

UDC 616.31:616.8]:378.147:004.8/.9

DOI <https://doi.org/10.11603/m.2414-5998.2026.1.16030>**Svitlana Lychko**ORCID <https://orcid.org/0000-0001-6906-1643>**Volodymyr Lychko**ORCID <https://orcid.org/0000-0001-5518-5274>,**Iryna Borovyk**ORCID <https://orcid.org/0009-0000-4770-7300>*Sumy State University*

## DIGITAL TRANSFORMATION OF NEURODENTAL EDUCATION: INTEGRATION OF SIMULATION TECHNOLOGIES AND ARTIFICIAL INTELLIGENCE INTO PRECLINICAL TRAINING

**Світлана Личко, Володимир Личко, Ірина Боровик***Сумський державний університет*

### ЦИФРОВА ТРАНСФОРМАЦІЯ НЕЙРОСТОМАТОЛОГІЧНОЇ ОСВІТИ: ІНТЕГРАЦІЯ СИМУЛЯЦІЙНИХ ТЕХНОЛОГІЙ ТА ШТУЧНОГО ІНТЕЛЕКТУ В ДОКЛІНІЧНУ ПІДГОТОВКУ

**Abstract.** The objective of this study was to conduct a critical analysis regarding the efficacy of implementing interactive simulators and artificial intelligence (AI) systems into the training process of prospective dental practitioners, based on current data spanning 2020–2025.

Research corroborates that VR/AR systems equipped with haptic feedback (e.g., Simodont, Unidental) provide effective simulation of tactile sensations when interacting with enamel, dentin, and pulp. The utilization of VR simulators during the preclinical stage facilitates superior development of manual skills and preparation precision compared to traditional phantom-based methods. Furthermore, the integration of AI enables the automation of student work assessment with an accuracy range of 96–98%. Machine learning algorithms, specifically Random Forest and SVM, demonstrate high performance (90% accuracy) in the differential diagnosis of orofacial pain and trigeminal neuralgia. Specialized platforms, such as AnesthesiaSim, allow for the safe practice of conduction anesthesia skills within a virtual environment featuring “transparent tissue” visualization to prevent trauma to nerve trunks.

The primary impediments include the substantial cost of equipment, ethical concerns regarding data privacy, and a degree of skepticism among faculty members concerning the perceived diminution of the educator’s role in the instructional process.

**Conclusions:** The optimal pedagogical approach is a hybrid model that synthesizes VR simulators with traditional methodologies. Simulation technologies and AI are currently becoming indispensable components of modern dental education, ensuring the preparation of competent and confident professionals.

**Key words:** virtual reality; augmented reality; haptic simulators; artificial intelligence; neurodental education; preclinical training; personalized learning.

**Анотація.** Метою роботи було проведення критичного аналізу ефективності впровадження інтерактивних симуляторів та систем штучного інтелекту (ШІ) у процес підготовки майбутніх лікарів-стоматологів на основі актуальних даних 2020–2025 років.

Дослідження підтверджують, що системи віртуальної та доповненої реальності (VR/AR) з гаптичним зворотним зв’язком (Simodont, Unidental) забезпечують ефективну імітацію тактильних відчуттів під час роботи з емаллю, дентином та пульпою. Використання VR-симуляторів на доклінічному етапі сприяє кращому розвитку мануальних навичок та точності препарування порівняно з традиційними фантомними методами. Інтеграція штучного інтелекту дозволяє автоматизувати оцінювання робіт студентів із точністю 96–98%. Алгоритми машинного навчання (Random Forest, SVM) демонструють високу ефективність (90% точності) у диференціальній діагностиці орофациального болю та невралгії трійчастого нерва. Спеціалізовані платформи, такі як AnesthesiaSim, дозволяють безпечно відпрацьовувати навички провідникової анестезії у віртуальному середовищі з візуалізацією «прозорих тканин» для уникнення травмування нервових стовбурів. Основними перешкодами є висока вартість обладнання, етичні питання конфіденційності даних та певний скептицизм із боку викладацького складу щодо зменшення ролі педагога в освітньому процесі.

**Висновки:** Оптимальним педагогічним підходом є гібридна модель, що поєднує VR-симулятори і традиційні методи. Симуляційні технології та штучний інтелект нині стають невід’ємною частиною сучасної стоматологічної освіти, забезпечуючи підготовку компетентних і впевнених фахівців.

**Ключові слова:** віртуальна реальність; доповнена реальність; гаптичні симулятори; штучний інтелект; нейростоматологічна освіта; доклінічне навчання; персоналізоване навчання.

**Introduction.** The modern paradigm of higher medical education is undergoing fundamental shifts driven by the rapid implementation of immersive technologies: virtual (VR) and augmented (AR) reality, haptic systems, and artificial intelligence (AI) algorithms. These innovations acquire particular significance in neurodentistry – a discipline that demands not only precise manual dexterity but also a profound understanding of topical diagnostics and interventions within regions characterized by complex innervation.

The traditional preclinical model, predicated on the use of phantoms and extracted teeth, encounters several critical limitations, such as the absence of biological tissue variability, the impossibility of fully simulating neurosensory responses, and the inherent subjectivity of faculty assessment. In the context of neurodentistry, where a margin of error of only a few millimeters during anesthesia or endodontic intervention may result in neuropathy, the necessity for high-precision simulators becomes virtually imperative.

The objective of this study was to conduct a critical analysis of the efficacy of implementing interactive simulators and AI systems into the training process of prospective dental practitioners, based on current data from 2020–2025.

Over the past five years, significant progress has been observed in the development of VR/AR simulators with haptic feedback, which are capable of simulating the interaction of instruments with the outer layers of dental tissues – enamel, dentin, and pulp – through the generation of corresponding resistance and vibration. Concurrently, the integration of AI has introduced new dimensions: automated assessment of work quality, personalized learning trajectories, performance forecasting, and adaptive real-time feedback (Li et al., 2021).

The COVID-19 pandemic, in turn, accelerated the digitalization of neurodental education, compelling institutions to implement distance and hybrid learning formats. This shift intensified the relevance of VR/AR technologies as an alternative or a complement to traditional methodologies. (Hashem et al., 2025).

To achieve the stated objective, a systematic analysis of the scientific discourse over the past five years was conducted. The methodological framework comprised:

**Comparative Analysis:** An examination of the outcomes resulting from the implementation of VR-Haptic platforms (Simodont, Unidental) in comparison with traditional methodologies.

**Synthesis of Global Data:** An analysis of reports from the VR-Haptic Thinkers consortium (2025),

encompassing the experiences of 156 educational institutions across 41 countries.

**Technological Stack Assessment:** An evaluation of the accuracy of automated assessment systems and Computer Vision algorithms in diagnosing pathologies, specifically carious lesions and innervation anomalies on radiographs.

Modern simulation technologies in dentistry are classified according to the level of immersion, the presence of haptic feedback, and the specific type of application (Moussa et al., 2022).

Virtual Reality (VR) refers to a computer-generated medical simulation of a three-dimensional (3D) image or environment, utilizing specialized software to construct a realistic computational space. Through the use of a head-mounted display (HMD), users are immersed in a specific environment where they can interact with the surroundings and virtual characters, experiencing a high degree of immersion. VR serves as a valuable tool in neurodental education by enabling the creation of a non-contact environment for training students in patient interaction protocols (Moussa et al., 2022).

Augmented Reality (AR) represents the superimposition of computer graphics onto a real-world scene. It differs fundamentally from VR, which does not depict natural conditions. AR is a technological modality that integrates real and virtual elements into a combined experience, allowing students to visualize complex spatial relationships and abstract concepts, as well as to experience phenomena that might be impossible to replicate in the physical world, particularly in the coaching of surgical procedures. Immersive Virtual Reality (IVR) is a subset of these technologies where the user interacts with a digital 3D environment rendered using 360-degree real-world recordings (Moussa et al., 2022).

Haptic Technology (HT) represents a more recent simulation modality that incorporates specific tactile sensations during interactions with computer-generated objects. Haptics refers to the sense of touch and encompasses the science of interacting with the external environment through contact. The integration of these technologies into dental education has prompted designers to develop virtual teeth, both with and without pathology, featuring multi-layered structures and varying degrees of mechanical hardness to enhance realism. (Moussa et al., 2022).

**Results.** Currently, virtual reality systems with haptic feedback (VR-Haptic) are most prominently represented by the Simodont Dental Trainer,

Unidental, and HapTEL platforms. These systems utilize stereoscopic displays for 3D visualization alongside haptic devices that generate force feedback (FFB) with a minimum refresh rate of 1 kHz to simulate tactile sensations. Simodont, for instance, projects a virtual oral cavity onto a mirror above the workstation; the student manipulates a physical handpiece, receiving tactile responses contingent upon the virtual material encountered, such as enamel, dentin, or pulp (Li et al., 2025).

AR systems integrate digital elements with a real phantom environment. DentSim, developed by Image Instruments (Germany), utilizes cameras to track a student's instruments on actual teeth, overlaying digital cues and assessments directly onto the working field. AR systems enable practice on physical models with digital guidance, thereby synthesizing the advantages of both approaches (Nassar & Tekian, 2020).

Specialized simulators have been developed for specific clinical procedures: PerioSim Haptics for periodontological interventions (scaling, root planing), and the modified VoxelMann for surgical operations (apicoectomy, gingivoplasty) (Dharmathilaka et al.).

In a 2025 study conducted by Li et al. at Peking University, involving 80 fourth-year students, the efficacy of two VR simulators (Unidental and Simodont) was compared with traditional phantom heads for training in veneer tooth preparation. Students were stratified by academic performance and randomized into eight groups based on learning outcomes. The study revealed no significant differences in learning results between the VR simulators and traditional phantom heads, suggesting that VR technology can serve as a viable alternative or supplementary tool in dental education. However, the absence of significant differences does not imply equivalence. Students characterized the VR technology as more engaging and realistic for instructional purposes (Li et al., 2025).

Felszeghy et al. (2024) conducted a comparative study regarding the sequence of utilizing VR-haptic (Simodont) systems and phantoms within a preclinical course on prosthetic dentistry. Group 1 initially trained using VR followed by phantoms, while Group 2 followed the reverse order. A crown preparation assessment conducted at the conclusion of the course demonstrated that Group 1 (VR-first) exhibited superior metrics in occlusal and axial reduction, convergence angles, and a lower incidence of damage to adjacent teeth compared to Group 2. All participants highly evaluated the VR-haptic system as an effective instrument for the enhancement of manual dexterity (Felszeghy et al., 2024).

Tan et al. (2025) compared real-time evaluation systems (Real-time Dental Training Evaluation System, RDTES) and virtual simulation

systems (Virtual Simulation System, VSS) with traditional methodologies. The study involved 121 undergraduate students. RDTES demonstrated significantly higher scores in preparation precision and feedback quality compared to VSS, which exhibited a substantial response latency and lower accuracy (Tang et al., 2025).

A number of literature reviews, specifically a systematic review by Moussa et al. (2022), analyzed 73 publications concerning VR and interactive simulators in dental education. There are 52 out of 73 studies (71.2%) demonstrated a significant improvement in educational outcomes when utilizing VR technologies, including manual skills, theoretical knowledge, spatial reasoning, and student confidence. VR technologies were positively perceived by all participants. The review identified the extensive application of VR in restorative dentistry, orthodontics, and maxillofacial surgery (Moussa et al., 2022).

The 2025 VR-Haptic Thinkers Consortium study aggregated 378 responses from educators representing 156 dental institutions across 41 countries. The findings indicated that 94% of respondents utilize VR-haptic simulators in preclinical training, whereas only 46% employ them in clinical settings. Simulation is most frequently applied for practicing clinical skills in restorative dentistry, orthodontics, and endodontics. Furthermore, 58% of participants maintain that the optimal approach involves the simultaneous use of VR-haptic systems and phantoms during the preclinical stage, while 30% prefer the use of a VR simulator prior to transitioning to phantom-based methods (Bencharit et al., 2025).

Another field of application for innovative technologies in education is the utilization of systems based on AI (Computer Vision) and geometric analysis for the objective assessment of student work quality.

It is critically important for students to receive consistent and accurate feedback from faculty after completing practical tasks. However, several factors, including subjective assessment scales and insufficiently calibrated evaluators, have contributed to discrepancies in grading. Consequently, consistent and reliable feedback was not achieved.

To address these deficiencies, digital human-assisted assessment using three-dimensional (3D) inspection and metrology software was considered as an alternative to eliminate the shortcomings of traditional visual inspection. This method involves a meticulous evaluation by trained specialists who assess scanned data of prepared teeth through digital measurements using visually calculated scales (Han et al., 2023).

In a 2023 study, Khan et al. developed a Software-based Automated Evaluation (SAE) system designed to analyze preparation volume, surface convergence,

marginal integrity, and other crown preparation parameters. The SAE demonstrated perfect intra-rater reliability and near-perfect inter-rater agreement with human assessments (Han et al., 2023).

In a 2024 study, Rampf et al. programmed AI for the diagnosis of dental caries on radiographs as a component of the educational process. The AI-driven system achieved an accuracy of 96.4% for superficial caries and 98.8% for moderate and deep caries, facilitating its utilization as an alternative expert assessment and a source of personalized feedback for students (Jha Kukreja & Kukreja, 2025).

One of the most complex aspects of neurodentistry is the differentiation between somatogenic and neurogenic pain. Contemporary research demonstrates the high efficacy of machine learning algorithms in differentiating between temporomandibular joint dysfunction and trigeminal neuralgia. Through the analysis of structured questionnaires and physical examination findings, AI models (Random Forest, SVM) achieve 90% accuracy, significantly surpassing the performance metrics of novice clinicians (Burchiel et al., 2025).

Systems based on the Multilayer Perceptron (MLP) are also being implemented, specializing in the detection of rare neurovascular and neuropathic conditions. It has been proven that such systems are capable of recognizing patterns of “referred” pain (for example, cardiogenic pain mimicking dental pain), serving as an intelligent “co-pilot” for students during clinical appointments (Clark et al., 2025).

In neurodental education, mastering regional anesthesia skills without the risk of injuring nerve trunks is critical. Platforms such as AnesthesiaSim (UNC Adams School of Dentistry) offer an immersive VR environment for practicing inferior alveolar and lingual nerve blocks. Students experience soft tissue resistance and contact with bony landmarks (the mandibular ramus).

VR allows for toggling view modes, rendering the mucous membrane transparent, which enables the student to see the needle’s position relative to the neurovascular bundle in real-time. The system automatically records errors – such as inserting the needle too deeply or penetrating a vessel – which helps form a stable neurosensory memory of the correct injection trajectory.

The study of neurodentistry is impossible without an understanding of neurovascular conflicts. The integration of AI services (e.g., for quantitative MRI analysis) allows students to more rapidly detect signs of demyelination or trigeminal nerve compression.

Educational programs utilizing generative models (such as BrainSynth) create synthetic databases of pathological MRI scans, enabling students to study rare neurodental anomalies that are seldom encountered in everyday practice (Jha Kukreja & Kukreja, 2025; Moussa et al., 2022).

AI is currently being utilized for the assessment of students’ practical skills as well. Specifically, machine learning algorithms analyze individual student performance, identify weaknesses, and automatically select appropriate exercises and difficulty levels. Adaptive learning systems track execution speed, error types, and preparation quality to generate personalized recommendations.

Research by Adnan et al. (2023) demonstrated that AI-supported VR systems received high ratings for scenario realism and feedback quality. Participants noted improvements in knowledge acquisition, practical skills, procedural confidence, and the understanding of complex concepts (Adnan et al., 2023).

Mahrous et al. investigated the gamified platform AiDental for teaching the design of removable partial dentures. The system utilizes AI for automated assessment and feedback generation, integrating game elements such as points, levels, and achievements. According to the research results, students in the AiDental group received more A/B grades compared to the traditional group and perceived the software positively (Jha Kukreja & Kukreja, 2025).

Interesting results were revealed by a longitudinal study spanning 2014–2024, conducted by a group of authors to evaluate the Simodont dental trainer. Overall, participants in this study rated various aspects of the dental trainer higher than their counterparts from the previous study ten years ago (Yasa, 2025).

Students showed greater engagement in the learning process and a higher inclination toward technology adoption compared to both faculty members and their peers from the 2014 student cohort. However, both faculty and students across both studies fully agreed that the Simodont dental trainer should not replace traditional training. Both groups also concurred that the feedback provided by the simulator must be supplemented by feedback from real instructors (Roganović et al., 2023).

Although studies have shown that students positively value the unlimited practice opportunities, they simultaneously emphasize the importance of the tactile sensation of handling real tissues and the necessity of interacting with instructors.

In contrast, feedback regarding various dental simulators from faculty members was almost polar opposite. A degree of skepticism persists among them concerning the advantages of VR/AI. In a study at a Turkish university, 40% of respondents expressed concerns regarding the insufficiency of practical skill development when using AI; only 48% supported including such simulations in the curriculum, while 40% were opposed. Their primary concerns included the diminishing role of the instructor, technical complexity, and inadequate staff training (Harte et al., 2025).

**Discussion.** During the implementation of innovative technologies into the educational process today, it is becoming evident that the economic aspect plays a key role in scaling such systems. Analysis shows that the initial investment for a single VR-haptic simulator ranges from 80,000 to 150,000 USD, which is 30–50 times higher than the cost of a traditional phantom unit. However, long-term financial sustainability is achieved through the total elimination of consumables – such as plastic or extracted teeth, burs, and auxiliary materials – as well as through water supply optimization and waste reduction. Furthermore, simulation centers reduce the burden on infrastructure, allowing institutions to effectively train a larger number of students.

An important point of debate is the ethical and organizational dimension of AI usage. Since these systems collect significant volumes of personal performance data, strict compliance with GDPR and HIPAA is critically necessary, alongside the development of internal institutional data protection policies. The implementation of such tools in clinical training must be accompanied by appropriate regulatory approval, similar to medical devices. Particular attention should be paid to the “black box” problem of AI: to ensure educational value, system decisions must be transparent and explainable. This is made possible through technologies like LIME, which visualize the decision-making logic used during the assessment of student work.

Evaluating this educational transformation, it is worth noting that combining VR/AR/Haptic with AI ensures not only objectivity but also the personalization of learning. Evidence suggests the equivalence or even superiority of VR systems over phantom methods in developing manual dexterity, spatial reasoning, and theoretical retention. The integration of AI algorithms allows for automated quality control with an extraordinary accuracy of 96–98%, enabling the adaptation of learning trajectories and the prediction of a student’s future clinical success.

Global trends confirm this vector: according to the VR-Haptic Thinkers Consortium (surveying 156 institutions), 94% of dental schools have already chosen VR-haptic for the preclinical stage. At the same time, 58% of experts emphasize the advantages of a hybrid model, where simulators and traditional phantoms are used in parallel. Despite existing barriers – high costs, certain technical limitations in tactile feedback, organizational resistance, and privacy concerns – these technologies are becoming an integral element of training.

However, simulation does not negate the role of the instructor; on the contrary, the optimal approach involves maintaining human expertise,

empathy, and individual adaptation to complement automated feedback. Currently, the urgent task remains overcoming educational variability through the development of unified accreditation criteria and validated competency assessment methodologies.

**Conclusions.** The implementation of AI in neurodental education presents several challenges. First, significant investments are required for infrastructure development, the procurement of modern equipment, and faculty training. It is also necessary to constantly update curricula to keep pace with rapid technological progress.

Ethical considerations, particularly regarding patient data privacy and the reliability of AI-driven decisions in clinical settings, must be carefully considered. Educators and professionals must be prepared to address these issues, ensuring the responsible and effective use of AI.

However, despite the fact that dental simulators currently cannot compete with traditional training methods for skill development in certain disciplines, they still possess advantages over traditional methods, and their effectiveness has been confirmed in specific cases. Compared to traditional phantom-based training, dental simulators offer many benefits that provide students with a superior learning environment. In addition to operative dental skills, students can also acquire relevant theoretical knowledge through these simulators. Since the latter allow for repeatable and reversible preclinical training of clinical skills, they provide students with a more flexible learning experience, enabling digital objective assessment and educational feedback. Furthermore, training on dental simulators is more clinically significant as they replicate situations similar to those encountered in a real clinical environment.

**Perspectives for further research.** Provided these conditions are met, simulation technologies and AI can become an integral part of modern neurodental education, producing competent, confident, and technologically literate dentists of the future. The future development of the field will depend on the unification of accreditation criteria for digital learning and the further refinement of the tactile realism of simulators.

**Funding.** None.

**Conflict of Interest.** None.

**Author Contributions.** Svitlana Lychko – conceptualization, methodology, formal analysis, writing – initial draft, visualization (50%).

Volodymyr Lychko – project administration, supervision, research, resources, data curation, writing – reviewing and editing (40%).

Iryna Borovyk – software, validation (10%). An all authors has approved the manuscript’s final version

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Електронна адреса для листування: [v.lychko@med.sumdu.edu.ua](mailto:v.lychko@med.sumdu.edu.ua)

Дата першого надходження статті до видання: 09.12.2025  
 Дата прийняття статті до друку після рецензування: 19.01.2026  
 Дата публікації (оприлюднення) статті: 26.03.2026



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