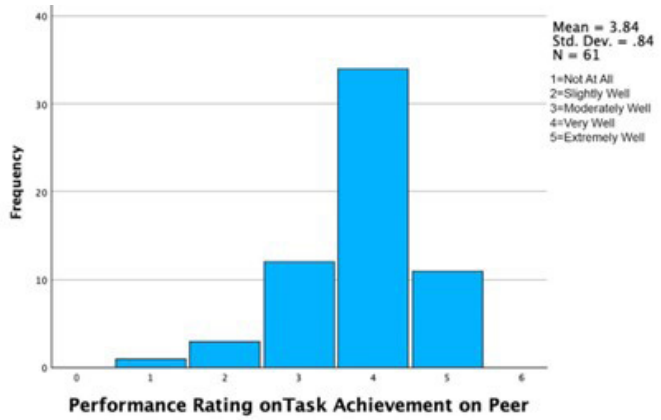


Figure 9. Overall mean performance rating on task achievement on peer

When students were asked to rank resources for improving their learning independently outside of class, the highest-ranked options were "other" and "nothing" followed by H-VRLA practice (Figure 10). PMLA was not provided as an option since it requires faculty supervision during pre-scheduled lab sessions.

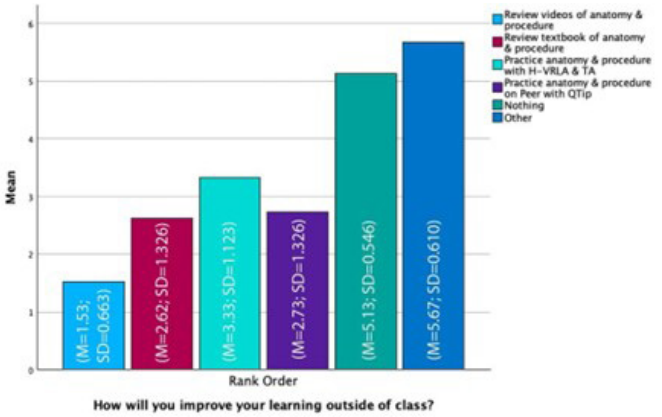


Figure 10. Mean rank order continued learning resources

Simulation preference comparison: Students compared PMLA and H-VRLA based on four criteria. In all categories related to procedural realism, PMLA was preferred as a stand-alone method (Table 5). A significant portion of students preferred "Both" methods (40.98% for general practice, 36.07% for anatomy learning). PMLA was valued for experiencing the procedural aspects like aspiration, injecting with a real syringe, and tactile sensation. H-VRLA was highly beneficial for visualizing the underlying anatomy. This combined approach was seen as maximizing the pros of both simulation methods.

Reflecting on which features of the H-VRLA and the PMLA simulation training were most realistic or like performing the IANB on a live person, students selected “visually locating anatomy” and “holding the syringe” most realistic for the H-VRLA and selected “holding the syringe”, “dispensing anesthesia”, “retracting the cheek”, and “aspirating” as most realistic for the PMLA (Figure 12).

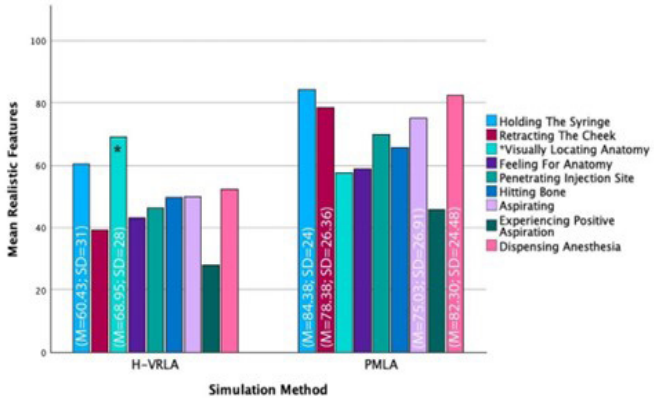
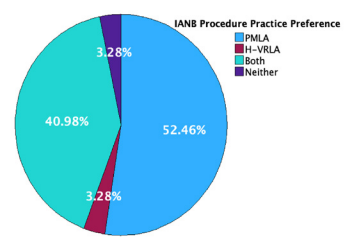
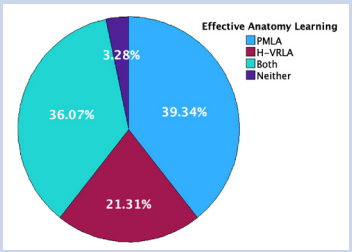
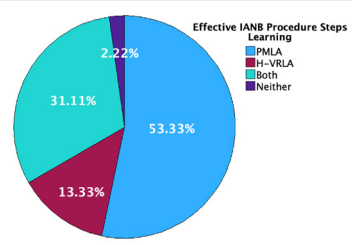
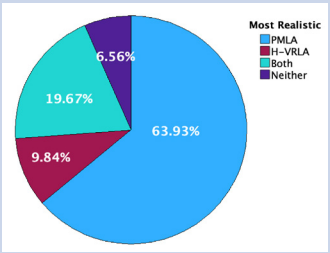


Figure 12. Mean realistic feature comparison between H-VRLA and PMLA

Paired t-tests comparing the two methods showed statistically significantly greater mean rating scores for each feature for the PMLA compared to the H-VRLA except “visually locating anatomy” which showed statistically significant greater mean rating scores for H-VRLA compared to PMLA (Table 6).

Skill transfer: Lastly, Students reported that practicing the IANB local anesthesia injections on the PMLA was more effective for transferring skills to a live patient (M=3.39, SD=0.954) than using the H-VRLA simulator (M=2.29, SD=1.038).

Table 5. Preference comparison

Preference category	Pie chart	Preferred standalone method	Primary qualitative rationale
Preferred practice prior to live injection (52% PMLA vs. 3.28% H-VRLA)	 (Figure 11A)	PMLA (52%)	Felt more real, closer to a live person, allowed feeling landmarks
Learning anatomy better (39.35% PMLA vs. 21.32% H-VRLA)	 (Figure 11B)	PMLA (39.35%)	Ability to feel landmarks, tactile feedback, and maneuver the manikin
Learning procedural steps better (53.33% PMLA vs. 13.33% H-VRLA)	 (Figure 11C)	PMLA (53.33%)	Ability to envision a real patient and use both hands
Most realistic/like live person (63.94% PMLA vs. 9.84% H-VRLA)	 (Figure 11D)	PMLA (63.94%)	More realistic because they could feel with both hands

H-VRLA: haptic-enhanced VR system, PMLA: Plastic manikins

Table 6. Realistic feature comparison (n=61)

Realistic feature	H-VRLA M (SD)	PMLA M (SD)	Paired samples test
Holding the syringe	60.43 (31.04)	84.38 (24.20)	t (60) =-5.681, p<.001*
Retracting the cheek	39.11 (30.67)	78.38 (26.37)	t (60) =-8.252, p<.001*
*Visually locating anatomy	68.95 (28.09)	57.49 (29.23)	t (60) =2.520, p=.007*
Feeling for important anatomy	43.21 (33.12)	58.82 (30.45)	t (60) =-2.823, p=.003*
Penetrating into site of injection	46.23 (34.42)	69.72 (27.26)	t (60) =-4.504, p<.001*
Hitting bone with the syringe	49.62 (33.73)	65.70 (29.99)	t (60) =-3.300, p<.001*
Aspirating	49.87 (33.06)	75.03 (26.91)	t (60) =-5.471, p<.001*
Experiencing a positive aspiration	28.02 (27.22)	45.85 (33.97)	t (60) =-3.895 p<.001*
Dispensing anesthesia with the syringe	52.16 (34.28)	82.30 (24.49)	t (60) =-6.008, p<.001*

* p<.05, H-VRLA: haptic-enhanced VR system, PMLA: Plastic manikins, SD: Standard deviation

DISCUSSION

Results showed that students began the training with limited clinical readiness, establishing a baseline for evaluating the impact of simulation training methods, confirming a need for effective pre-clinical simulation to build clinical readiness. The initial similarity in learning outcomes found immediately post-simulation across both groups, despite the feature differences, reinforces existing research suggesting that any

form of pre-clinical practice, even on simulated models, is beneficial for building initial experience and confidence.[8] Prior research found, any form of simulation training can still enhance confidence prior to live procedures, mirroring our students' initial low experience but post-training confidence gains.[8]

A major limitation of traditional PMLA training identified in the literature is the inability to visualize key anatomical structures (e.g., bones, nerves, surrounding blood vessels), forcing students to follow procedural steps "blindly".[9] Virtual reality (VR) simulations were proposed as a solution to bridge this gap by visually showing students the hidden layers of anatomy three-dimensionally.[1] This study confirms the superiority of the custom Haptic-Enhanced VRLA (H-VRLA) in addressing this visualization deficiency. The "Anatomy Helped" variable showed the clearest difference: H-VRLA rated it as more helpful, and this rating strongly predicted their post score. Qualitative results reinforced this, as H-VRLA users found locating hidden anatomical structures (nerves, bone) easiest, while PMLA users reported that identifying landmarks was the most challenging aspect of their training. Similar to findings in prior research[10,11] these results indicate that H-VRLA successfully achieved its goal of leveraging 3D visualization to enhance anatomical learning, a feature largely absent in PMLA training.

Both groups significantly increased their confidence, but only H-VRLA significantly increased their post score. The lack of a significant interaction suggests the intervention generally moved both groups equally, but the post-hoc t-tests show the change only achieved reliability for H-VLRA. The difference in confidence regression findings is noteworthy. In PMLA, pre simulation confidence predicted post-simulation confidence (B=0.543), suggesting a stable, trait-like confidence structure. In H-VRLA, this relationship was non-significant (p=0.785), implying that their intervention or experience may have destabilized or fundamentally changed the relationship between their initial and final confidence, suggesting a successful intervention effect.

While PMLA showed a positive average gain in post knowledge test scores (MGain=3.50), this increase was not statistically significant (p=0.193). Given the small sample size (n=30) and the low statistical power (~48% power to detect a medium effect), it is plausible this result constitutes a Type II error. The true effect may be positive but was not reliably detected due to high individual variability.

The data shifted significantly after students completed live peer-to-peer practice, highlighting the recognized challenge of transferring skills from manikins to real patients due to the manikin's inability to replicate fully tactile feedback and anatomical complexity. Prior research detailed how prior, non-haptic VRLA systems were criticized for lacking realism, particularly for procedural elements requiring haptic feedback such as tissue penetration, bone contact, aspiration, and the crucial element of bimanual instrument handling.[2] The post-peer-to-peer data confirmed that the PMLA remained superior in aspects requiring higher tactile fidelity and procedural realism. Students overwhelmingly preferred the PMLA over H-VRLA alone as their practice method prior to live injections (52%) and PMLA was rated as the training method that felt most realistic (63.94%). This preference was largely driven by PMLA's superiority in features requiring higher tactile fidelity and procedural realism, such as bimanual use (holding the syringe, retracting the cheek), aspiration, and dispensing anesthesia. These results align with previous usability studies, which showed that immersive simulations with force feedback improve spatial awareness and accuracy but still require refinement in bimanual control to reach manikin-level realism.[12,13]

The findings reinforce prior research suggesting that VR simulations function best as supplements rather than replacements for PMLA due to PMLA's realistic bimanual tactile experience. A significant portion of students (40.98%) preferred the combination of both methods for general practice, valuing the complementary strengths of PMLA for procedural realism and H-VRLA for anatomical visualization. This supports the conclusion that a hybrid simulation model integrating both methods offers the most comprehensive training approach. This mirrors earlier evidence suggesting that tactile experience remains a critical factor for procedural realism, underscoring the value of haptic integration in simulation design.[1,3]

To enhance H-VRLA realism and better support skill transfer, future development should address reported limitations, primarily concerning bimanual haptic control and tactile fidelity. Specific recommendations include:

- **Implement Bimanual Haptics:** Add a second haptic technology device for the non-dominant hand to allow for palpation of important anatomy and maintenance of cheek retraction during the procedure, thereby enhancing overall realism
- **Refine Haptic Feedback:** Introduce improvements such as more resistance at the point of injection, a clearer tactile "click" upon bone contact, and simulated feedback for aspiration and anesthesia flow with the haptic syringe
- **Integrate Fulcrum Support:** Add a mechanism that enables fulcruming to stabilize the syringe, which would increase the realism and learning effectiveness of the procedure
- **Introduce Artificial Intelligence (AI):** Incorporate AI features such as prompts to adjust angle or depth, immediate feedback explaining errors and correcting incorrect insertion points, and post-simulation playback and performance analysis

Limitations

A key limitation of this study is the sample size (n=61). Power analysis indicated that the achieved power to detect a medium effect (Cohen's d=0.50) was approximately 48% for both independent and paired t-tests. Researchers should be cautious in interpreting the non-significant findings, as the study was underpowered to reliably detect effects of a medium size. Limitations to this research include a lack of a control group not using any simulation method as well as random sampling. The setting of this evaluation is context specific to the goals of the course making it difficult to replicate. While conducting an in-situ evaluation allows researchers to determine its educational value and effectiveness within the context of the curriculum, it lacks control over other unforeseen variables that may have contributed or detracted from the outcomes. Assessing performance with other means such as having an expert evaluate student performance of the IANB technique on a live person can be a challenge due

to students' learning stages. The goal is not mastery during practice but an introduction to best familiarize students with key concepts.

CONCLUSION

Despite adding customized haptics for the non-dominant hand, the findings reinforce prior research indicating that VR simulations function best as supplements rather than replacements for traditional PMLA training due to the bimanual tactile experience it provides. Student preferences also support a hybrid approach, with nearly 41% favoring the combined use of both methods. Students valued the H-VRLA for its ability to visualize internal anatomy and the PMLA for providing realistic tactile procedural feedback. To optimize training, programs should adopt hybrid simulation models integrating these complementary strengths and enhancing haptic realism, feedback, and usability, especially for bimanual skill development. Future research will continue to address limitations to the H-VRLA to improve realism for both hands and challenge the PMLA.

ETHICAL DECLARATIONS

Ethics Committee Approval

Since the study involved no human or animal subjects, clinical interventions, or identifiable patient data, ethics committee approval was not required.

Informed Consent- Retrospective

As this was a retrospective study, formal written informed consent was not required and was therefore not obtained.

Peer Review Process

This manuscript was subject to external peer review.

Conflict of Interest

The authors declare no conflicts of interest related to this study.

Financial Disclosure

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Author Contributions

Concept: R.N., M.E., E.M., P.K., M.L., D.S.; Design: R.N., M.E., E.M., P.K., M.L., D.S.; Review: R.N., M.E., E.M., P.K., M.L., D.S.; Data Collection: E.M.; Analysis: E.M.; Literature Review: E.M.; Article Writing: R.N., M.E., E.M., P.K., M.L., D.S.

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Original Article

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Development of a new teaching tool for visualizing invisible tips by adjusting full dentures

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ABSTRACT

Aims: Dental clinical skills include subtle techniques, such as applying an appropriate amount of force depending on the procedure. This study investigated the training effects of using pressure sensors on force magnitude control during the dental procedure.

Methods: Forty-two dental trainees participated in this study. The experimental task was a fit test, assessing the pressure contact of a denture against the mandible. The force applied by each participant was measured using a modified mannequin equipped with a digital force gauge. Fit test training was performed under conditions specifying the presence or absence of fit test material and various degrees of force, with 50 N set as the standard. After training, the ability to control force magnitude was statistically evaluated by examining the error between the specified and actual values.

Results: The presence of the fit test material did not affect the force magnitude, and the time required decreased in proportion to the number of trials. Initially, not all participants were able to apply 50 N without special instructions. However, after training, the measured values exceeded 50 N. The error from the target value was significantly larger when 70 N was designated compared to 50 N. Errors between the specified and actual values obtained at 30–60 N exhibited a decreasing trend in each successive cycle.

Conclusion: Visualized numerical data are effective for developing practical force control. This form of experiential learning may contribute to the early retention of basic dental skills.

Keywords: Clinical competence, dental education, fit test, experiential learning, mannequin simulation

INTRODUCTION

Dentistry is a precise medical practice involving advanced skills, and many countries conduct various qualification examinations to ensure the competency of dentists.[1] Dental treatment performed in a narrow oral cavity involves sensory tips that are difficult for learners to visualize. Practical dental skills are typically acquired through clinical experience. Conventionally, several effective educational methods have been developed to solve this problem, including instructional videos,[2-4] simulation-based learning systems,[5,6] efficient teaching schedules,[7] objective evaluations of procedural outcomes by 3D scanner,[8-11] and verification of treatment effects or skill training using sensors.[12,13] Recently, research has been conducted to analyze behavior during dental practice for application in clinical skills education.[14,15] Experiential learning methods, such as haptic devices[16,17] and virtual reality systems[18,19] have also been introduced. One of the most critical educational factors that cannot be visualized is the application of an appropriate force to the patient or the affected teeth, depending on the procedure. Dental treatment involves the handling of various materials and tools; therefore, controlling the force magnitude applied during procedures is an indispensable technical skill required by dentists. To address this issue, a modified mannequin equipped with a pressure sensor was developed, which quantitatively demonstrated that the magnitude of the force applied by practitioners during dental treatment differs among students, resident dentists, and teaching faculty members. This study aimed to evaluate the use of this device in clinical dental training and to investigate the influence of visual information on force control during dental procedures, focusing on a fit test involving a complete mandibular denture.

METHODS

The study was carried out with the approval of the Ethics Committee of Niigata University Medical and Dental Hospital (Date: 05.08.2015, Decision No: 2015-5055). All participants were informed both in writing and orally about the content and purpose of the study, and assured that personal information would be deleted from the obtained data. They were also informed that participation carried no disadvantages and

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that they could withdraw at any time. Written consent was obtained from all participants. All procedures were carried out in accordance with the ethical rules and the principles of the Declaration of Helsinki.

Participants and Force Measurement Methods

Forty-two dental trainees (17 men and 25 women, 26.1±2.5 years old) at Niigata University Medical and Dental Hospital participated in this study. The test operation consisted of a fitting examination, in which a full denture (FD) was applied to the edentulous mandible. To quantify the force magnitude applied by the practitioner to the patient and the duration of the procedure, a modified mannequin (Simple Mannequin, Nissin, Kyoto, Japan; Figure 1) incorporating a digital force gauge (ZTA-100 N, IMADA, Aichi, Japan) was fabricated. A model of the edentulous mandible (P9-X,1133, Nissin, Kyoto, Japan) and an FD fitted to this model were prepared. Participants were instructed to place their thumbs around the second premolar of the FD and apply force with both hands, clamping the other four fingers between the metal frames corresponding to the lower margin of the mannequin's mandible (Figure 2). Measurements were recorded using dedicated software (Force Recorder; IMADA, Aichi, Japan) installed on a notebook PC connected to a force gauge. The following two experiments were conducted during the second half of the training period.

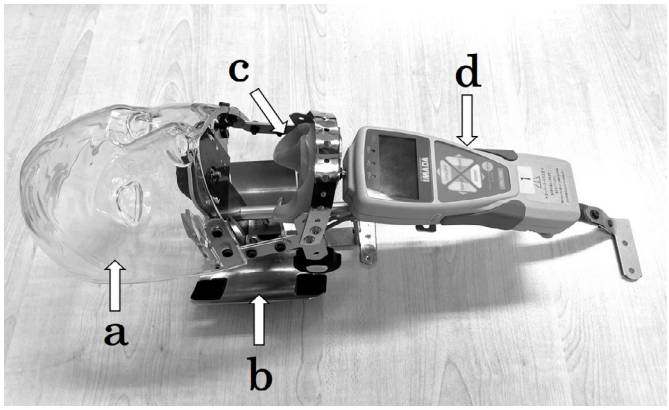

Figure 1. A modified mannequin incorporating a digital force gauge.
a: Face part of dental mannequin (Nissin)
b: Headrest mount (Nissin)
c: Model of the edentulous mandible (Nissin)
d: Force gauge (Imada)
Other than the above parts are self-made

Figure 2. The instructed method for applying force to the FD
Participants were instructed to place their thumbs around the second premolar of the FD and apply force with both hands by clamping the other four fingers between the metal frames corresponding to the lower margin of the mandible

Experiment 1: Influence of the presence of a fit checker on the magnitude and duration of the denture fit test (pressure contact).

Participants were given no specific instructions other than to perform an FD fit test, and the force magnitude was measured once under each of the following two conditions: (1) checked by eye and fitting material (FC: Fit Checker: GC, Tokyo, Japan) and (2) checked by eye alone.

Experiment 2: Changes in force control through training using objective numerical values as indicators (Figure 3).

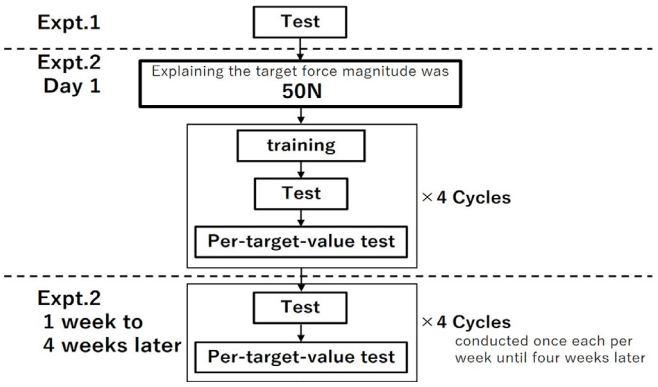

Figure 3. Flow of experiment

Participants were informed that the target force magnitude was 50 N and were trained to press the FD onto the model while observing the digital force gauge value. "Training" consisted of denture pressure contact exercises using force levels of 30-70 N, centered on 50 N. Each force application lasted 9 s, followed by a 15 s break (Figure 4). The pressure magnitude was measured in the order of "test" and "per-target-value test." In the "test," participants were instructed to pressurize the FD with the FC at 50 N, and after completing the experiment, the maximum value of the pressure magnitude was presented to each participant. A 1 min break was provided between the "test" and "per-target-value test." In the "per-target-value test," participants were instructed to pressurize without the FC at 50 N, 30 N, 60 N, 40 N, and 70 N, respectively. Pressure magnitude was not disclosed to the participant after the experiment. Four cycles of "training," "test," and "per-target-value test" were performed on the same day. Thereafter, the "test" and "per-target-value test" were conducted once per week for 4 weeks.

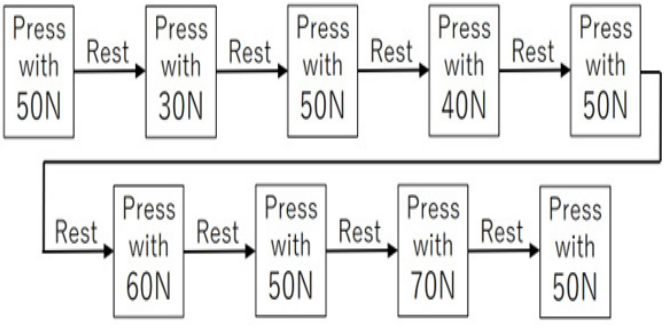

Figure 4. Force variation across training sessions in experiment 2
This cycle was repeated with 7 s of pressure and 15 s of rest. Practice pressures of 30N–70N were applied in the above order, with participants receiving feedback from the force gauge values during pressure application

Of the 42 participants in Experiment 1, 20 (11 men and nine women, 26.0±2.4 years old) participated in Experiment 2, which was conducted 1 month later.

Analysis of Measurement Results

The analysis interval was defined as the period between the maximum rate of increase or decrease in the measured

pressure in each trial, and the elapsed time was defined as the pressure contact time (Figure 5). The force magnitude for each participant was the maximum value recorded by the force recorder during the analysis interval. Trials A and B in Experiment 1 were defined as T_a and T_b, respectively, and their force magnitudes and pressure contact time were analyzed using the Wilcoxon signed-rank test. Each trial from the first to eighth "test" in Experiment 2 was defined as T_1, T^2, ... T_8, respectively. Since the T_a in Experiment 1 and the "test" in Experiment 2 were performed under the same conditions using FC, the T_a was defined as T0. A Friedman test was performed on the force magnitude and compression time from T_0 to T_8, followed by multiple comparisons using the Bonferroni method. For the "per-target-value test" in Experiment 2, the absolute difference between the target value and force magnitude was determined as the error from the target value. The Kruskal–Wallis test was used to analyze the error from the target value and the pressure contact time across the first to eighth measurements. Multiple comparisons were made between the target value of 50 N and other target values using the Steel method. The coefficients of variation for the errors between the first and eighth measurements and target values were also obtained. All statistical analyses were performed using EZR (Jichi Medical University, Tochigi, Japan), a graphical user interface for R (The R Foundation for Statistical Computing, Vienna, Austria). EZR is a modified version of R Commander, designed to add statistical functions frequently used in biostatistics.[20] The significance level for all the tests was set at 5%.

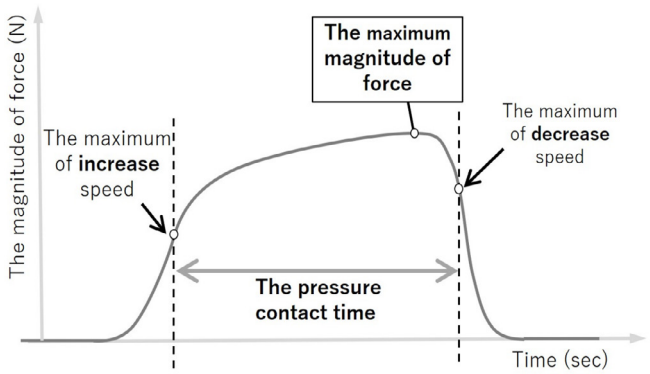

Figure 5. Definition of the maximum force magnitude and the pressure contact time

RESULTS

Experiment 1: The median and quartile ranges of the force magnitude and pressure contact time are presented in Table 1. No significant differences were observed in the force magnitude (p=0.301). The pressure contact time of Ta was significantly greater than that of Tb (p<0.001).

Table 1. Experiment 1

	Force magnitude (N)	Pressure contact time (s)
T_a	38.8 (28.5-47.8)	8.8 (6.8-11.9)
T_b	41.4 (28.9-53.5)	4.2 (2.7-6.4)
p-value	0.301	<0.001*

*: p<0.05

Experiment 2: Measurement of "test": The median and quartile ranges of the force magnitude and pressure contact time are presented in Table 2. The results of multiple comparisons for the force magnitude and pressure contact time are shown in Tables 3 and 4. The force magnitude at T0 was significantly lower than those at T1, T2, T4, and T5. For the pressure contact time, T0 was significantly longer than T1–T8, and T1 was significantly longer than T3, T4, T7, and T8 (p<0.05).

Table 2. "Test" for experiment 2

	Force magnitude (N)	Pressure contact time (s)
T_0	38.4 (27.4-48.0)	9.3 (6.7-14.1)
T_1	67.0 (58.9-73.2)	5.2 (3.9-6.6)
T_2	57.8 (54.7-63.4)	4.4 (3.1-6.2)
T_3	54.2 (51.0-59.0)	3.7 (2.8-4.8)
T_4	55.8 (53.9-60.8)	3.5 (2.5-4.9)
T_5	61.5 (53.1-71.9)	3.7 (2.9-5.7)
T_6	54.6 (50.0-59.5)	3.6 (2.7-5.5)
T_7	51.2 (44.3-57.7)	3.7 (2.5-4.5)
T_8	53.7 (42.4-61.5)	3.5 (2.7-4.0)

Table 3. Multiple comparisons of the force magnitude

	T_0	T_1	T_2	T_3	T_4	T_5	T_6	T_7
T_1	<0.001*							
T_2	0.008*	>0.99						
T_3	0.071	>0.99	>0.99					
T_4	0.017*	0.34	>0.99	>0.99				
T_5	0.024*	>0.99	>0.99	>0.99	>0.99			
T_6	0.263	0.23	>0.99	>0.99	>0.99	>0.99		
T_7	0.959	0.175	0.84	>0.99	>0.99	>0.99	>0.99	
T_8	>0.99	0.263	>0.99	>0.99	>0.99	0.773	>0.99	>0.99

*:p<0.05

Table 4. Multiple comparisons of the pressure contact time

	T_0	T_1	T_2	T_3	T_4	T_5	T_6	T_7
T_1	<0.001*							
T_2	<0.001*	>0.99						
T_3	<0.001*	0.003*	0.114					
T_4	<0.001*	0.037*	0.098	>0.99				
T_5	<0.001*	0.127	>0.99	>0.99	>0.99			
T_6	<0.001*	0.061	0.207	>0.99	>0.99	>0.99		
T_7	<0.001*	0.008*	>0.99	>0.99	>0.99	>0.99	>0.99	
T_8	<0.001*	0.023*	0.575	>0.99	>0.99	0.935	>0.99	>0.99

*:p<0.05

Experiment 2: Measurement of the "per-target-value test": The median and quartile ranges of the error from the target value and the results of multiple comparisons are shown in Table 5. The average error from the target value is shown in Figure 6, and the coefficient of variation is shown in Figure 7. The error from the target value was significantly larger when

Table 5. "Per-target-value test" for experiment 2

	Error from the target value (n)					Pressure contact time (s)				
Target value	**30 N**	**40 N**	**50 N**	**60 N**	**70 N**	**30 N**	**40 N**	**50 N**	**60 N**	**70 N**
Session 1	13.6 (8.6-21.5)	16.2 (11.9-21.4)	14.4 (8.9-22.9)	10.3 (7.1-18.0)	10.7 (5.5-21.2)	2.8 (1.9-3.3)	3.2 (1.8-3.6)	3.1 (2.2-4.4)	3.0 (2.5-3.7)	3.2 (2.1-3.8)
Session 2	9.1 (3.8-17.5)	6.3 (3.3-16.2)	8.8 (3.5-15.7)	3.8 (1.5-11.6)	10.7 (4.5-14.6)	2.5 (1.8-3.0)	2.5 (2.1-3.7)	3.5 (2.9-5.1)	3.0 (2.3-3.8)	3.1 (2.54.0)
Session 3	11.1 (8.8-15.3)	9.5 (6.1-13.8)	10.2 (7.2-14.4)	10.2 (4.6-17.8)	12.9 (6.9-18.8)	2.1 (1.8-2.9)	2.5 (2.1-2.9)	2.6 (2.2-3.1)	2.6 (2.3-3.8)	2.8 (2.3-3.8)
Session 4	9.0 (3.6-12.9)	7.5 (5.2-11.8)	9.1 (4.3-14.0)	6.3 (4.7-12.3)	9.3 (3.2-14.3)	2.3 (1.8-2.8)	2.5 (2.1-3.2)	2.4 (2.0-3.6)	2.7 (1.9-3.9)	3.0 (2.1-4.3)
Session 5	9.0 (4.4-15.5)	8.8 (4.7-16.8)	6.3 (3.2-14.4)	5.4 (3.6-15.5)	10.9 (2.8-23.6)	1.9 (1.3-2.5)	2.3 (1.7-2.7)	3.1 (2.1-4.0)	2.6 (1.8-3.2)	2.5 (2.1-3.2)
Session 6	11.3 (4.4-14.1)	6.9 (4.2-14.0)	8.8 (3.5-13.1)	10.6 (4.2-14.7)	16.0 (7.9-27.2)	2.0 (1.2-2.4)	1.9 (1.5-2.7)	2.4 (1.9-3.7)	2.4 (1.8-3.2)	2.6 (2.1-3.2)
Session 7	7.4 (5.0-12.4)	9.3 (4.7-13.1)	6.6 (5.1-8.7)	9.1 (3.6-16.6)	10.8 (6.7-17.9)	1.7 (1.1-2.3)	2.1 (1.6-2.7)	2.1 (1.5-3.1)	2.4 (1.6-4.0)	2.3 (1.9-3.4)
Session 8	10.8 (5.4-16.1)	7.9 (4.6-15.4)	6.9 (5.5-12.4)	11.8 (3.9-18.3)	13.2 (8.3-23.5)	1.6 (1.1-2.2)	1.9 1.5-2.4)	2.0 (1.7-2.9)	2.1 (1.5-2.9)	2.2 (1.5-3.6)
Session 1~8	10.1 (5.4-16.1)	9.2 (4.6-16.3)	8.8 (4.5-14.8)	8.5 (3.9-15.7)	11.6 (5.5-18.8)	2.0 (1.4-2.8)	2.3 (1.7-2.9)	2.8 (1.9-3.6)	2.6 (1.9-3.5)	2.7 (2.13.8)
p-value (compared with 50n)	0.462	0.975	-	> 0.99	0.032*	> 0.001*	0.010*	-	0.797	0.952

*:p<0.05

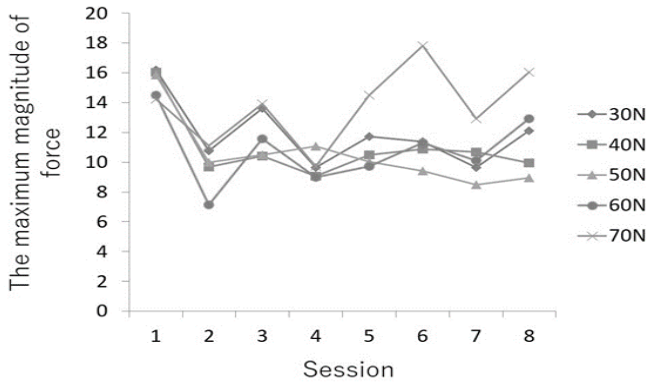

Figure 6. The average error from the target force during repeated measurements

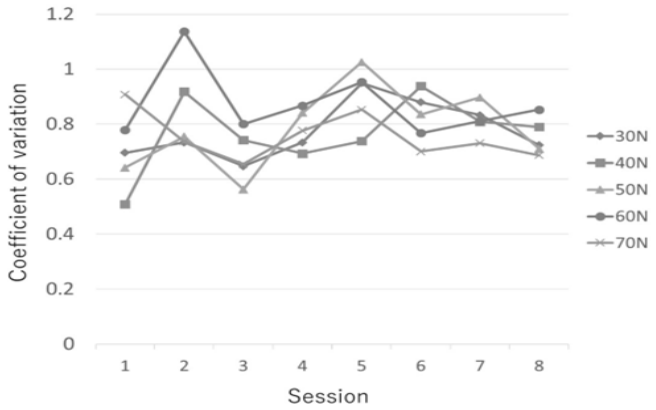

Figure 7. Coefficient of variation in the measurement "per-target-value test."

the designated force magnitude was 70 N compared to when it was 50 N. For designated forces between 30 and 60 n, the median force magnitude applied by the participants was approximately 15 N higher than the average target value in the measurement after the first training session. However, these values decreased significantly in the second measurement, and from the third measurement onward, they tended to remain approximately 10 N higher than the target value. At the target value of 70 N, the difference from the target value after the fifth time point was larger than that at ≤60 N. The coefficient of variation was>1 in the second trial, setting the target value at 60 N and the fifth at 50 N. The pressure contact time tended to increase with increasing force and decrease with an increasing number of training sessions.

DISCUSSION

In Experiment 1, visual information, such as differences in hand sensation during pressure contact with and without FC or the spread of FC, had little influence on the pressure contact force, as no significant difference in force magnitude was found between T_a and T_b. Conversely, the significantly longer pressure contact time for T_a compared to T_b was presumed to indicate that the participants judged the situation by observing how the FC spread. In Experiment 2, based on the research by Fontijn-Tekamp et al.,[21] which reported that the occlusal force on the mandibular first molar of a female wearing complete dentures was approximately 40-50 N, the target value for the pressure contact force magnitude was set at 50 N.

In this experimental environment, when the FD was pressure-welded to the model with the FC while checking the force gauge value, it spread uniformly at 50 N and showed no significant difference compared with 55 N and 60 N. Therefore, the target values set in this study were considered similar to those used in actual clinical practice. Yamaji et al.[22] reported that participants were instructed to intermittently exert grip strength at 50%, 75%, and 100% of their maximal voluntary grip contraction (MVC) and that the exerted force capacity at the 50% MVC requirement showed minimal decrease after 6 min. The test and training setup in this study lasted <5 min; therefore, it was assumed that the participants' muscle fatigue had little effect on the results. Each participant had clinical experience in denture adjustments. However, T0 was significantly smaller than T_1-T_8, and the median value did not reach the target value of 50 N. The median value exceeded 50 N from T_1 to T_8 after training with the target value. These results indicate that an appropriate amount of pressure cannot

be acquired only by guidance lacking objective indicators, such as chairside advice or feedback based on actual clinical experience. Shea and Kohl[23] reported that, in an experiment where the right hand exerted 175 N of force (the criterion task), the group that practiced an insertion task, in which different force magnitudes were exerted at intervals, performed better on a test 24 h later than those who practiced only the criterion task. The results of this study were the same, suggesting that the participants reaffirmed the magnitude of the criterion while self-mapping for other force magnitudes with 50 N as the criterion. However, relatively large forces >60 N varied widely among the participants, even though they had some degree of control over them. Suzuki et al.[24] reported that the average pinch force for pinching an object with the thumb and index finger of one hand was 7.9±1.1 kg for the dominant hand and 7.5±1.1 kg for the non-dominant hand. The denture pressure application movement performed in this study had more factors related to finger pinch force than grip strength, and it is possible that some participants had difficulty controlling fine forces in the region ≥60 N. The pressure contact time decreased with each training session, and the intended force magnitude was reached in a shorter time. This suggests that the process of thinking while performing a motion can be shortened by accurately understanding force magnitude. As time greatly affects the efficiency of medical treatment, it is important to continue research with the aim of applying this device in educational settings for teaching appropriate force application. The benefits of using this system in education are two-fold: reduced patient burden and shorter skill acquisition time. It prevents patients from experiencing excessive force and pain, and also reduces chair time. Previously, preclinical training provided students only with knowledge about fitting examinations; however, by incorporating this system into the curriculum, students will be able to acquire the skills necessary to properly perform fitting examinations before entering clinical settings. In Japan, a device (iWakka) was developed in 2012 that displays grasping force and target values on a monitor in real time. The device has been introduced into the medical field as an evaluation and training tool for patients who have difficulty controlling their grasping force, such as older people and post-stroke hemiplegics.[25-28] The device used in this study was suggested to quantitatively guide technical elements that are difficult to visualize using conventional methods and has the potential to be developed into a device similar to iWakka.

Limitations

This study demonstrated that learned force control abilities, measured as objective numerical indicators of the force applied by practitioners to patients during experiential learning, were maintained for approximately 4 weeks. However, no comparison was made with a control group that did not undergo training, and factors potentially affecting force control ability, such as individual grip strength, fatigue, and sex differences, were not investigated. Previous studies have reported that cardio pulmonary resuscitation skills decline within 2-3 months after training.[29] Since force control is considered important in dental treatment, future research should address these issues by examining different conditions and survey periods with reference to prior studies, while also verifying the applicability to other treatments.

CONCLUSION

The influence of the fitting material as visual information was considered smaller than that of the numerical data, visualizing the force magnitude in objectively assessing the force applied by the operator during the fitting examination of a mandibular complete denture. In addition, this study suggested that a hands-on learning method in which the force magnitude is numerically displayed can promote early skill retention, and that a modified mannequin equipped with a force gauge can serve as an effective tool for teaching force control during procedures.

ETHICAL DECLARATIONS

Ethics Committee Approval

The study was carried out with the approval of the Ethics Committee of Niigata University Medical and Dental Hospital (Date: 05.08.2015, Decision No: 2015-5055).

Informed Consent

Written informed consent was obtained from all individual participants prior to their inclusion in the study. Participants were fully informed about the study's aims, procedures, potential risks and benefits, and their rights-including the right to withdraw at any time without consequence. All participants voluntarily signed a written informed consent form.

Peer Review Process

This manuscript was subject to external peer review.

Conflict of Interest

The authors declare no conflicts of interest related to this study.

Financial Disclosure

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Author Contributions

Concept: M.H.[1], T.S.; Design: M.H.[1], T.S., F.N., S.T.; Control: M.H.[1], T.S., N.F.; Data Collection and/or Processing: M.H.[1], T.S., F.N., S.T.; Analysis and/or Interpretation: M.H.[1], T.S., M.H.[2], N.F.; Literature Review: M.H.[1], T.S., M.H.[2], N.F.; Article Writing: M.H.[1], T.S., N.F.

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Comparative evaluation of the performance of ai-powered chatbots in answering basic sciences questions of the dentistry specialization examination*

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ABSTRACT

Aims: The aim of this study is to evaluate the correctness rate/probability of answers provided by AI-powered chatbots (Gemini Advanced 2.5 Pro, ChatGPT-4 omni, ChatGPT-5 and DeepSeek v3) to single-answer, multiple-choice basic sciences questions from the Dentistry Specialization Examination (DUS) administered between 2012 and 2025.

Methods: A total of 539 multiple-choice questions from the basic sciences section of the DUS from 2012 to 2025 were used. Each question was presented directly in a new session. The rates of correct/incorrect answers were calculated based on the subject of the question, the year it was asked, and the chatbot model. The rate and probability of incorrect answers were evaluated using chi-square and binary logistic regression analyses.

Results: The rate of incorrect answers was highest in 2012, with a significant decrease observed in subsequent years ($p<0.05$). Among the subjects, Anatomy had the highest rate of incorrect answers, while Pathology had the lowest ($p<0.05$). When comparing chatbot models, Gemini Advanced 2.5 Pro was found to have a statistically significantly lower error rate than ChatGPT-4 omni and DeepSeek v3 ($p<0.05$). In the regression analysis, the risk of providing an incorrect answer was statistically significantly higher for the years 2012 and 2018; for the fields of Anatomy, Physiology and Microbiology; and for the ChatGPT-4 omni and DeepSeek v3 models, compared to their respective reference groups ($p<0.05$).

Conclusion: AI-powered chatbots provided more accurate answers to more recent questions. In the subject-based performance analysis, the rate of incorrect answers for Anatomy questions was high. In the chatbot comparison, Gemini Advanced 2.5 Pro produced more accurate answers than DeepSeek v3. While AI-powered chatbots can be a potential supplementary tool in the preparation process for DUS, their accuracy and competence across different subjects are limited.

Keywords: Basic sciences, chatbot, dentistry specialization examination

*This study was presented orally at the 'Genç Endodontistler Konuşuyor Sempozyumu'.

INTRODUCTION

Artificial intelligence (AI) is at the forefront of many aspects of our lives, transforming how we analyze information and improving decision-making processes through problem-solving, reasoning, and learning.[1] Through the creation and analysis of intelligent software and hardware, known as "intelligent agents," AI is integrating into many areas of daily life and performing various tasks.[2] In recent years, it has been rapidly adopted to enhance the speed and quality of the healthcare sector, becoming increasingly important.[3] In dentistry, it is used in numerous areas such as diagnosing caries and predicting its progression risk,[4] interpreting panoramic radiographs,[5] treatment planning,[6] detecting painful pathologies like pulpitis, trauma, cysts and tumors[7] and determining root canal system anatomy and working length.[8]

Alongside AI, subfields like machine learning (ML) have made significant advancements in recent years, leading to groundbreaking developments.[3] Machine learning is a subset of AI that improves its performance based on data provided to a general algorithm derived from experience, rather than defining rules in traditional approaches. One of the primary examples of AI systems evolved from ML is chatbots.[2] The term "chatbot" is a combination of the words "chat" and "robot" and it emerged initially as a text-based, AI-powered conversational system designed to simulate human language.[9] These systems can imitate human language, provide personalized responses and engage in meaningful conversations.[10] Over time, chatbots have been developed using various deep learning models and different training techniques.[11] They are used in many different fields. They have the potential to accelerate and enhance scientific research, thereby advancing technological progress and their problem-solving skills can be evaluated by

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testing them in various domains and against real professional examinations.[12]

For dentists in Turkiye to pursue specialization, they must succeed in the Dentistry Specialization Examination (DUS), organized by the Ministry of Health and the ÖSYM (Assessment, Selection, and Placement Center). The DUS, held annually since 2012, is a comprehensive exam that measures knowledge with a total of 120 multiple-choice questions, covering 8 specialty areas and basic medical sciences, with 40 questions in basic sciences and 80 in clinical sciences. The success ranking of candidates is determined by the results of this exam, which then dictates their placement into specialty programs. Furthermore, until 2024, the basic and clinical sciences sections had equal weighting coefficients, contributing equally to the total exam score.[13] Therefore, candidates' proficiency in basic sciences is as crucial as their knowledge in clinical sciences. The basic sciences exam consists of 6 questions each from Anatomy, Physiology, Biochemistry and Microbiology, and 4 questions each from Histology-Embryology, Pathology, Pharmacology and Medical Biology-Genetics.

The Basic Sciences section of the Dental Specialty Examination (DUS) was selected as the focus of this study based on both methodological and educational considerations. This section is composed of standardized, knowledge-based questions that emphasize theoretical understanding and factual recall, rather than clinical decision-making or procedural skills. Such characteristics render the Basic Sciences section particularly appropriate for assessing the information-processing and reasoning capacities of AI-based chatbot models.

Furthermore, the scope and longitudinal integration of basic medical sciences within undergraduate dental education are generally more limited when compared with medical curricula. Consequently, dental graduates may experience difficulties in consolidating and applying foundational medical knowledge in high-level theoretical examinations. Within this framework, AI-driven chatbot systems may function as readily accessible supportive learning tools, facilitating reinforcement and clarification of fundamental concepts in basic sciences.

Additionally, questions in the Basic Sciences section are less susceptible to clinical heterogeneity or examiner-related subjectivity, enabling a more objective and reproducible evaluation of chatbot performance across multiple disciplines and examination years. Accordingly, assessing AI performance in this domain establishes a baseline for interpreting the educational utility of AI systems in dental training and exam preparation, prior to extending analyses to clinically oriented or case-based assessments.

In recent years, various companies have designed and introduced different chatbots.[10] ChatGPT (OpenAI Global, San Francisco, CA, USA) is a chatbot based on the language model developed by OpenAI and has been trained for conversation using a technique called reinforced learning from human feedback.[14] OpenAI launched ChatGPT-4 omni on May 13, 2024, as a multimodal chatbot. Subsequently, it introduced GPT-5 on August 7, 2025, describing it as "our best AI system ever," representing a significant leap in intelligence compared to its predecessors. The company claims this model offers state-of-the-art performance in mathematics, coding, writing, and healthcare, presenting it as versatile and reliable.[15]

In 2023, Gemini (Google, Mountain View, California, USA) was introduced as Google's largest and most capable AI system.[16] It has three versions: Gemini Nano, Gemini Pro and Gemini Ultra, with Ultra being the most powerful in terms of problem-solving.[17] DeepSeek-V1 was developed by a Chinese research group in late 2023, primarily aiming to enhance its language modeling capabilities using publicly available open-source data. On the other hand, DeepSeek-V3 was claimed to be successful enough to compete with ChatGPT-4 omni shortly after its launch in January 2025 and quickly gained worldwide popularity.[18]

Interest in the performance of these AI-powered chatbots in the context of medical and dental examinations is steadily increasing.[19-22] These chatbots could facilitate the preparation process for specialization candidates when used for practice in the DUS basic sciences section. Thus, this study aims to evaluate whether AI-powered chatbots (Gemini Advanced 2.5 Pro, ChatGPT-4 omni, ChatGPT-5.0, DeepSeek v3) can correctly answer the basic sciences questions (Anatomy, Histology-Embryology, Physiology, Biochemistry, Microbiology, Pathology, Pharmacology and Medical Biology-Genetics) from the DUS administered between 2012 and 2025. By comparing the accuracy rates of the answers given by different chatbot models, the study examines whether the chatbots' knowledge level is consistent with the exam standards according to the years the exams were held and the subjects covered.

METHODS

Since the study involved no human or animal subjects, clinical interventions, or identifiable patient data, ethics committee approval was not required. This study included 539 multiple-choice questions from the Basic Sciences section of the DUS conducted between 2012 and 2025 (held once a year between 2015-2022; and as spring and autumn sessions between 2012-2014 and from 2023 onwards). The questions covered the following topics: anatomy, histology-embryology, physiology, biochemistry, microbiology, pathology, pharmacology and medical biology-genetics. the questions used were obtained from the publicly accessible website of ÖSYM and were analyzed solely for academic research purposes and were not reproduced in any way. Since ÖSYM began publishing only 10% of the DUS questions from 2022 onwards, the question counts from those years were evaluated collectively. Canceled questions (1) and questions with visual content (4) were excluded from the study.

Each question was posed to Gemini Advanced 2.5 Pro, ChatGPT-4 omni, ChatGPT-5 and DeepSeek v3 chatbots by a single operator simultaneously on September 1, 2025, with each model having only one attempt per question. Before the questions were asked, all chatbots were given the following prompt: "I will present you with a series of multiple-choice questions, each with 5 options and a single correct answer. You do not need to provide any explanation. Just tell me which option is correct." The answers were categorized and recorded as either correct or incorrect.

Statistical Analysis

The data were analyzed using IBM SPSS v23. The significance of the relationship between independent categorical variables (year, subject and chatbot model) and the accuracy of the answers (Correct/Incorrect) was examined using the Pearson

Chi-Square test. In cases where the Chi-Square test was significant, a post-hoc analysis was conducted to identify the differences between the incorrect answer rates. Column proportions were compared pairwise using the z-test and the Bonferroni correction was applied for multiple comparisons. The effect of independent variables on the dependent variable was examined using binary logistic regression analysis. Descriptive statistics for categorical variables were presented as frequency and percentage. The significance level was set at $p<0.05$.

RESULTS

Table 1 presents the rates and analysis of correct and incorrect responses, categorized by year, subject and chatbot.

Table 1. Presentation of correct/incorrect answer ratios and analysis by year, subject, and chatbot

	Answer	
	Correct n (%)	Incorrect n (%)
Year		
2012	293 (91.6)	27[a] (8.4)
2013	298 (94.3)	18[ab] (5.7)
2014	309 (96.6)	11[ab] (3.4)
2015	155 (96.9)	5[b] (3.1)
2016	153 (95.6)	7[ab] (4.4)
2017	159 (99.4)	1[b] (0.6)
2018	140 (92.1)	12[ab] (7.9)
2019	154 (98.7)	2[b] (1.3)
2020	155 (96.9)	5[b] (3.1)
2021	148 (94.9)	8[ab] (5.1)
2022 and onwards	95 (99)	1[b] (1)
Subject		
Anatomy	284 (91)	28[a] (9)
Histology-embryology	209 (96.8)	7[ab] (3.2)
Physiology	308 (95.1)	16[ab] (4.9)
Biochemistry	312 (97.5)	8[ab] (2.5)
Microbiology	315 (94.9)	17[ab] (5.1)
Pathology	209 (98.6)	3[b] (1.4)
Pharmacology	212 (96.4)	8[ab] (3.6)
Medical biology-genetics	210 (95.5)	10[ab] (4.5)
Chatbot		
Gemini advanced 2.5 pro	526 (97.6)	13[a] (2.4)
ChatGPT-4 omni	511 (94.8)	28[ab] (5.2)
ChatGPT-5	515 (95.5)	24[ab] (4.5)
DeepSeek v3	507 (94.1)	32[b] (5.9)

Pearson Chi-Square. a-b: Rows with the same letter are not significantly different from each othe

Results Regarding the Distribution of Answers by Year

A statistically significant relationship was found between the year and the distribution of correct and incorrect answers ($\chi^2=31.097$, $p=0.001$). The incorrect answer rates ranged from 0.6% to 8.4 % across the years. The post-hoc analysis revealed that the year 2012, with the highest incorrect answer rate (8.4%), had a statistically significantly higher error rate than the years with the lowest rates-2015, 2017, 2019, 2020 and 2022 ($p<0.05$). The error rates for the other years (2013, 2014, 2018 and 2021) did not show a statistically significant difference from these two extreme groups ($p>0.05$).

Results Regarding the Distribution of Answers by Subject

A statistically significant relationship was detected between the subjects examined and the accuracy of the answers ($\chi^2=23.834$, $p=0.002$). The incorrect answer rates for subjects were found to range from 1.4% to 9.0 %. According to the pairwise comparison results, a statistically significant difference was found between Anatomy, which had the highest incorrect answer rate (9.0 %), and Pathology, which had the lowest (1.4%) ($p<0.05$). The incorrect answer rates of the other six subjects (Histology-Embryology, Physiology, Biochemistry, Microbiology, Pharmacology and Medical Biology-Genetics) did not show a statistically significant difference from these two extremes ($p>0.05$).

Results Regarding the Distribution of Answers by Chatbot Model

A statistically significant relationship was observed between the chatbot models used and the accuracy of the answers ($\chi^2=8.668$, $p=0.034$). The incorrect answer rates of the models varied from 2.4% to 5.9%. Post-hoc analysis showed that Gemini Advanced 2.5 Pro, with the lowest incorrect answer rate (2.4%), performed statistically significantly better than both ChatGPT-4 omni (5.2%) and DeepSeek v3 (5.9%) ($p<0.05$). The performance of the ChatGPT-5 model (4.5%) did not show a significant difference from the other models ($p>0.05$). No statistically significant difference was found between the performances of the ChatGPT-4 omni and DeepSeek v3 models ($p>0.05$).

Results Regarding the Regression Model

The effect of the independent variables on the responses was examined using univariate and multiple binary logistic regression (Table 2).

The effect of independent variables on the answers was examined using univariate and multiple binary logistic regression (Table 2). In both the univariate and multiple models, with the years 2022 and after as the reference, the odds of chatbots giving an incorrect answer to questions from the 2012 exam were 8.754/9.946 times higher and for the 2018 exam, the odds were 8.143/9.787 times higher ($p<0.05$). With Pathology as the reference subject, the odds of chatbots giving an incorrect answer to questions in Anatomy were 6.869/7.428 times higher ($p<0.05$). This ratio was 3.619/3.789 times higher for Physiology and 3.76/3.968 times higher for Microbiology ($p<0.05$). With Gemini Advanced 2.5 Pro as the reference, the odds of ChatGPT-4 omni giving an incorrect answer were 2.217/2.261 times higher and for DeepSeek v3, the odds were 2.554/2.618 times higher ($p<0.05$).

DISCUSSION

The purpose of this study is to examine the knowledge proficiency of AI-powered chatbots in the DUS basic sciences field and their performance in assessment and evaluation processes. In this context, DUS basic sciences questions were posed to four different AI-powered chatbots; the responses received were analyzed in terms of accuracy/error rates and

Table 2. Investigation of the effect of independent variables on answers using logistic regression analysis

	Answer		Univariate		Multiple	
	Correct n (%)	Incorrect n (%)	OR (95 % CI)	p	OR (95 % CI)	p
Year						
2012	293 (91.6)	27 (8.4)	8.754 (1.174-65.29)	0.034	9.946 (1.327-74.568)	0.025
2013	298 (94.3)	18 (5.7)	5.738 (0.756-43.555)	0.091	6.455 (0.846-49.249)	0.072
2014	309 (96.6)	11 (3.4)	3.382 (0.431-26.534)	0.246	3.765 (0.477-29.683)	0.208
2015	155 (96.9)	5 (3.1)	3.065 (0.353-26.631)	0.310	3.407 (0.39-29.779)	0.268
2016	153 (95.6)	7 (4.4)	4.346 (0.526-35.881)	0.172	4.857 (0.585-40.337)	0.143
2017	159 (99.4)	1 (0.6)	0.597 (0.037-9.664)	0.717	0.657 (0.04-10.682)	0.768
2018	140 (92.1)	12 (7.9)	8.143 (1.041-63.669)	0.046	9.787 (1.243-77.052)	0.030
2019	154 (98.7)	2 (1.3)	1.234 (0.11-13.792)	0.865	1.401 (0.125-15.747)	0.785
2020	155 (96.9)	5 (3.1)	3.065 (0.353-26.631)	0.310	3.407 (0.39-29.779)	0.268
2021	148 (94.9)	8 (5.1)	5.135 (0.632-41.715)	0.126	5.923 (0.725-48.412)	0.097
2022 and onwards	95 (99)	1 (1)	**Reference**			
Subject						
Anatomy	209 (98.6)	3 (1.4)	**Reference**			
Histology-embryology	284 (91)	28 (9)	6.869 (2.061-22.896)	0.002	7.428 (2.213-24.925)	0.001
Physiology	209 (96.8)	7 (3.2)	2.333 (0.595-9.146)	0.224	2.39 (0.606-9.426)	0.213
Biochemistry	308 (95.1)	16 (4.9)	3.619 (1.041-12.576)	0.043	3.789 (1.084-13.244)	0.037
Microbiology	312 (97.5)	8 (2.5)	1.786 (0.468-6.811)	0.396	1.805 (0.471-6.916)	0.389
Pathology	315 (94.9)	17 (5.1)	3.76 (1.088-12.989)	0.036	3.968 (1.142-13.788)	0.030
Pharmacology	212 (96.4)	8 (3.6)	2.629 (0.688-10.046)	0.158	2.74 (0.712-10.536)	0.142
Medical biology-genetics	210 (95.5)	10 (4.5)	3.317 (0.9-12.226)	0.072	3.473 (0.936-12.883)	0.063
Chatbot						
Gemini advanced 2.5 Pro	526 (97.6)	13 (2.4)	**Reference**			
ChatGPT-4 omni	511 (94.8)	28 (5.2)	2.217 (1.136-4.328)	0.020	2.261 (1.15-4.449)	0.018
ChatGPT-5	515 (95.5)	24 (4.5)	1.886 (0.95-3.744)	0.070	1.913 (0.957-3.827)	0.067
DeepSeek v3	507 (94.1)	32 (5.9)	2.554 (1.325-4.922)	0.005	2.618 (1.348-5.086)	0.004

OR (95% CI): Odds Ratio (95% Confidence Interval), CI: Confidence interval

risk, according to the years the questions were asked, the subjects and the chatbot models. The data obtained were compared to evaluate the potential of AI as a learning and assessment tool in dental education.

A study found that ChatGPT-3.5 answered pedodontics questions with 54.3% accuracy.[23] In another study, DUS prosthodontics questions were posed to ChatGPT-3.5 and Gemini, and the answers were evaluated using a Likert scale. Both models were reported to have limited capabilities, but it was also emphasized that these were the most basic versions of the models.[24] In our study, which used the Gemini Ultra model and GPT-5, we achieved accuracy rates above 90 %, demonstrating a remarkable increase in the performance of newer models.

In our study, the accuracy rates of AI chatbots were examined using DUS basic sciences questions from 2012 to 2025. The data revealed that chatbots generally showed a high level of accuracy, although this varied by year. However, the relatively lower success rates in some years (e.g., 2012 at 91.6% and 2018 at 92.1%) may stem from differences in the scope or difficulty level of the questions. The notably higher error rates observed in the 2012 examination can be attributed to the historical context of the DUS; 2012 marked the inaugural year of the DUS in Turkiye. Consequently, the standardization of question structure and item difficulty during this pilot period may have differed from the more refined datasets of subsequent years, posing challenges for AI pattern recognition. Similarly, the performance drop in 2018 aligns with ÖSYM's periodic updates to the examination framework, aimed at increasing the discriminative power of the test by introducing more complex clinical scenarios or changing the distribution of topic-specific questions. These structural shifts in the exam likely presented 'out-of-distribution' data points that the tested LLMs struggled to interpret accurately. One study showed that chatbots achieved 100% accuracy for DUS questions in some years but observed a performance drop in 2018 and 2019.[25] Similarly, in our study, the rate of incorrect answers by chatbots increased in 2012 and 2018. This disparity might be due to the difficulty of the question content and variations in the number of questions.

When the performance of chatbots in the basic sciences of dentistry was evaluated by subject, accuracy rates were seen to range from 91% to 98.6%. The highest accuracy was in Pathology (98.6%), and the lowest was in Anatomy (91%). This result suggests that chatbots are more successful in areas based on conceptual knowledge and recognition (e.g., Pathology, Biochemistry and Histology) but are relatively limited in fields requiring visual memory and three-dimensional relational skills (e.g., Anatomy). The observed variation in error rates across basic science disciplines may be attributed to inherent differences in content structure and cognitive demands. Anatomy questions typically require strong spatial reasoning, three-dimensional visualization, and precise interpretation of anatomical relationships,

which may pose challenges for AI-based chatbot models that primarily rely on text-based knowledge representations. In contrast, Pathology questions are more frequently concept-driven and terminology-oriented, often emphasizing pattern recognition, definitions, and disease mechanisms, which may be more compatible with large language model architectures trained on extensive biomedical text corpora. High success in pathology and biochemistry can be explained by the models' proficiency with textual and theoretical information, whereas the lower accuracy in anatomy questions may be due to the models' limitations in processing visuospatial data and the fact that anatomical knowledge is often learned through images rather than text.

The performance comparison of chatbots showed that all four models achieved high accuracy rates on DUS basic sciences questions. The highest accuracy was recorded for Gemini Advanced 2.5 Pro at 97.6%, followed by ChatGPT-5 (95.5%), ChatGPT-4 omni (94.8%), and DeepSeek v3 (94.1%). Furthermore, no significant difference was found between Gemini Advanced 2.5 Pro, ChatGPT-5 and ChatGPT-4 omni. This indicates that the three models exhibit a similarly reliable level of performance on basic sciences questions. In a study similar to ours,[25] ChatGPT-5 achieved 93 % accuracy and Gemini 2.5 Pro achieved 96.9 % on DUS oral and maxillofacial surgery questions. Another study reported that Gemini Advanced showed the best performance among seven different chatbots in answering endodontics questions.[26] However, a 2025 study that had ChatGPT-4 omni and Gemini Advanced solve DUS questions from 2020 and 2021 reported that ChatGPT-4 omni performed better than Gemini Advanced.[20] This variance could be due to the fact that only two years of DUS questions were used or due to a different version of Gemini.

A study evaluating the accuracy of answers from ChatGPT-4 omni, ChatGPT-4, Gemini 1.5 Flash, Gemini 1.5 Pro, Gemini 2.0 Flash, Copilot, Deepseek-V3 and Qwen2.5-Max on DUS endodontics questions showed that DeepSeek v3 had a lower accuracy performance than ChatGPT-4 omni.[21] In a study where UK medical board exam questions were posed to seven chatbots (ChatGPT-3.5, ChatGPT 4, Bard, Perplexity, Claude, Bing and Claude Instant), the accuracy varied significantly, with ChatGPT-4 generally performing the best. The authors suggested ChatGPT-4 as a secondary learning resource for medical students.[19] However, another recent study indicated that DeepSeek-R1 could be a valuable aid in diagnosing oral diseases, outperforming ChatGPT-4o in this regard.[27] This shows that different versions of DeepSeek may have varying performance in different fields.

In a study evaluating the responses of chatbots [ChatGPT-3.5, ChatGPT-4 omni, Google Bard (now Gemini), Microsoft Copilot] to oral radiology questions from the DUS between 2012-2021, ChatGPT-4 omni (86.1%) was reported to have a higher accuracy rate than Gemini (61.8%).[22] In our study, across all basic sciences, ChatGPT-4 omni achieved 94.8% and Gemini Advanced 2.5 Pro achieved 97.6% accuracy. The accuracy rate for both chatbots was significantly higher. This might be because oral radiology is more specific to dentistry, whereas basic medical sciences receive intensive attention from all medical-related fields, and chatbots may be more extensively trained on this broader subject matter.

Overall, the fact that all models demonstrated over 90% accuracy indicates that AI-powered chatbots have a very high potential for understanding the level of knowledge in dentistry. The findings suggest that AI-powered models can be a potential supplementary tool for DUS preparation. In particular, Gemini Advanced 2.5 Pro, ChatGPT-5 and ChatGPT-4 omni, with their high accuracy rates, can support students in topic review, concept clarification and question-solving practice. However, it should be noted that these systems cannot always correctly interpret the context of exam questions and can make conceptual errors in some subjects. Therefore, information obtained from these models should not be used alone without human supervision and caution should be exercised, especially in areas with high terminological complexity.

Limitations

One of the strengths of this study is its statistical analysis of chatbot performance on a yearly and subject-specific basis. This approach allowed for the measurement of the AI systems' knowledge level not just by overall accuracy but also according to different variables. Nevertheless, certain limitations of our study should be considered. Only text-based questions were evaluated, excluding those with images, and the models were not asked to provide justifications for their answers. This limited a detailed analysis of the models' reasoning processes and the causes of incorrect inferences. Additionally, the non-standardized number of questions across years and subjects directly impacted the analysis results. In this study, only 10% of the exam questions from 2022 onwards were published, which led to the evaluation of these exams together and prevented a separate analysis of them. Furthermore, asking the questions in Turkish instead of English may have contributed to the models providing incorrect answers.

CONCLUSION

In summary, AI-powered chatbots, particularly Gemini Advanced, ChatGPT-5 and ChatGPT-4 omni, hold the potential to be useful tools in basic sciences education for dentistry, especially in preparing for the DUS. However, to enhance the effectiveness of these systems, it is necessary to improve both the currency of their training data and their capabilities to include clinical and visual components. With such advancements, it is believed that AI models have the potential to evolve from merely assessing exam performance to becoming reliable educational assistants that support the learning process. Furthermore, asking correct and well-structured questions is vital for users to obtain reliable and accurate answers from these chatbots.

ETHICAL DECLARATIONS

Ethics Committee Approval

Since the study involved no human or animal subjects, clinical interventions, or identifiable patient data, ethics committee approval was not required.

Informed Consent

Since the study was conducted without the participation of any living being, no written consent form was obtained.

Peer Review Process

This manuscript was subject to external peer review.

Conflict of Interest

The authors declare no conflicts of interest related to this study.

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Author Contributions

Author Contributions Concept: M.Y.Ö.; Design: T.M., A.A., M.Y.Ö.; Control: M.Y.Ö.; Data Collection and/or Processing: T.M., A.A.; Analysis and/or Interpretation: M.Y.Ö.; Literature Review: T.M.; Article Writing: T.M.; Critical Review: M.Y.Ö.

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Original Article

Alkasite restorative materials in dentistry: a bibliometric analysis from 2020 to 2025

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ABSTRACT

Aims: The aim of this study was to evaluate the global scientific output related to alkasite restorative materials in dentistry through a bibliometric analysis covering the period from 2020 to 2025.

Methods: A comprehensive literature search was conducted using the Scopus database. English-language original research articles (including in vitro and clinical studies) published between 2020 and 2025 and indexed under the subject area of dentistry were included. A total of 70 articles met the inclusion criteria. Bibliometric indicators such as publication trends, citation performance, contributing countries, journals, and keyword networks were analyzed using Microsoft Excel and VOSviewer software.

Results: The results demonstrated a steady increase in alkasite-related publications, with the highest research output and citation counts observed in 2022. India, Turkiye, and Egypt were the leading countries in terms of publication volume, whereas China, Croatia, and Thailand showed high citation impact despite limited output. Journal analysis revealed that general dental journals published the majority of studies, while specialized journals in adhesive and restorative dentistry achieved higher citation impact. Keyword analysis indicated a predominant focus on in vitro evaluations, particularly microleakage and shear bond strength.

Conclusion: This study provides the first bibliometric overview of alkasite research in dentistry, highlighting evolving research trends, geographical distribution, and scientific impact, and offers a valuable reference for future investigations.

Keywords: Alkasite, Cention N, bibliometric analysis, restorative dentistry, dental materials

INTRODUCTION

Advances in restorative dentistry have been largely driven by the growing demand for materials that combine esthetics with improved functional performance. This demand has encouraged extensive research efforts aimed at enhancing the optical and mechanical properties of restorative materials used in daily clinical practice.[1] Consequently, several innovative restorative materials have been developed to overcome the limitations of conventional systems and to better fulfill the requirements of contemporary esthetic dentistry.[2] Resin-based composite materials currently represent the most frequently utilized restorative option, as they offer a favorable balance between strength, durability, and esthetic appearance.[3] While these materials are fundamentally composed of a resin matrix reinforced with filler particles, ongoing modifications in their composition have resulted in multiple generations of composites with enhanced clinical properties.[4] Within this context, Cention N (Ivoclar Vivadent, USA) has recently been introduced as a tooth-colored restorative material and classified under the category of "alkasites," which are considered a distinct subgroup within resin-based composite materials.[5]

Bibliometric analyses have been increasingly utilized in the field of dentistry as a systematic approach to evaluate research productivity, scientific impact, and evolving trends within specific disciplines. These studies enable the quantitative assessment of published literature by analyzing publication output, citation patterns, authorship networks, and collaborative structures, thereby providing an objective overview of the scientific landscape.[6-8] In recent years, bibliometric methods have been widely applied across various dental specialties, including restorative dentistry, orthodontics, periodontology, and oral and maxillofacial surgery, reflecting their growing importance in evidence-based research evaluation.[9-12] By identifying influential authors, institutions, journals, and countries, bibliometric studies contribute to a deeper understanding of research dynamics and help guide future investigations in dentistry.

In recent years, there has been an increase in the number of studies in the literature on the physical, mechanical performance, and clinical performance of alkasite restorative materials.[13-16] However, a comprehensive bibliometric analysis covering recent years and focusing specifically on "alkasite"

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materials is yet to be found in the literature. The aim of this study is to analyze the global scientific output related to alkasite materials between 2020 and 2025 using the Scopus database and to document the evolution of this new group of materials in the dental literature.

METHODS

This study was conducted in accordance with the fundamental principles of the Declaration of Helsinki and was based exclusively on the analysis of bibliometric data derived from articles indexed in a single electronic database. As the research did not involve experiments on human participants, animals, or biological specimens, formal approval from an ethics committee was not required. Scopus is a widely recognized and bibliographic database known for its high-quality content. It was chosen as the source for extracting publications related to alkasite restorative materials in dentistry.

A comprehensive literature search was conducted using the Scopus online database to identify English-language studies focusing on alkasite materials in the field of restorative dentistry. In the Scopus database, the subject area was limited to "Dentistry" and the publication language to "English," and a search was performed using the keyword "Alkasite." Articles published within the last five years (2020–2025) and classified as original research articles (including in vitro and clinical studies) were included. Conference papers, letters to the editor, data set reports, and other non-relevant publication types were excluded from the analysis. After applying all inclusion criteria and keyword restrictions, a total of 70 articles were retrieved. No records unrelated to the topic were identified, and thus all 70 articles were included in the final analysis. Following detailed screening, key bibliometric parameters for each study such as title, journal name, first author, country of origin, year of publication, citation counts, and keywords were recorded. To minimize potential variations in citation data resulting from continuous database updates, data collection was independently completed by a single researcher within a single day (18 December 2025).

Data Analysis and Visualization

The analysis and visualization of the 70 included publications and their associated datasets were carried out using multiple tools and software packages, namely MS Excel (version 16.0) and VOSviewer (version 1.6.20). VOSviewer was employed to generate Graph Modeling Language (GML) files from the original data. In VOSviewer maps, node size reflects the number of publications, while the thickness of the links between nodes represents the strength of the connections. Bibliometric indicators related to citations, documents, sources, authors, institutions, and countries were examined. In addition, publication and citation trends, authorship patterns, bibliographic coupling (at the levels of journals, countries, and authors), keyword co-occurrence, author cocitation networks, and thematic evolution were visualized using these tools.

RESULTS

Research on Alkasites

Figure 1 presents the annual publication and citation trends related to alkasite restorative materials in restorative dentistry from 2020 to 2025. A total of 70 articles were analyzed, showing an overall increase in research output over time. The highest number of publications was recorded in 2022 (n=18; 25.7%), followed by 2024 (n=17). In terms of citation impact, articles published in 2022 received the highest number of citations (177), while more recent publications, particularly those from 2024 and 2025, showed lower citation counts due to their recency.

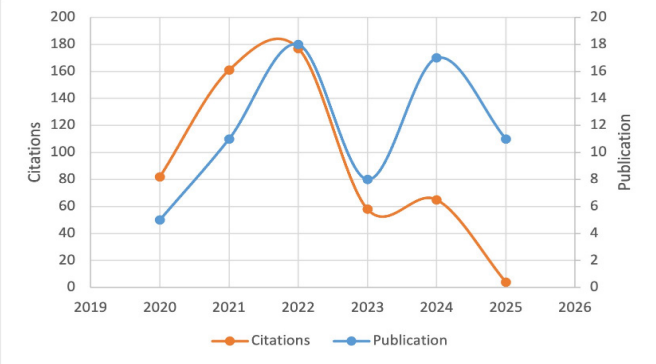

Figure 1. Annual publication and citation trends

Publishing and Citation Structure of Alkasite Research

Table 1 presents the annual publication and citation profile of alkasite related studies published between 2020 and 2025. It also shows the total publications (TP), total citations (TC), number of cited publications (NCP), citation/publication (C/P), and citation/cited publication (C/CP).

Table 1. Citation structure of alkasites research between 2020 and 2025

PY	TP	TC	NCP	C/P	C/CP
2020	5	82	5	16	16
2021	11	161	11	14	32
2022	18	177	18	9	35
2023	8	58	6	7	11
2024	17	65	13	3	13
2025	11	4	1	0	0

PY: Publishing year, TP: Total publications, TC: Total citations, NCP: Number of cited publications, C/P: The average citations per publication, C/CP: Average citations per cited publication

A total of 70 publications were identified, receiving 547 citations overall. The highest publication output was observed in 2022 (TP=18), which also accounted for the greatest number of citations (TC=177).

Publications published in 2021 and 2022 showed the strongest citation impact, with average citations per cited publication (C/CP) of 32 and 35, respectively. In contrast, articles published in 2025 demonstrated lower citation impact, likely due to their recent publication. Overall, the results indicate an increasing research interest in alkasite materials, with citation patterns influenced by publication age.

Leading Countries in Alkasite Research

Table 2 summarizes the leading countries contributing to alkasite research based on publication output and citation performance (Citation Index (CI)) =Citation/Publication). India ranked first in terms of total publications (TP=22), receiving 118 citations (CI= 5.36), followed by Turkiye (TP=15; TC=76; CI=5.07) and Egypt (TP=11; TC=49; CI=4.45).

Table 2. Leading countries in alkasites research between 2020 and 2025

Country	TP	TC	CI
India	22	118	5.36
Turkey	15	76	5.07
Egypt	11	49	4.45
Brazil	3	3	1.00
Croatia	3	82	27.33
Saudi Arabia	3	47	15.67
Indonesia	2	13	6.50
Iraq	2	3	1.50
Thailand	2	40	20.00
United Kingdom	2	33	16.50
China	1	45	45.00
Malaysia	1	20	20.00
Mexico	1	10	10.00
Singapore	1	0	0.00
Switzerland	1	8	8.00

TP: Total publications, TC: Total citations, CI: Confidence interval

Despite lower publication volumes, some countries demonstrated high citation impact. China showed the highest citation impact (CI=45.00) based on a single publication, while Croatia and Thailand, Malaysia also exhibited strong citation performance (CI=27.33 and 20.00, respectively). These findings indicate that citation impact is not necessarily proportional to publication output and varies considerably across countries.

Leading Journals.

Table 3 presents the leading journals contributing to alkasite related research based on publication output and citation performance. A total of 42 journals were initially identified; however, based on citation impact (CI=TC/TP), the top 20 journals were selected for inclusion in the analysis. Among these sources, BMC Oral Health ranked first in terms of publication volume (TP=7), followed by the Journal of Contemporary Dental Practice (TP=4) and the European Archives of Paediatric Dentistry (TP=3).

In terms of citation impact, several journals demonstrated notably high citation performance despite limited publication counts. The Journal of Adhesive Dentistry showed the highest citation impact (CI=45.0) based on a single publication, followed by the Saudi Dental Journal (CI=36.0) and the Journal of Dentistry (CI=35.0). Journals such as Acta Stomatologica Croatica and the Journal of Esthetic and Restorative Dentistry also exhibited strong citation impact with CI values.

With respect to publishers, "Springer Nature" emerged as the most prominent publisher among the leading journals. Overall, the results indicate that while publication output is concentrated in a limited number of journals, citation impact varies considerably and is not directly proportional to the number of publications.

Keyword Co-Occurrence Analysis

Figure 2 illustrates the keyword co-occurrence network based on author-provided keywords in alkasite-related research. The analysis was conducted using VOSviewer, with the minimum number of occurrences of a keyword set to one. The visualization reveals the overall structure of research themes and the relationships among keywords within the field. Closely related keywords were grouped into clusters, reflecting major thematic areas of alkasite research. The size of each node represents the frequency of keyword occurrence, while the thickness of the links indicates the strength of co-occurrence between keywords. Overall, the

Table 3. Leading journals and publishers in alkasites research between 2020 and 2025

Journal	TP	TC	CI	Publisher	CS
Journal of Adhesive Dentistry	1	45	45	Quintessenz Verlags-GmbH	4.30
Saudi Dental Journal	1	36	36	Springer Nature	3.20
Journal of Dentistry	1	35	35	Elsevier Ltd	7.50
British Dental Journal	1	32	32	Springer Nature	2.70
Acta Stomatologica Croatica	2	47	23.5	University of Zagreb	3.30
Clinical Oral Investigations	1	22	22	Springer Nature	6.30
Journal of Esthetic and Restorative Dentistry	2	33	16.5	John Wiley & Sons	7.70
Biomaterial Investigations in Dentistry	1	15	15	Medical Journals Sweden AB	5.10
Journal of Applied Oral Science	2	27	13.5	Faculdade de Odontologia de Bauru da Universidade de Sao Paulo	3.90
Pesquisa Brasileira em Odontopediatria e Clinica Integrada	1	13	13	Association of Support to Oral Health Research (APESB)	1.00
European archives of paediatric dentistry: official journal of the European Academy of Paediatric Dentistry	3	31	10.3	Springer Nature	5.00
Journal of Conservative Dentistry	2	18	9	Wolters Kluwer Health	2.10
International Journal of Dentistry	1	9	9	John Wiley & Sons	4.40
Journal of Contemporary Dental Practice	4	35	8.7	Jaypee Brothers Medical Publishers (P) Ltd	1.90
Journal of Oral Science	1	7	7	Nihon University, School of Dentistry	4.20
Journal of Indian Society of Pedodontics and Preventive Dentistry	1	7	7	Wolters Kluwer Health	1.70
Journal of Stomatology	1	6	6	Termedia Publishing House Ltd.	0.60
BMC Oral Health	7	38	5.4	Springer Nature	3.90
Contemporary Clinical Dentistry	3	15	5	Wolters Kluwer Health	2.20
Ain Shams Dental Journal (Egypt)	1	5	5	Ain Shams University, Faculty of Dentistry	0.50

PY: Publishing year, TP: Total publications, TC: Total citations, NCP: Number of cited publications, C/P: The average citations per publication, C/CP: Average citations per cited publication

network highlights the diversity of research topics and the interconnected nature of keywords within the literature. As a result, all 201 identified keywords met the threshold and were included in the analysis. Among the most prominent keywords, alkasite demonstrated the highest connectivity, with 24 occurrences, 76 links indicating its central role within the research network. Cention-N also showed strong co-occurrence characteristics, with 11 occurrences, such as microleakage (9 occurrences), glass ionomer cement (6 occurrences) and shear bond strength (5 occurrences).

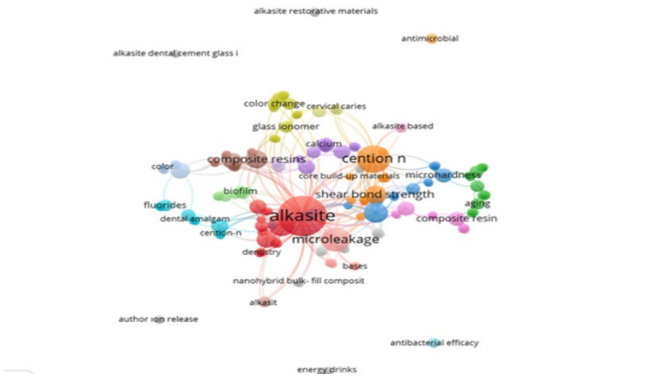

Figure 2. Keyword co-occurrence analysis

Bibliographic Coupling of Authors

Figure 3 illustrates the bibliographic coupling network of authors contributing to alkasite-related research. The analysis was performed using VOSviewer, with the minimum number of documents per author set to two. Under this criterion, 18 authors out of a total of 250 met the inclusion threshold and were incorporated into the network visualization.

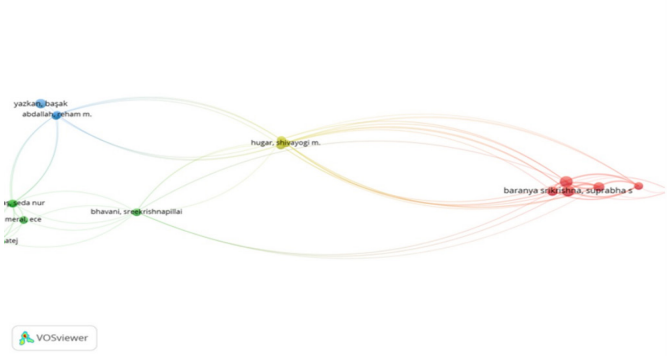

Figure 3. Bibliographic coupling of authors

The resulting map reveals patterns of shared references among authors, indicating similarities in research focus and intellectual background. Authors were grouped into distinct clusters based on the strength of their bibliographic coupling relationships. Cluster 1 exhibited the strongest coupling activity, with authors showing the highest numbers of links and total link strength, particularly Baranya and Rao (9 links; total link strength=130). Cluster 2 comprised authors with moderate coupling intensity, characterized by link counts ranging from 5 to 7 and total link strength values up to 32. In contrast, Clusters 3 and 4 demonstrated lower but notable coupling activity, with total link strength values varying between 2 and 56. Overall, the results indicate heterogeneous bibliographic coupling patterns among authors, reflecting varying degrees of shared reference structures within the field.

Citation Analysis of Sources

Figure 4 presents the citation network of sources based on alkasite-related publications. The analysis was conducted using VOSviewer, with the minimum number of citations per source set to two. Out of 43 identified sources, 16 met the threshold and were included in the visualization. The resulting network illustrates the citation relationships among the most influential sources in the field.

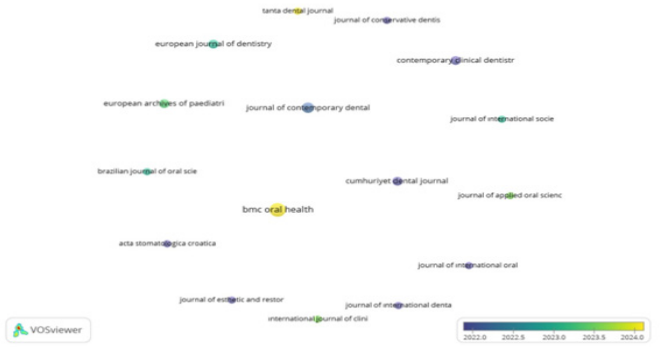

Figure 4. Citation analysis of sources

Co-Citation Analysis of Cited References

Figure 5 illustrates the co-citation network of cited references in alkasite-related research. The analysis was performed using VOSviewer, with the minimum number of citations per cited reference set to three. Of the 525 cited references identified, 23 met the threshold and were included in the analysis. The resulting visualization highlights the most frequently co-cited references and their interrelationships, reflecting the intellectual foundations of the field.

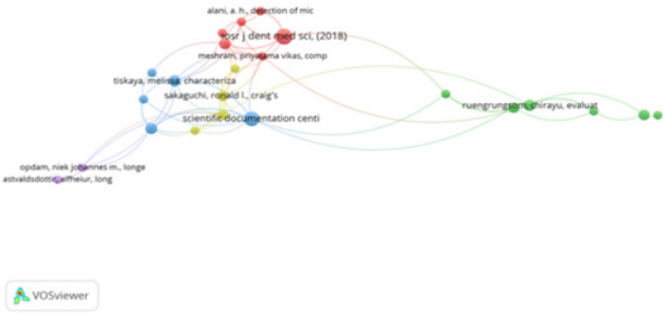

Figure 5. Co-citation analysis of cited references

DISCUSSION

To the best of the authors' knowledge, this study represents the first bibliometric analysis specifically focusing on alkasite restorative materials in dentistry. Although an increasing number of experimental and clinical studies have investigated the physical, mechanical, and clinical performance of alkasite restorative materials in recent years, the overall structure, growth patterns, and global distribution of scientific research in this field have not previously been systematically evaluated. By quantitatively analyzing publication trends, citation patterns, contributing countries, and leading journals, the present study provides a comprehensive overview of the evolution of alkasite related research and places this emerging material class within the broader context of contemporary dental materials science.

In previous bibliometric analyses conducted in the field of dentistry, a variety of software tools have been employed throughout the stages of data collection, screening, analysis, and visualization. For network analysis and visualization, VOSviewer has been widely used to map keyword co-occurrence, author collaboration, and citation networks.[17-20] More advanced network analyses and graph modeling have been performed using Gephi software, while Bibliometrix has been applied to examine publication trends and thematic evolution. In addition, basic tools such as Microsoft Excel and Microsoft Access have been utilized for the systematic organization of data and the execution of descriptive analyses and simple calculations.[21] In the present study, VOSviewer and Microsoft Excel programs were used.

In the present study, the analysis of global scientific output on alkasite restorative materials revealed that India, Turkiye, and Egypt were the top three contributing countries. This geographical distribution presents a distinct pattern compared to bibliometric analyses in technology-intensive fields such as digital dentistry or virtual reality, which are typically dominated by high-income countries.[22] The prominence of developing and emerging economies in alkasite research can be attributed to the specific clinical positioning of this material group. Alkasite restorative materials were introduced as cost-effective, bulk-fill alternatives to dental amalgam and expensive resin composites.[5] Therefore, it is unsurprising that research interest is concentrated in countries with high caries prevalence and a strong demand for affordable, time-saving restorative solutions.

India emerged as the most productive country (TP=22). This finding aligns with recent bibliometric trends in dentistry, where India has shown exponential growth in scientific output, driven by a vast number of dental institutions and a large pool of postgraduate students requiring thesis topics.[23] Similarly, Turkiye ranked second (TP=15), maintaining its status as a significant contributor to dental literature in the region. Previous bibliometric studies focusing on Turkiye's dental research output have linked this productivity to the increasing number of universities and the academic promotion criteria that encourage publication.[24] An interesting discrepancy was observed between publication volume and citation impact. While India and Turkiye led in the number of articles, China demonstrated the highest Citation Index (CI=45.00) despite having only a single publication. This suggests that while emerging economies are driving the quantity of research, high-impact studies may still originate from or be collaborative efforts with major research hubs that garner more immediate global attention.

The frequent occurrence of the keywords "microleakage" and "shear bond strength" in our keyword analysis indicates that researchers have primarily focused on the most critical clinical performance parameters of this novel restorative material. A review of the existing literature reveals that the microleakage values of Cention N are generally reported to be lower than those of glass ionomer cements which explains the central role of this keyword within the research network.[25,26] Similarly, studies evaluating bond strength have demonstrated that alkasite materials exhibit a dentin bonding potential that is competitive with other esthetic restorative materials, thereby supporting the prominent clustering of the term "bond strength" observed in our bibliometric analysis.[27,28]

The analysis of journals publishing alkasite-related research revealed a heterogeneous distribution in terms of publication volume and citation impact. "BMC Oral Health" stood out as the most productive journal thanks to its comprehensive range of publications. However, journals with a smaller number of publications, such as the "Journal of Adhesive Dentistry" (CI:45, CS: 4.30) and the "Journal of Dentistry" (CI:35, CS: 7.5), demonstrated substantially higher citation indices, suggesting that studies published in more specialized or higher-impact journals tend to achieve greater scientific visibility.

This finding is consistent with previous bibliometric studies in dentistry, which have shown that publication quantity does not necessarily correlate with citation performance.[21,29] Journals focusing on specific subfields, particularly adhesive and restorative dentistry, often attract a more targeted readership, resulting in higher citation rates despite lower publication volumes (Journal of Adhesive Dentistry CI:45, "Journal of Esthetic and Restorative Dentistry" TC:16.5). In contrast, general dental journals may serve as platforms for disseminating early or exploratory research on novel materials, such as alkasites.

From a publisher perspective, the dominance of major publishing houses, particularly "Springer Nature", highlights their role in shaping the dissemination of alkasite research. Journals published by major publishers in developed countries such as the USA, UK, and Switzerland (Elsevier, Wiley, Sage, Nature, Springer, etc.) have a much stronger international reach thanks to their proficiency in the English language and global distribution networks.[16] Overall, these findings suggest that both journal scope and publisher influence play a critical role in determining the academic impact of alkasite-related publications.

Limitations

Despite providing a comprehensive overview of alkasite related research, the present bibliometric analysis has several limitations that should be acknowledged. First, the study was restricted to publications indexed in a single database (Scopus), which, although widely recognized for its extensive coverage and data quality, may not capture all relevant studies indexed in other databases such as Web of Science or PubMed. Second, only English-language articles were included, potentially excluding valuable research published in other languages and introducing a degree of language bias. In addition, the analysis was limited to publications published between 2020 and 2025, which may not fully reflect earlier exploratory research or long-term citation trends associated with alkasite materials. Future studies could expand the time frame to include earlier years as the field matures, allowing for a more comprehensive evaluation of research evolution and citation dynamics. Finally, as citation counts are time-dependent, recently published articles may be underrepresented in terms of citation impact. Despite these limitations, the findings provide a reliable snapshot of current research trends and offer a solid foundation for future bibliometric investigations in this emerging field.

CONCLUSION

This bibliometric study presents the first comprehensive overview of alkasite research in dentistry between 2020 and 2025. The results demonstrate a growing research interest,

predominantly driven by developing and emerging countries, with notable differences between publication output and citation impact. Current studies predominantly focus on in vitro investigations evaluating clinically relevant outcomes such as microleakage and bond strength. Overall, these findings provide a useful reference for understanding research trends and guiding future investigations in restorative dentistry.

ETHICAL DECLARATIONS

Ethics Committee Approval

Since the study involved no human or animal subjects, clinical interventions, or identifiable patient data, ethics committee approval was not required.

Informed Consent

As this was a retrospective study, formal written informed consent was not required and was therefore not obtained.

Peer Review Process

This manuscript was subject to external peer review.

Conflict of Interest

The authors declare no conflicts of interest related to this study.

Financial Disclosure

The authors received no financial support for the conduct or publication of this research.

Author Contributions

The author is solely responsible for the conception, data collection, analysis, and writing of this manuscript

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Review

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Oral pigmentations

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ABSTRACT

Gingival pigmentation refers to discoloration in the gingival tissues caused by the accumulation of endogenous or exogenous pigments. Endogenous pigmentations are related to the accumulation of pigments such as melanin, hemoglobin, hemosiderin, and carotene in the oral and gingival tissues. This group includes pigmentations resulting from physiological melanin accumulation as well as those associated with systemic diseases such as Addison's disease, Peutz-Jeghers syndrome, and neurofibromatosis. Exogenous pigmentations may be caused by factors such as amalgam tattoos, heavy metal exposure, and drug-induced discolorations. In the present review vascular lesions such as varicose veins and hemangiomas, as well as melanin-based lesions such as nevi and melanoma, are also included in the current review. Additionally, the process of pregnancy and other hormonal changes on pigmentation has been addressed. Correctly and clearly identifying the underlying cause of gingival pigmentation, which is a clinical condition, is of great importance for diagnosis, prognosis, and treatment planning. In the present study, gingival and oral mucosal pigmentations were comprehensively classified and evaluated based on their etiologies, clinical appearances, and histological features. It is aimed to contribute to the clinical diagnosis and differential diagnosis processes of various oral and particularly gingival pigmentations encountered by clinicians.

Keywords: Oral pigmentations, gingiva, melanin, pigmentation, hyperpigmentation

INTRODUCTION

The oral cavity is completely covered with mucosa, and the epithelium of the tongue is of endodermal origin, while that of the lips, cheeks, gingiva, vestibulum oris, palate, and floor of the mouth is of ectodermal origin.[1] The epithelium of movable parts such as the cheeks, inner part of the lips, ventral surface of the tongue, floor of the mouth, and soft palate is non-keratinized, while the epithelium of the dorsal surface of the tongue, hard palate, and gingiva is keratinized.[2]

Pigmentation of the oral mucosa can be described as a condition resulting from the accumulation of one or more pigments in the mucosa and the resulting change in color tone.[3] Melanocytes, which produce melanin pigment, are located in the basal layer of the mucosa. The color of mucosal pigmentation varies from brown to blue or black, depending on the depth of the pigment in the mucosa.[4]

Oral pigmentation can be physiological or pathological, endogenous or exogenous in origin. Endogenous pigmentation is seen in physiological causes or diseases (such as Addison's disease) and syndromes [such as Peutz-Jeghers syndrome (PJS)].[4] Hemoglobin, hemosiderin, and bilirubin are other pigments that cause endogenous pigmentation. Exogenous pigmentation can be caused by foreign substances containing tattoo pigment, amalgam filling material, pencil lead, and colored foods (such as liqueur, red wine, coffee, and tea).[4]

Pigmentation may occur after trauma and chronic inflammation. Smoking and the use of certain systemic medications can also cause oral pigmentation.[4]

Endogenous Pigmentation

Oral pigmentation can be exogenous or endogenous. Endogenous pigmentation is related to the accumulation of pigments such as melanin, hemoglobin, hemosiderin, and carotene in oral and gingival tissues.[5] The physiological discoloration in gingival tissue, which is part of the oral mucous membrane, is primarily due to the activity of non-keratinocytic melanocyte cells that produce melanin, an endogenous pigment. Pigmented lesions caused by increased melanin accumulation can be brown, blue, gray, or black, depending on the amount of melanin in the tissues and its location.[6]

Physiological pigmentation: Physiological pigmentation develops within the first decade of life, but it may only attract the patient's attention later on.[7] It is most commonly seen in people living in Africa, Asia, and the Mediterranean basin. The color can range from light brown to black. The color tone may increase with age, smoking, hormonal effects, or the effects of certain medications. In the oral mucosa, it most commonly appears as a bilateral, well-defined, dark brown, band-like stripe on the gums, leaving the marginal gingiva empty. It may also be localized on the cheek mucosa, palatal

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mucosa, lips, and tongue.[8] Pigmentation in areas other than the gums typically has irregular borders.[7] The diagnosis of physiological pigmentation is clinical, and no treatment is required.[9]

Pigmentation Associated with Systemic Diseases and Conditions

Addison's disease: Addison's disease is the result of insufficient aldosterone and cortisol production due to damage to the adrenal cortex.[10,11] Various conditions such as tuberculosis and neoplasms can cause Addison's disease, but the most common cause is autoimmune adrenalitis.[12] Addison's disease can affect all individuals regardless of gender and age. In response to insufficient corticosteroid levels, the pituitary gland synthesizes excessive adrenocorticotropic hormone (ACTH). An increase in ACTH leads to an increase in α-melanocyte-stimulating hormone, and these two hormones promote melanogenesis and mucocutaneous pigmentation.[10,13] Oral pigmentation appears earlier than skin bronzing.[10,14] Oral pigmentation associated with Addison's disease often manifests as blue-black linear or patchy discolorations on the buccal and palatal mucosa, particularly on the lips, tongue, and gums.[15] Due to the increased need for corticosteroids in stressful situations, it may be necessary to temporarily increase the dosage of medication prior to long-term medical or dental treatment.[13,14,16]

Peutz-Jeghers syndrome (PJS): It is a genetic disorder characterized by gastrointestinal polyps with a high probability of developing into rare malignancies.[15,17,18] Although it is more likely to occur at an early age, it can occur at any age. Women and men are affected equally. The characteristic pigmentation of the lips and perioral skin, resembling numerous dark freckles, is one of the most readily recognizable and apparent symptoms of PJS and typically appears during childhood or adolescence.[13,14,19] Oral and perioral pigmentation persists throughout life and does not require treatment. However, if the patient chooses cosmetic intervention, laser therapy may be applied.[20]

Albright syndrome: Albright syndrome is a syndrome characterized by milky coffee spots on the skin, early puberty, hyperthyroidism, pituitary adenoma, and hormonal abnormalities such as Cushing syndrome, along with polycystic fibrous dysplasia.[21] Hyperthyroidism may develop due to lesions in the thyroid gland, which can result in acromegaly. Oral pigmentation begins in the first months after birth and manifests itself as localized macules on the lips.[15,22]

Von Recklinghausen's neurofibromatosis: Neurofibromatosis is an autosomal dominant, multisystem disease that affects approximately 1 in 3,500 people.[23] The clinical manifestations of neurofibromatosis type 1 include neurofibromas, café-au-lait spots, skin freckles, skeletal abnormalities, Lisch nodules, and optic gliomas.[24,25] Oral neurofibromas are most commonly found on the tongue and rarely on the gums, jawbone, or floor of the mouth.[26]

Bilirubin pigmentation: Bilirubin is a breakdown product of hemoglobin and is an important marker for assessing health problems such as neonatal jaundice, liver cirrhosis, and hepatitis.[27,28] The liver normally metabolizes bilirubin and excretes it from the body. In diseases such as cirrhosis, hepatitis, or pancreatic cancer, the liver cannot clear this waste product. Bilirubin tends to bind to elastin fibers, and this yellowish-orange bilirubin tends to accumulate intraorally along the soft palate and floor of the mouth near the lingual frenulum.[29]

Gender hormones and pregnancy: The effect of pregnancy on oral tissues has been proven in numerous clinical studies. During this process, due to varying hormonal changes, gum tissue becomes more sensitive to inflammation. It is known that the incidence of gingivitis in pregnant individuals is 25-100%, and the incidence of pyogenic granuloma is 10%.[30,31]

During pregnancy, estrogen and progesterone hormones also cause an increase in saliva levels. Estrogen has been reported to increase plaque on tooth surfaces, be effective against certain microorganisms, affect salivary peroxidases, influence collagen metabolism, and reduce gingival keratinization, thereby decreasing the epithelial barrier function.[32] Progesterone, on the other hand, has been found to increase the levels of prostaglandins (PGE1-PGE2) with proinflammatory effects in gingival pocket fluid, negatively affect the metabolism of periodontal ligament fibroblasts, thereby reducing glycosaminoglycan synthesis, increase vascular permeability, thereby increasing the likelihood of bleeding, and consequently cause a hyperemic appearance.[33]

Melanocytic nevi result from the proliferation of melanocytes that gather in specific areas and produce higher melanin density in that region. Although the molecular pathways are not well understood, it is believed that the new hormonal environment stimulates melanocytes to produce more melanin and potentially causes excessive pigmentation in the skin. Melasma, also known as the "pregnancy mask" or chloasma, refers to irregular hyperpigmented patches on the face.[34] Melasma tends to develop in the second half of pregnancy and is reported to affect 50-70% of pregnant women, disproportionately affecting those with darker skin tones.[35] Melasma can be classified as malar, limited to the cheeks, forehead, upper lip, nose, and chin; or mandibular, affecting the area above the mandibular ramus. The most commonly affected areas include the upper lip, forehead, chin, and eyebrows, followed by the nose and cheeks.[36]

Carotenemia: Carotenemia is a clinical condition characterized by yellow discoloration of the skin (xanthoderma) and elevated beta-carotene levels in the blood. In many patients, it results from prolonged and excessive consumption of carotene-rich foods such as carrots, squash, and sweet potatoes. It is a common finding in children. It is harmless, but jaundice in a single area may lead to misdiagnosis. Carotene may cause a golden yellow discoloration of the oral mucosa and skin. Treatment involves eliminating the causative foods.[37]

Kaposi's sarcoma: Kaposi sarcoma is a malignant neoplasm originating in the blood vessels. It used to be quite rare but has become more common recently due to the increase in diseases that cause immune deficiency, such as acquired ımmune deficiency syndrome (AIDS). Kaposi sarcoma is more likely to affect keratinized mucous membranes such as the palatal mucosa and gingiva within the oral cavity. The buccal mucosa and tongue are even less commonly affected areas.[38,39] Treatment options for Kaposi sarcoma include surgical excision, localized radiation therapy, intralesional vinblastine, cryotherapy, and single- or multi-agent chemotherapy.[40]

HIV-oral melanosis: AIDS is defined as a pathological condition originating from infection with the human immunodeficiency virus (HIV).[41] The virus attacks the immune system and often inhibits the activity of lymphocytes and macrophages. As a result, it causes progressive and ultimately irreversible immunosuppression, allowing for the development of fatal opportunistic infections, cancers, and rare autoimmune diseases. Oral lesions, which are commonly observed in HIV-infected individuals and are the first clinical indicators of the disease, are of diagnostic importance. Patients may experience salivary gland enlargement, sialadenitis, herpes labialis, buccal petechiae, and an increase in the incidence of caries.[42,43] Oral melanoma is a rare malignancy arising from the malignant transformation of melanocytes in the oral cavity.[44] Oral melanoma typically affects the maxillary gingiva, then the palate, and less commonly the mandibular gingiva.[45] The initial signs and symptoms are typically soft and pigmented upon palpation, initially asymptomatic, with irregular borders and a color spectrum ranging from dark brown to bluish black.[46]

Gingival Diseases

Inflammatory effects: Various periodontal diseases cause an increase in capillary permeability, which results in discoloration of the gingiva ranging from pink to red. Once the disease is under control, the gingiva returns to its original color.[47]

Necrotizing gingivitis: Necrotizing gingivitis is a rapidly progressing gum disease that usually starts at the tip of the interdental papillae and progresses toward the marginal gingiva, characterized by necrotic breakdown of gingival tissues and pseudomembranes.[48] It is more common in individuals with stress and weakened immune systems. It occurs equally in both women and men and in individuals between the ages of 18 and 26. It is more common in malnourished children, individuals with mental retardation (Down syndrome), and HIV-infected individuals.[49] A punctate appearance on the papillae is a pathognomonic finding. Other clinical findings include the presence of pseudomembranes covering the necrotic gingiva, which are yellow-gray in color, and foul breath. In advanced cases, systemic symptoms such as fever, fatigue, and lymphadenopathy may accompany the condition.[50,51]

Stomatitis lesions: The etiology of oral stomatitis lesions is not fully understood. It is thought that the cause of these lesions is multifactorial, involving a cell-mediated immunological reaction and genetic predisposition. Histopathological changes are observed before ulceration occurs. Lymphocytes (mononuclear cells) infiltrate the oral epithelium, edema develops, and keratinocytes (oral epithelial cells) undergo vacuolization and vasculitis. This process leads to localized swelling and subsequent ulceration of the epithelium.[52]

It affects approximately 5-25% of the general population. They are more common in childhood or adolescence.[53] The main oral symptoms of stomatitis are difficulty and pain in oral functions such as swallowing, speaking, and chewing.[54,55] Stomatitis is characterized by painful ulcers with a round or ovoid base covered with gray-white pseudomembranes and surrounded by an erythematous ring.[56] The edges of the ulcers are slightly raised. In ulcers, superficial vascular inflammation and erythrocyte extravasation in the outer layers of the lamina propria are observed, along with erythema around the lesion.[57] The most common sites of occurrence are the lip mucosa, oral floor, tongue, and buccal mucosa, and, less commonly, the soft palate.[58]

Tissue necrosis: Mucosal necrosis in the oral cavity may be a treatment-related effect. It is more commonly caused by trauma resulting from gavage procedures and/or the presence of foreign bodies (hair strands, food material). Necrosis and ulceration in the traumatized area may lead to suppurative or chronic active inflammation and granulation tissue formation. If necrosis extends to the surface and does not appear to be part of an ulcer, or if there is no loss of epithelial cells, the lesion is considered necrosis rather than erosion or ulceration. Infection caused by Actinomyces species can lead to deep infection and necrosis. Gingival inflammation and necrosis can also occur around the incisor teeth.[59]

Desquamative lesions: Desquamation refers to the peeling and shedding of the outermost layer of the skin. The factors contributing to the origin of oral lesions are quite diverse. These include dermatoses, endocrine causes, aging, metabolic disorders, irritant factors, unknown factors, and chronic infections.[60] Since many of the patients are postmenopausal women, hormonal imbalances (estrogen and testosterone deficiency, hypothyroidism) are also thought to play a role in the origin of desquamative lesions. Lesions typically present as erythema on the attached gingiva of the anterior teeth, accompanied by local or generalized desquamation/erosion. Treatment involves the use of local or systemic corticosteroids after eliminating local causes.[46]

Melanin-Containing Pigmentations

Nevus: Nevuses are congenital or acquired, benign, colored neoplasms of the skin or mucosa characterized by the presence of melanin-producing neuroectodermal cells.[61,62] They are more commonly seen on the skin than in the oral cavity. Based on their histopathological characteristics, they are classified as intramucosal, junctional, compound, and blue nevi. The most common type is intramucosal, while the least common is junctional. Their color may range from gray, brownish, or blue. Nevi are asymptomatic and are frequently found on the palate and lips.[63]

Intramucosal nevus: This is a type of nevus localized in the connective tissue. Intramucosal nevi are the most common type of nevus in the oral cavity, with a prevalence of 55%. Clinically, lesions are generally well-defined, round or oval, flat or slightly raised spots or plaques. The ideal treatment for intramucosal nevi is excisional biopsy with a 2 mm safety margin and histopathological examination to rule out the possibility of malignant transformation.[64]

Blue nevus: Blue nevus (MN) is a melanocytic lesion characterized by the proliferation of dermal dendritic melanocytes.[65] Nevi are rarely observed intraorally, with an incidence of approximately 0.1%.[66] Nearly 25% of nevi that appear in the mouth are blue nevi.[62,67] Blue nevus lesions are most commonly found on the palatal mucosa. Blue nevi are 20% more common in women than in men and are most frequently observed in the third and fourth decades of life.[68] Clinically, classic blue nevi are typically asymptomatic. Most lesions are solitary, with borders that are sometimes indistinct but often distinct and smooth in appearance.[69]

Junctional nevus: A junctional nevus is a benign proliferation of nevus cells. They are localized, symmetrical, uniform, and

typically less than 5 mm in diameter. Acquired nevi appear during childhood and reach their peak number during adolescence. Their number then decreases.[70] These lesions are characterized by the presence of melanocyte nests. In junctional nevi, the nests are seen in the dermoepidermal junction region along with single cells.[71]

Compound nevus: Oral compound nevi are one of the least common forms of oral mucosal nevi, accounting for only 5.9% to 16.5% of cases.[72] Compound nevi primarily affect the palate. Most compound nevi are raised lesions. However, one-third appear as macules, making it difficult to distinguish them from flat-colored lesions, including melanoma in situ.[72]

Melanoma: Melanoma occurs in the 4th to 7th decades of life.[73] Mucosal melanomas account for 1.3% to 6.8% of all melanomas.[73] Although the origin of oral melanoma is unknown, chronic inflammatory stimuli such as tobacco use and mechanical irritation have been proposed as potential risk factors.[74] Most oral melanomas arise from apparently normal mucosa, but nearly 30-37% begin with oral pigmentation that persists for several months or even years.[75,76] Clinically, oral melanoma is typically characterized by color variation, including black, brown, gray, purple, and red tones or depigmentation, and presents as well-defined brown or black macules/patches or nodules. The hard palate or alveolar gingiva are the most commonly affected areas.[74,75] The prognosis for individuals with oral melanoma is significantly worse than for those with cutaneous lesions, with a 5-year overall survival rate of 15%. The best way to improve prognosis is through early diagnosis of the disease.[77]

Oral melanotic macule: It is one of the most commonly observed colored lesions in the oral cavity. It is a benign lesion caused by increased melanin production, sometimes accompanied by an increase in the number of melanocytes.[3] Although lesions can occur at any age, the average age of onset is 42. Studies have indicated that the incidence rate is higher in women than in men.[78] Lip lesions tend to be diagnosed earlier than oral lesions, likely due to the fact that the vermilion border of the lips is more easily visualized by the patient compared to oral regions.[64] Clinically, a melanotic macule appears as a solitary, well-defined, uniformly colored, flat lesion ranging in color from skin tone to dark brown. Multiple lesions have also been reported.[79] The size of the lesions varies from 0.1 to 2.0 cm, with most being smaller than 1 cm.[3] The vermilion border of the lip is the most commonly affected area in all series studied and is most frequently seen on the lower lip.[80] Within the oral cavity, it is most commonly found on the gingiva, palate, and buccal mucosa. Lambertini et al.[81] recommended serial photography for melanotic macules <0.5 cm and biopsy for lesions >0.5 cm. If labial lesions exhibit irregular borders, irregular pigmentation, color differences, ulceration, or other suspicious characteristics, a biopsy is recommended regardless of size to rule out melanoma. Once a melanotic macule diagnosis is confirmed by biopsy, no further treatment is necessary.[82]

Melanoplakia: Oral pigmentation is associated with various external and internal causes, including medications, heavy metals, genetic factors, hormonal disorders (Addison's disease), syndromes (Albright syndrome, Peutz-Jegher syndrome), and post-inflammatory reactions, among various external and internal causes.[83] Physiological pigmentation is often symmetrical and appears on the gums, cheek mucosa, hard palate, lips, and tongue.[84]

Smoker's melanosis: Smoker's melanosis is an increase in melanin pigmentation seen in heavy smokers.[85] Smoker's melanosis is more common in women, and it is thought that estrogen may be a contributing factor. This pigmentation is thought to result from increased melanin production in response to exposure to heat or tobacco smoke.[86] The increased melanin is believed to have a protective effect against the harmful components of tobacco smoke.[87,88] The most common site of smoker's melanosis is the labial gingiva, but any oral region may be affected. Smokers' melanosis in pipe smokers is usually found on the buccal mucosa or lip commissure, along the red border.[86] Affected patients exhibit widespread dark brown pigmentation. Clinical history and tobacco staining on the teeth are helpful in diagnosis. Pigmentation regresses within 3 years after smoking cessation.[89]

Ephelid (freckle): Freckles are benign pigmented spots commonly seen in Caucasians and Asians.[71] Ephelides are usually small pigmented spots (typically 1-2 mm, but can also be larger), vary in color from red to light brown, and are seen in individuals with fair skin and/or red hair. They first appear at 2-3 years of age, increase during puberty, and often partially disappear with age.[71]

Lentigo: These are pigmentations that appear more frequently on the outer surfaces of the hands as a result of aging. They are more common in the 4th and 5th decades of life. Lesions are yellow, light brown, and oval or round in shape, ranging from 2 to 4 mm in size.[90] Solar lentigines are flat or slightly raised spots with clearly defined edges that develop on sun-exposed skin areas such as the face, backs of the hands, and forearms. Their color may vary from light brown to dark brown or black, depending on the individual's skin tone. In PJS, polyps develop throughout the gastrointestinal tract, and widespread lentigines appear on the mouth, lips, genital organs, palms, and soles of the feet.[91]

Pigmentation Due to Hemosiderin Deposition

This variation is a color change caused by trauma-related bleeding, which leads to hemosiderin accumulation and results in a bluish-black pigment change. The color varies from red to blue and purple, depending on the age of the lesion and the degree of degradation of the extravasated blood. The etiology may include thrombotic purpura, coagulation disorders associated with hemophilia, and hemochromatosis (iron repositioning and deposition).[92]

Vascular Pigmented Lesions

Vascular anomalies can affect the head and neck region but can also be seen in any intraoral location.[93] Most oral mucosal lesions are small and superficial, but they can also be large, voluminous tumors involving deep submucosal structures. Deep-seated lesions may appear normal in color, while superficial lesions may appear erythematous, blue, or purplish in color due to the mixture of arterial, capillary, and venous vascular channels.[93,94] Oral vascular lesions generally exhibit a compressible structure. Qualitatively, applying slight pressure causes color loss or tissue discoloration, indicating that the reddish color originates from blood within a lesion vessel.[93]

Varicose veins/varicocele: Varicocele represents a dilated and tortuous vein, presumed to result from age-related

deterioration of elastic support for the vein wall. It often presents as a solitary, reddish- to bluish-purple nodule. Although they can form on any oral mucosal surface, the lips, cheek mucosa, and ventral part of the tongue are more commonly affected areas.[95] The most common intraoral location is the ventral surface of the tongue, where varicose veins are found as numerous bluish-purple, irregular, soft elevations that whiten under pressure.[8] Varicose veins are essentially dilated veins, and blanching occurs when pressure is applied to these lesions. If a varicose vein contains a thrombus, it appears as a nodule that does not blanch with pressure. Treatment is not required if there is no aesthetic concern.[8]

Hemangioma: Hemangioma is a benign proliferation of endothelial cells lining the inner part of a blood vessel.[61] Hemangioma is a developmental anomaly characterized by its onset in infancy. The lesion regresses as the patient ages. The mouth and tongue are the most commonly affected areas.[96] The lesion may be flat or slightly raised and may vary in color from red to bluish-purple depending on the type of affected vessels (capillaries, veins, or arteries) and the location of the lesion in the tissues.[97,98] Treatment is required for head and neck hemangiomas when they bleed or exert pressure on vital organs. Hemangiomas of the larynx and tongue root, in particular, can cause breathing difficulties. Another reason for treatment may be the patient's aesthetic concerns. While medical and conservative methods are more important in the choice of treatment in children, surgical excision is often preferred in adults.[99]

Angiosarcoma: Angiosarcomas are malignant, poorly prognostic, and very rare sarcomas originating from vascular endothelial cells.[100] Angiosarcomas are often found in the skin or bone areas.[101] Men and women are affected equally. Angiosarcoma of the oral cavity is very rare; only a few case reports and case series are described in the literature.[102] In general, angiosarcoma is a highly aggressive tumor. Angiosarcoma of the oral cavity can be found in various tissues such as oral soft tissue, minor salivary glands, and bones.[102]

Telangiectasia: Telangiectasia is a rare autosomal recessive neurodegenerative disease that typically begins in early childhood and is characterized by persistent ataxia, telangiectasia of the sclera and skin, cutaneous findings (hypertrichosis, vitiligo, seborrheic dermatitis, acanthosis nigricans), and immunodeficiency.[103] Telangiectasias are irregularly shaped capillary areas in the oral cavity and nasal cavities that turn white when pressure is applied and immediately turn red again when pressure is released. Telangiectasias are generally located superficially in the mucosa and are prone to rupture with minimal trauma.[104]

EXOGENOUS PIGMENTATION

The best examples of pigmented substances directly deposited on the mucosa include amalgam pigmentation, graphite ink, and colored substances (chewing colored plants, liquids containing dye, etc.). Coloring agents, heavy metals (bismuth, mercury), amalgam tattoos, and drug-related factors can cause discoloration.[105]

Drug-Induced Discoloration

Drugs can cause discoloration of the skin and mucosa through various mechanisms.[106] In some cases, drug metabolites may accumulate in local areas. Although the mucosa may appear discolored clinically, such coloration cannot be interpreted as true pigmentation.[107] Drugs from the tetracycline group are representatives of this phenomenon.[71] However, there are several other drugs, including antimalarial drugs and drugs from different classes, that can cause discoloration. Some drugs, including chloroquine and chlorpromazine, have been found to physically bind to melanin.[108] Drug-induced discoloration may be irregular, localized to a single mucosal area, or multifocal, affecting multiple areas. Additionally, pigmentation may be macular in style and colored.[107] If discoloration is associated with the use of a specific drug known to cause pigmentation over a certain time period, then further intervention is generally not required. The discolored areas may resolve over time.[109]

Heavy Metal Pigmentations

Discoloration of the oral mucosa may occur due to elevated levels of heavy metals such as lead, bismuth, mercury, silver, arsenic, and gold in the blood (Table).[110] It may also occur in cases where diseases are treated with heavy metals. In the past, discoloration has been observed in cases where syphilis was treated with arsenic. Children can experience this condition due to lead-tainted water or medications that contain silver or mercury. Clinically, blue-black pigmentation along the gum line is quite typical.[110] Early diagnosis of pigmentation caused by heavy metals is important because it prevents the development of severe systemic toxic effects caused by metals.[8,111]

Table. Drugs and chemicals causing pigmentation in the oral cavity

Medicine/ chemical agent	Color	Localization
Arsenic	Brown	Tongue
Bismuth	Blue-grey/brown/black	Gingiva/tongue/buccal mucosa
Bromine	Brown	Tongue
Busulfan	Brown	Buccal mucosa
Chlorhexidine	White	Tongue
Chloroquine	Blue-brown	Hard palate/gingiva/lip
Doxorubicin	Dark-brown	Buccal mucosa/tongue
Gold	Purple	Gingiva
Heroin inhalation	Dark brown maculae	Tongue
Iron	Dark-brown	-
Lead	Blue-grey	Gums/tongue
Manganese	Dark-brown	-
Mercury	Blue-grey/blue-black	Gingival/buccal mucosa
Methyldopa	Dark	Tongue
Oral contraceptives	Dark	Mucosa
Phenylalanine	Brown	Tongue
Phenothiazine	Blue-brown	Mucosa
Quinidine	Blue-black	Palatinal mucosa
Kinin	Blue-black	-
Thallium	Blue-brown	Gingival
Tobacco	Misty gray/brown	-
Vanadium	Green	Tongue
Zidovudine	Dark	Soft palate/lip/tongue
Silver	Brown	Gums

Amalgam Tattooing

This condition is one of the most common causes of oral pigmentation. It occurs after improper dental amalgam treatments. These are localized, flat, blue-gray, painless lesions, several millimeters in diameter, most commonly occurring on the alveolar mucosa and attached gingiva, and may be single or multifocal.[110] Amalgam staining may occur during the placement or removal of a restoration when amalgam particles enter an abrasion, extraction site, or gingival pocket. Most amalgam tattoos are 6 mm or smaller in size.[112] Multiple lesions may be present. Evidence of radio-opaque metallic deposits may aid in the diagnosis of amalgam staining, but radiographic images are often absent often.[14,113] There is no indication for treatment of amalgam or foreign body staining. Extensive lesions in the aesthetic area can be effectively treated with surgical excision and gingival grafting.[114]

Colorant Agents

Black hairy tongue is caused by the proliferation of chromogenic bacteria in the filiform papillae of the tongue. Poor oral hygiene, excessive smoking, antibiotics, and overuse of antiseptic mouthwashes are often implicated.[115] Yellow-brown-black discoloration appears in the papilla region of the tongue.[116] Staining caused by certain fruits and foods colored with various additives is the most common type of non-permanent mucosal discoloration. In individuals with poor oral hygiene, heavy smokers, and some users of broad-spectrum antibiotics, pigmentation may occur in the filiform papillae of the tongue due to hyperkeratosis. Exogenous pigmentation may also occur due to the spread of old materials used in endodontic fillings into bones and tissues. This condition manifests as discoloration of the mucosa at the root tip of the affected tooth.[117]

DEPIGMENTED CONDITIONS

In diseases such as albinism and vitiligo, the skin appears white instead of its normal color due to a lack of pigment.[118]

Albinism

Albinism is a genetically transmitted group of autosomal recessive conditions characterized by a hereditary decrease or absence of melanin pigment production, which gives the skin, iris of the eyes, and hair their natural color.[119] Some degree of pigment deficiency is present in all types of albinism, but the amount of pigment varies from type to type. An individual with albinism may exhibit any of the following symptoms:[118]

- Lack of color in the hair, skin, or iris of the eye;
- Skin and hair that are lighter in color than normal;
- Patchy, uneven skin color;
- Strabismus (crossed eyes);
- Light sensitivity (photophobia);
- Rapid eye movements (nystagmus);
- Vision problems or functional blindness;
- Severe gingivitis;
- Oral mucosal ulceration; and
- Periodontal diseases.

In albinism, photophobia, severe gingivitis, oral mucosal ulcerations, and periodontal disease are prominent.[102] Patients with albinism should be informed that they should visit the dentist regularly to maintain oral hygiene, as they are prone to recurrent gingivitis.[121]

Vitiligo

This is a non-contagious acquired pigmentation disorder characterized by distinct white patches of varying shapes and sizes that increase in number and size over time.[122] Vitiligo has a global prevalence of 1%.[123] Although the origin of vitiligo is unknown, its pathogenesis has been attempted to be explained by various hypotheses, including the genetic hypothesis, autoimmune hypothesis, neural hypothesis, autocytotoxic hypothesis, new microenvironment-related hypothesis, and convergence theory.[122,124] Nagarajan et al.[122] According to their study, oral mucosal depigmentation is present in the lips (42%), palate (8%), cheek mucosa (5%), lip mucosa (5%), and gums (2%). Oral depigmentation may be the first sign of vitiligo, which can appear in inconspicuous areas. In such cases, dentists can diagnose vitiligo early.[125]

CONCLUSION

Oral pigmentations are common conditions characterized by discoloration of the oral mucosa and may arise from physiological, systemic, genetic, or environmental factors. In addition to endogenous sources (such as melanin and hemosiderin) and exogenous sources (such as amalgam, drugs, and heavy metals), depigmented conditions and vascular lesions also play a role in intraoral discolorations.Correct diagnosis is crucial for determining the need for treatment and for the early detection of systemic diseases. It is important for clinicians to distinguish the causes of pigmentation and to manage cases appropriately.

ETHICAL DECLARATIONS

Referee Evaluation Process

Externally peer-reviewed.

Conflict of Interest Statement

The authors have no conflicts of interest to declare.

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Author Contributions

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