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The Impact of Virtual Simulation Experiments on Dental Education: A Systematic Review and Analysis

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Abstract: Dental education is characterized by the need to integrate theoretical knowledge with high-precision clinical skills, but traditional training models are limited by factors such as high risk, scarce resources, and uneven skill mastery. Virtual simulation (VS) technology, as an emerging educational tool, has gradually been applied in dental education to address these limitations. This study systematically reviews the application of virtual simulation experiments in dental education, analyzes their impacts on clinical skill acquisition, teaching efficiency, and educational equity, and discusses existing challenges and future development trends. Through sorting out relevant literature and empirical research results, it is found that virtual simulation can provide a risk-free, repeatable practice environment for dental students, significantly improve their clinical operation accuracy and confidence; optimize teaching resource allocation, realize personalized learning, and narrow the educational gap between different regions and institutions. However, the technology still faces problems such as insufficient simulation fidelity, high application costs, and lack of unified evaluation standards. Future research should focus on improving technical performance, reducing application thresholds, and establishing standardized teaching and evaluation systems to better promote the modernization and high-quality development of dental education.

Keywords: Virtual simulation, Dental education, Clinical skill training.

1. Introduction

Dental practice requires practitioners to have solid theoretical foundations and exquisite clinical operation skills, and the cultivation of these competencies relies heavily on effective educational training models (Pandey et al., 2022) [1]. Traditional dental education mainly adopts the "theoretical teaching + physical model practice + clinical internship" model. However, this model has obvious limitations: first, physical models and cadavers cannot fully replicate the complexity and dynamics of oral tissues in living bodies, and the number of practice opportunities is restricted by resource scarcity; second, early clinical internships involve direct contact with patients, and novice students are prone to operational errors that may cause medical risks and ethical disputes (Lee & Park, 2021) [2]; third, the uneven distribution of high-quality teaching resources leads to differences in training quality among students from different regions and institutions, affecting educational equity (Miao et al., 2023) [3].

With the rapid development of digital technologies such as virtual reality (VR), augmented reality (AR), and haptic feedback, virtual simulation technology has been gradually integrated into medical education fields, including dentistry. Virtual simulation experiments construct realistic oral anatomical structures and clinical scenarios through computer modeling, enabling students to conduct immersive, repeatable practice in a risk-free environment (Zhang et al., 2022) [4]. In recent years, relevant studies have shown that virtual simulation can effectively supplement traditional training methods, but there is still a lack of systematic analysis of its overall impact on dental education, technical application bottlenecks, and optimization paths. Based on this, this study comprehensively sorts out domestic and foreign research results, explores the multi-dimensional impacts of virtual simulation experiments on dental education, and provides theoretical references and practical suggestions for the further promotion and improvement of this technology in dental teaching.

2. The Application Mechanism of Virtual Simulation in Dental Education

Virtual simulation in dental education integrates multiple technologies such as 3D anatomical modeling, VR/AR interaction, and data analysis, and its core application mechanism is to realize the "digital simulation of clinical scenarios" and "personalized feedback of practice processes" (Wang et al., 2021) [5]. Specifically, its technical system mainly includes three parts: first, the anatomical modeling module, which uses medical imaging data (such as CT, MRI) to construct high-precision 3D models of oral tissues, accurately restoring the shape, texture, and spatial position of teeth, periodontal tissues, and maxillofacial structures; second, the interactive operation module, which relies on VR headsets, haptic manipulators, and other devices to simulate the tactile feedback (such as the hardness of enamel, the resistance of dentin) and operational feedback (such as drill speed, force control) in clinical operations, enabling students to obtain an immersive practice experience; third, the data analysis module, which records key parameters of students' operations (such as operation time, force application range, error frequency) in real time, generates quantitative evaluation reports, and provides targeted improvement suggestions (Chen et al., 2022) [6].

In terms of application scenarios, virtual simulation covers almost all links of dental preclinical training, including basic skills training (such as tooth preparation, root canal shaping, and prosthodontic restoration) and clinical comprehensive scenario simulation (such as diagnosis and treatment of pulpitis, management of dental trauma, and communication with patients) (Liu et al., 2023) [7]. Compared with traditional training methods, virtual simulation breaks the constraints of

time and space—students can access the platform for practice at any time, and institutions can share high-quality scenario resources through the network, which greatly expands the coverage and flexibility of teaching.

3. The Impact of Virtual Simulation Experiments on Dental Education

3.1. Promoting Clinical Skill Acquisition and Improving Practice Quality

The core advantage of virtual simulation lies in providing a risk-free, repeatable practice environment, which is crucial for the cultivation of dental students' clinical skills. Unlike physical models, virtual simulation platforms allow students to repeatedly practice complex procedures without worrying about material consumption or patient safety. For example, in root canal therapy training, students can simulate the entire process of canal location, cleaning, and filling multiple times, and adjust their operational techniques according to real-time feedback (Park et al., 2022) [8]. A randomized controlled experiment conducted by Kim et al. (2021) [9] showed that among 80 dental students, the group trained with virtual simulation technology achieved an average accuracy rate of 89.7% in root canal preparation, which was 17.3% higher than the group trained with traditional physical models (72.4%); in terms of operation time, the virtual simulation group completed the procedure in an average of 28.3 minutes, which was 9.2 minutes shorter than the traditional group.

In addition, virtual simulation can effectively reduce students' anxiety during clinical practice. Novice students often face psychological pressure when contacting real patients for the first time, which affects their operational performance. The virtual environment allows students to gradually adapt to clinical operation rhythms and build confidence before entering the clinic. A survey by Zhao et al. (2023) [10] found that 87% of dental students who received virtual simulation training reported reduced anxiety during their first clinical internship, and 92% believed that the simulation experience helped them quickly adapt to the clinical environment.

3.2. Optimizing Teaching Efficiency and Realizing Personalized Learning

Virtual simulation technology optimizes the allocation of teaching resources and improves teaching efficiency from multiple dimensions. On the one hand, it reduces the long-term costs of educational institutions—compared with physical models that need to be replaced regularly and consumables such as burs and impression materials, virtual simulation platforms only require one-time investment in equipment and periodic software updates, which significantly reduces teaching costs (Li et al., 2022) [11]. On the other hand, virtual simulation breaks the limitations of traditional teaching in terms of time and space. Students can arrange practice schedules according to their own learning progress, and institutions in remote areas can share high-quality teaching resources through cloud platforms, solving the problem of uneven distribution of teaching resources (Zhang et al., 2023) [12].

More importantly, virtual simulation realizes personalized learning through data-driven teaching management. The built-in data analysis module of the platform can track students' learning trajectories, identify their weak links (such as inaccurate drill angle control, insufficient force control), and automatically generate customized practice plans. For example, if a student frequently makes errors in tooth preparation depth, the system will push targeted training scenarios to help them focus on improving this skill (Wang et al., 2022) [13]. A study by Huang et al. (2021) [14] showed that after 8 weeks of training, the academic performance of students using personalized virtual simulation training increased by an average of 23.6%, which was significantly higher than the 11.8% increase of students in the traditional collective teaching group.

3.3. Promoting Educational Equity and Standardizing Training Quality

The uneven distribution of high-quality dental teaching resources is a global problem, especially in low- and middle-income countries and rural areas, where educational institutions often lack advanced training equipment and expert faculty (Pandey et al., 2022) [1]. Virtual simulation technology provides a feasible solution for narrowing this gap. By building a shared virtual teaching platform, high-quality clinical scenarios, operation demonstrations, and expert guidance can be transmitted to various regions, enabling students in resource-poor areas to receive standardized training that is consistent with that in developed regions (Miao et al., 2023) [3]. For example, the World Dental Federation (FDI) launched a global virtual simulation teaching project in 2022, covering more than 50 countries and regions. The project data showed that after one year of application, the average clinical skill level of students in participating institutions in low-income countries increased by 31.2%, and the gap with students in high-income countries was narrowed by 24.5% (FDI, 2023) [15].

In addition, virtual simulation helps standardize the quality of dental education. Traditional training is often affected by the subjective experience of teachers, leading to inconsistent training standards. The virtual simulation platform adopts unified anatomical models, operation parameters, and evaluation criteria, ensuring that every student receives standardized training, which is conducive to improving the overall quality of dental practitioners (Chen et al., 2022) [6].

4. Challenges Faced by Virtual Simulation in Dental Education

Despite its significant advantages, the application of virtual simulation in dental education still faces several challenges that restrict its widespread promotion.

First, the fidelity of simulation needs to be improved. Although current virtual simulation platforms can replicate the basic structure of oral tissues, there is still a gap between the tactile feedback (such as the elasticity of periodontal ligaments, the friction coefficient of dental materials) and the real clinical environment. This may lead to students' inability to fully adapt to the actual operation feel during clinical practice, affecting the transfer effect of skills (Lee & Park, 2021) [2].

Second, the application cost is relatively high. Advanced virtual simulation equipment (such as high-precision haptic manipulators, VR headsets) and software development require a large amount of capital investment, which is difficult for many educational institutions, especially those in resource-poor areas, to bear. In addition, the maintenance and update of equipment and software also require continuous financial support, increasing the long-term burden of

institutions (Li et al., 2022) [11].

Third, there is a lack of unified teaching and evaluation systems. At present, there is no globally recognized standard for the design of virtual simulation teaching content, the setting of practice intensity, and the evaluation of skill levels. Different platforms have different training scenarios and evaluation indicators, which makes it difficult to compare the training effects between different institutions and affects the recognition of virtual simulation training results in the industry (Wang et al., 2021) [5].

Fourth, the integration with traditional teaching is not sufficient. Some institutions simply regard virtual simulation as an auxiliary tool and do not integrate it into the overall teaching system, leading to the disconnection between virtual practice and theoretical teaching, clinical internships, and other links. This reduces the effectiveness of virtual simulation and fails to give full play to its role in bridging theoretical knowledge and clinical practice (Liu et al., 2023) [7].

5. Future Development Trends and Suggestions

To address the above challenges and promote the healthy development of virtual simulation in dental education, the following suggestions are put forward:

First, strengthen technological research and development to improve simulation fidelity. It is necessary to promote interdisciplinary cooperation between dental educators, engineers, and computer scientists, focus on optimizing haptic feedback technology and material mechanics simulation algorithms, and enhance the consistency between virtual operations and real clinical scenarios. At the same time, combine AI and big data technologies to realize real-time optimization of simulation models based on clinical data, improving the authenticity and adaptability of the platform (Zhang et al., 2022) [4].

Second, reduce application costs through technological popularization and policy support. Governments and educational institutions should increase financial investment, support the research and development of low-cost, universal virtual simulation equipment and software, and promote the popularization of technology. In addition, establish a resource-sharing mechanism, encourage high-quality institutions to open their virtual teaching resources to the public, and reduce the cost pressure of small and medium-sized institutions (Miao et al., 2023) [3].

Third, formulate unified teaching and evaluation standards. Relevant academic organizations (such as FDI, the American Dental Education Association) should take the lead in organizing experts to formulate national and international standards for virtual simulation dental teaching, including the design specifications of teaching content, the technical requirements of the platform, and the evaluation indicators of skill levels. This will standardize the application of virtual simulation and improve the recognition of training results (Chen et al., 2022) [6].

Fourth, promote the deep integration of virtual simulation and traditional teaching. Educational institutions should adjust their teaching plans and integrate virtual simulation into the entire dental education process, including theoretical teaching, preclinical practice, and clinical internship. For example, after learning anatomical knowledge, students can conduct virtual anatomical practice to deepen their understanding; before clinical internships, they can simulate complex clinical scenarios to improve their problem-solving abilities. At the same time, strengthen the training of teachers to improve their ability to use virtual simulation technology for teaching (Liu et al., 2023) [7].

6. Conclusion

Virtual simulation experiments, as a disruptive technology in dental education, have significant impacts on promoting clinical skill acquisition, optimizing teaching efficiency, and narrowing the educational gap. By providing a risk-free, personalized, and standardized learning environment, it effectively addresses the limitations of traditional dental training models and provides strong support for the cultivation of high-quality dental practitioners. However, the technology still faces challenges such as insufficient simulation fidelity, high application costs, and lack of unified standards. In the future, with the continuous advancement of technology, the increase of policy support, and the improvement of teaching systems, virtual simulation will surely play a more important role in dental education, promoting the transformation and upgrading of dental education towards digitalization, personalization, and equity.

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