

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

 Rina Nowka¹,  Mohamad Eid²,  Elizabeth McAlpin³,  Pi Ko⁴,  Marci Levine⁵,  Dianne Sefo⁶

¹Department of Dental Hygiene & Dental Assisting, NYU College of Dentistry, New York, USA

²Department of Electrical Engineering, New York University, Saadiyat Island, United Arab Emirates

³Educational Technology Research RIT, NYU IT, New York, USA

⁴Department of Electrical Engineering, New York University, Saadiyat Island, United Arab Emirates

⁵Department of Oral and Maxillofacial Surgery, NYU College of Dentistry, New York, USA

⁶Department of Dental Hygiene & Dental Assisting, Clinical Associate Professor, NYU College of Dentistry, New York, USA

Cite this article as: Nowka R, Eid M, McAlpin E, Ko P, Levine M, Sefo D. Comparing haptic enhanced virtual reality simulation to plastic manikin local anesthesia training: an in-situ evaluation. *J Dent Sci Educ.* 2026;4(1):1-10.

Received: 09.09.2025

Accepted: 03.12.2025

Published: 27.02.2026

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 ($R^2=0.26$). 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

*Corresponding Author: Elizabeth McAlpin, em341@nyu.edu



This work is licensed under a Creative Commons Attribution 4.0 International License.



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.

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

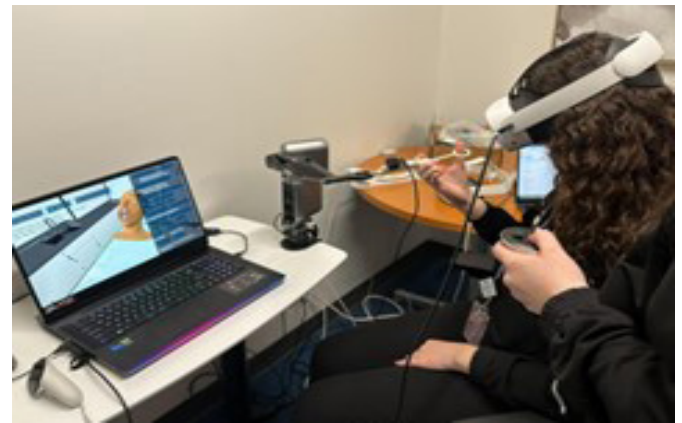


Figure 1. H-VRLA simulation



Figure 2. H-VRLA simulation (close up)

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 Haply™ 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 Haply™ 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-VRLA
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 anatomy	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).

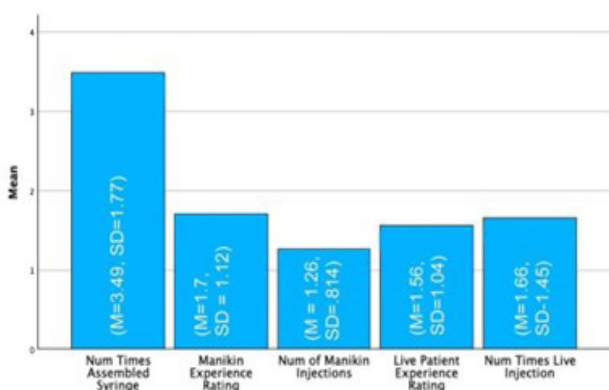


Figure 4. Overall mean prior experience

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).

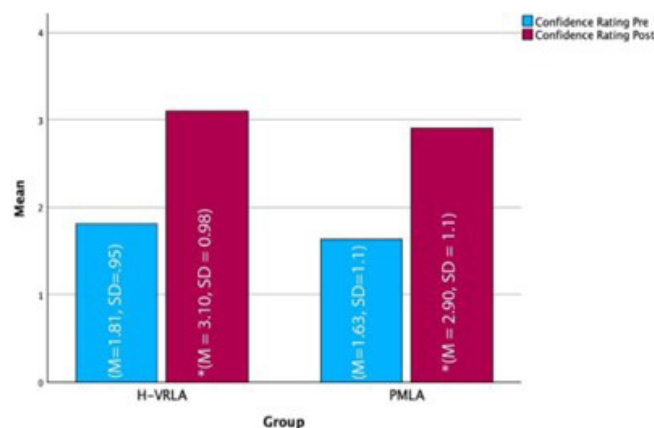


Figure 5. Pre and post simulation mean confidence rating for both groups

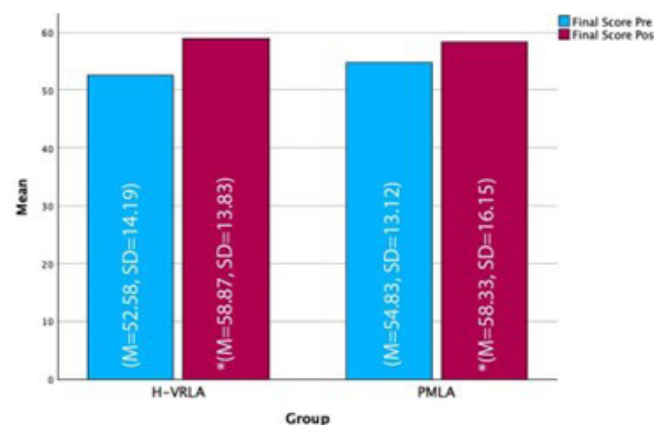


Figure 6. Pre and post simulation mean knowledge test scores for both groups

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.

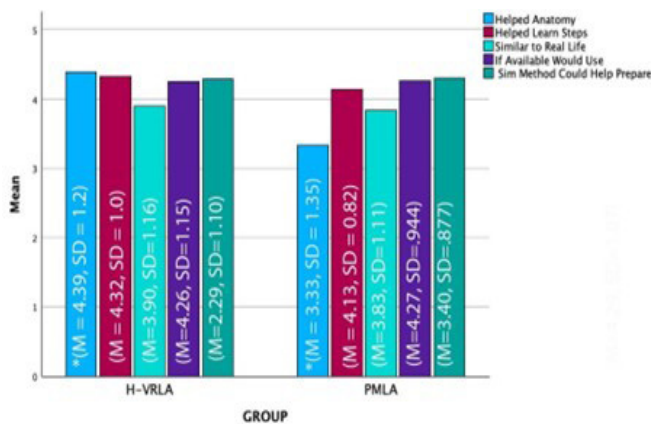


Figure 7. Mean learning perceptions for H-VRLA & PMLA training methods

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 ($R^2=0.259$). For PMLA, the rating was not a significant predictor ($B=-2.057, p=0.365, R^2=0.029$). 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).

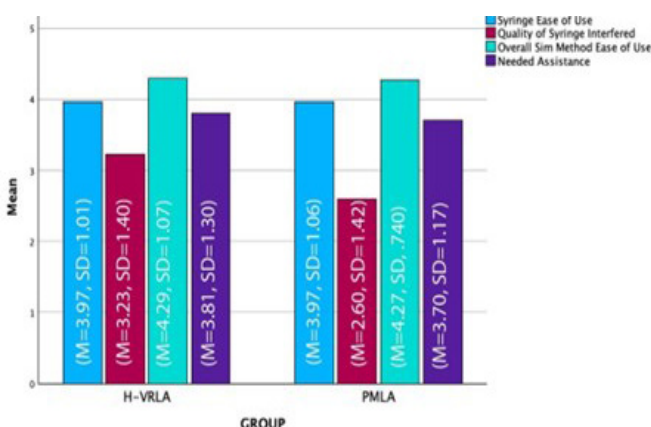


Figure 8. Mean usability ratings for the H-VRLA and PMLA training methods

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-VRLA 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 ($M_{Gain}=3.50, 95\% CI=[-1.87, 8.87]$) 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).

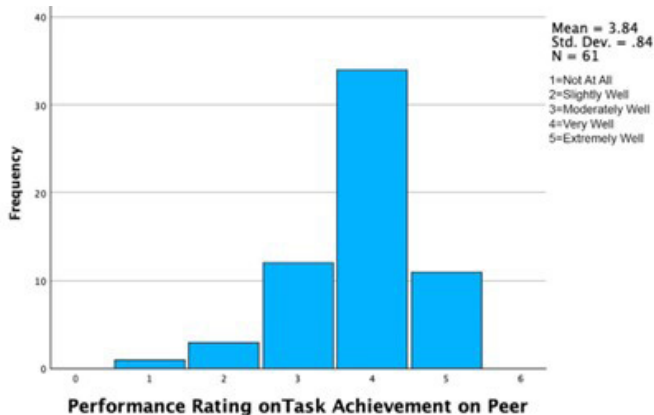


Figure 9. Overall mean performance rating on task achievement on peer

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.

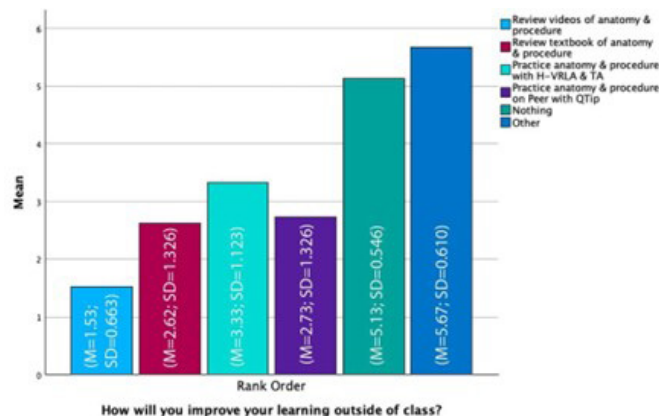


Figure 10. Mean rank order continued learning resources

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).

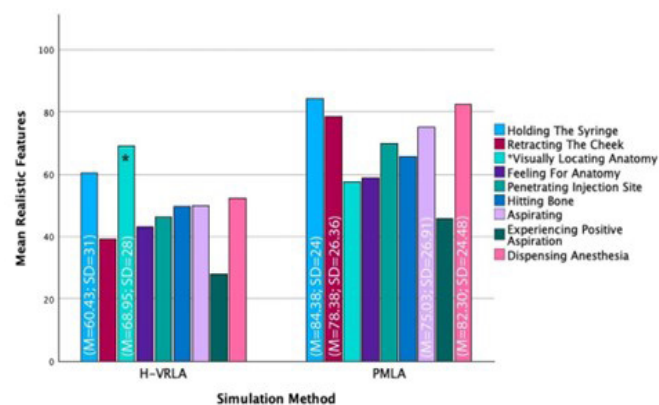


Figure 12. Mean realistic feature comparison between H-VRLA and PMLA

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)	<p>(Figure 11A)</p>	PMLA (52%)	Felt more real, closer to a live person, allowed feeling landmarks
Learning anatomy better (39.35% PMLA vs. 21.32% H-VRLA)	<p>(Figure 11B)</p>	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)	<p>(Figure 11C)</p>	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)	<p>(Figure 11D)</p>	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

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

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.

Acknowledgments

We would like to thank the students, Danna Wahid El Awdan, Noelle Gerace, Emma Sharretts, and Dhvani Thakkar for their assistance with the H-VRLA training. A special thank you to NYU College of Dentistry leadership, NYU IT leadership, and Provost for their continued support.

REFERENCES

1. Al-Saud LM, Mushtaq F, Allsop MJ, et al. Feedback and motor skill acquisition using a haptic dental simulator. *Eur J Dent Educ.* 2017;21(4):240-247. doi:10.1111/eje.12214
2. Eid M, Levine M, Gyawali A, McAlpin E. (2024) A custom haptic syringe to improve a VR local anesthesia simulation for foundational dental education: a feasibility study. *Open J Applied Sciences.* 2024;14:3460-3479. doi:10.4236/ojapps.2024.1412226.
3. Xia P, Lopes AM, Restivo MT. Virtual reality and haptics for dental surgery: a personal review. *The Visual Computer.* 2013;29:433-447. doi:10.1007/s00371-012-0748-2
4. Cox MJ, Quinn BF, San Diego JP, Patel J, Gawali K, Woolford M. Innovations in teaching and learning strategies to improve the effectiveness of using haptic simulators in higher education for dental students and other health care disciplines. In IFIP World Conference on Computers in Education. Cham: Springer International Publishing. 2017;(pp. 387-397).
5. Al-Saud LM. The utility of haptic simulation in early restorative dental training: a scoping review. *J Dent Educ.* 2021;85(5):704-721. doi:10.1002/jdd.12518
6. Cohen J. The effect size. Cohen L. (Ed.) *Statistical Power Analysis for the Behavioral Sciences* (2nd ed.). Abingdon: Routledge (Taylor & Francis Group). 1988:77-83.
7. Saldana J. The coding manual for qualitative researchers. *Am J Qualitative Res.* 2022;6(1):232-237. doi:10.29333/ajqr/12085
8. Lee JS, Graham R, Bassiur JP, Lichtenthal RM. Evaluation of a local anesthesia simulation model with dental students as novice clinicians. *J Dent Educ.* 2015;79(12):1411-1417.
9. Knipfer C, Rohde M, Oetter N, Muench T, Kesting MR, Stelzle F. Local anaesthesia training for undergraduate students-how big is the step from model to man? *BMC Med Educ.* 2018;18(1):308. doi:10.1186/s12909-018-1389-6
10. Buchanan JA. Experience with virtual reality-based technology in teaching restorative dental procedures. *J Dent Educ.* 2004;68(12):1258-1265. doi:10.1002/j.0022-337.2004.68.12.tb03875.x
11. Quinn F, Keogh P, McDonald A, Hussey D. A study comparing the effectiveness of conventional training and virtual reality simulation in the skills acquisition of junior dental students. *Eur J Dent Educ.* 2003;7(4):164-169. doi:10.1034/j.1600-0579.2003.00309.x
12. Collaço E, Kira E, Sallaberry LH, et al. Immersion and haptic feedback impacts on dental anesthesia technical skills virtual reality training. *J Dent Educ.* 2021;85(4):589-598. doi:10.1002/jdd.12503
13. Lamira JM, Wilson CS, Leppek NC, Orr CM, De la Rosa LM, Greany TJ. A pilot study of local anesthesia training using a mixed-reality haptic fidelity model. *J Dent Educ.* 2023;87(4):583-591. doi:10.1002/jdd.13151