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Construction and Application Effect Evaluation of an AI Knowledge Graph and AR/Naked-Eye 3D Technology-Based Intelligent Teaching System for Ophthalmic Lacrimal Duct Irrigation

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Abstract

Objective

To address limitations in traditional lacrimal duct irrigation teaching—including abstract anatomical representations, difficulty in repeatedly observing procedural details, and lack of immersive hands-on feedback—this study aimed to construct and preliminarily apply an AI knowledge graph and AR/naked-eye 3D technology-based intelligent teaching system for ophthalmic lacrimal duct irrigation.

Methods

A multidisciplinary team designed and developed an integrated teaching system combining “AI knowledge graph multimodal virtual simulation + intelligent assessment.” The system comprises an intelligent theoretical learning module, a multimodal interactive virtual simulation training module, and a data-driven intelligent assessment and teaching management module. The study employed a multi-stage applied validation design. A total of 94 participants—including ophthalmology interns, newly hired nurses, and specialized nurses—from a tertiary hospital were assigned to the intervention group. A parallel control group was established. Effectiveness was evaluated through metrics including theoretical assessment scores, procedural skill assessment scores, clinical error rates, training efficiency, and satisfaction levels.

Results

The intervention group demonstrated significantly superior outcomes across multiple metrics compared to the control group. Trainees using this system required 45%-46.1% fewer practice sessions to master operational skills, reduced total training duration by 40%-41.7%, achieved 10.4%-20.1% higher theoretical assessment scores, and increased procedural assessment pass rates to 93.3%-94.4%. Additionally, pre-clinical anxiety levels were markedly reduced. Furthermore, the system demonstrated high efficiency and reliability (Kappa = 0.87) in specialty nurse assessments, reducing single-assessment duration by over 50% while accurately identifying skill weaknesses. Trainee satisfaction was high (overall rating 4.32/5), with widespread recognition of features like 3D visualization, real-time guidance, and multi-case simulation. The system achieved a weekly active user rate of 82.4% and exhibited stable performance.

Conclusion

The AI-powered knowledge graph and AR/Naked-Eye 3D-based intelligent teaching system for ophthalmic lacrimal duct irrigation effectively integrates theoretical knowledge, immersive skill training, and data-driven assessment. It significantly enhances teaching efficiency, procedural safety, and nursing competency.

Introduction

Visual health is a vital component of national health, with growing demands for the diagnosis, treatment, and care of eye diseases. Lacrimal duct irrigation, as a fundamental procedure in ophthalmic clinical diagnosis and treatment, is widely applied in managing conditions such as lacrimal duct obstruction, chronic dacryocystitis, and dacryocystitis[1]. Its purpose is to assess the patency of the lacrimal duct, clear accumulated secretions from the lacrimal sac, and facilitate the instillation of medicinal solutions[2,3]. The standardization of this procedure directly impacts diagnostic accuracy and therapeutic outcomes.

The lacrimal system comprises the lacrimal puncta, lacrimal ducts, lacrimal sac, and nasolacrimal duct, exhibiting microscopic and complex anatomical features: the lacrimal puncta measure only 0.3–0.5 mm in diameter, the lacrimal ducts span approximately 10 mm in total length and are divided into vertical and horizontal segments, while the lower opening of the nasolacrimal duct is located on the anterior portion of the lateral wall of the inferior nasal meatus[4]. The spatial relationships and varying diameters of these structures demand extremely high precision during procedures. During clinical procedures, needle insertion depth must be controlled within 1–1.5 mm, with angular deviation limited to less than 15°[5]. Any deviation from these parameters may lead to complications such as lacrimal duct rupture or pseudotract formation. Standardized protocols, precise anatomical localization, and gentle manipulation are critical to ensuring procedural success while minimizing patient discomfort and preventing complications. Clinical data indicates that improper tear duct irrigation can cause corneal injury, tear point rupture, or infection spread, underscoring the critical importance of standardized training[6.]

However, the current teaching and training model for ocular lacrimal duct irrigation faces multiple severe challenges. The traditional teaching approach primarily employs a three-stage model of “theoretical instruction + model practice + clinical hands-on training,” relying on master-apprentice oral transmission, two-dimensional video viewing, and static silicone model exercises, which present significant limitations[7]. The lacrimal system features intricate structures located within body cavities, characterized by deep positioning and complex anatomical relationships. Abstractions in anatomical understanding make it difficult for novice nurses to establish accurate three-dimensional spatial concepts using flat diagrams or simplified models. This leads to unclear comprehension of needle insertion angles, depths, and trajectories—the primary root cause of procedural errors. Furthermore, physical models differ significantly from human tissue in material properties and force feedback, making it difficult for students to distinguish between normal resistance and obstruction resistance. Repeated use causes model wear and distortion of anatomical structures. Clinical internships are crucial for skill transfer, but performing initial practice procedures directly on patients imposes immense psychological pressure and medical risks, rendering hands-on training highly hazardous. Low patient tolerance and poor cooperation often complicate procedures. Mistakes may cause pain, bleeding, or even disputes[8], making instructors reluctant to delegate, thus depriving trainees of valuable hands-on experience. Furthermore, during lacrimal duct irrigation, encountering obstructed or narrowed ducts risks improper assessment by the

operator, potentially causing irrigation fluid to spray onto the nurse's head, face, or other body parts, posing a high risk of nosocomial infection[9]. Scarce high-quality clinical teaching resources and heavy teaching workloads for senior nurses make it difficult to provide consistent, one-on-one, repeatable guidance to every trainee, resulting in fragmented teaching resources. Trainees' learning outcomes heavily depend on individual aptitude and sporadic hands-on opportunities, leading to inconsistent training quality. Finally, assessment feedback remains subjective. Traditional evaluations rely on instructors' subjective observations and experiential judgments, lacking objective, quantifiable standards. Key parameters like needle insertion angle and pressure control cannot be quantified, making it difficult to pinpoint specific deficiencies in trainees' aseptic concepts, technique details, or procedural sequences. Feedback often remains at the level of “it feels wrong,” failing to provide precise directions for improvement. Therefore, cultivating specialized nurses capable of performing this procedure with standardized technique, proficiency, and confidence is a core element in ensuring the quality of ophthalmic care and patient safety.

With the advancement of medical technology and the digital transformation of medical education, digital technologies such as AI knowledge graphs, virtual reality (VR), augmented reality (AR), and glasses-free 3D are opening new pathways for medical education. AI knowledge graphs construct structured knowledge networks, transforming discrete medical concepts into semantically connected cognitive systems. This endows machines with capabilities for understanding, reasoning, and intelligent question-answering, injecting a “smart brain” into teaching systems[10]. AR technology achieves real-time visualization of anatomical structures and procedural guidance through the overlay of virtual and real elements. Glasses-free 3D technology presents stereoscopic images without requiring auxiliary devices, resolving the inconvenience of wearing traditional 3D glasses and the limitations of their field of view[11]. The integration of these three technologies forms a complete “cognition-interaction-presentation” chain, validated in high-risk skill training like aviation and surgery. It creates high-fidelity, repeatable training environments, supporting learners in building comprehensive cognitive maps and muscle memory through deliberate practice[12,13]. However, this deeply integrated model remains exploratory in China's ophthalmic nursing field. Specifically, intelligent teaching systems combining AI knowledge graph cognitive reasoning with AR/glasses-free 3D immersive interaction for precise procedures like lacrimal duct irrigation represent an industry gap. Therefore, this study aims to develop and apply an AI knowledge graph-based, AR/glasses-free 3D technology-integrated intelligent teaching system for ophthalmic lacrimal duct irrigation. This approach seeks to overcome traditional teaching challenges while enhancing training quality and efficiency.

1. System Development

1.1 Research Team

This study established a multidisciplinary collaborative team comprising three ophthalmic nurse practitioners, one ophthalmologist, two nursing education specialists, one software engineer, and one 3D

modeler. The ophthalmic nurse specialists primarily provided detailed standard operating procedures for tear duct irrigation, common clinical issues and solutions, and participated in the systematic development of virtual simulation experiment scripts. They supplied highly relevant firsthand materials—including authentic case studies, clinical images, and procedural videos—tailored to instructional needs. The ophthalmologist ensures precise medical content, validates procedural standards, reviews anatomical and pathophysiological accuracy of 3D models, and provides professional guidance for case scenario design. Nursing education specialists translate clinical knowledge into structured learning pathways and interactive scripts, designing progressive teaching modules aligned with educational principles while establishing quantifiable, actionable assessment systems. Technical implementation is jointly executed by software engineers and 3D modelers. Software engineers focus on constructing knowledge graphs, integrating AR/3D technologies, and developing/integrating system platforms, handling system architecture design and functional implementation. 3D modelers reference actual ophthalmology ward environments and physical elements like medical staff, patients, and medical devices to create high-precision eye anatomy models using 3D modeling techniques, optimizing their display across various devices.

1.2 System Architecture

Centered on the pedagogical principles of “Precision-Based Learning, Immersive Training, Data-Driven Development, and Personalized Advancement,” the system establishes an integrated teaching framework comprising “1 Intelligent Foundation + 2 Major Training Modules + 1 Assessment Management System.” Powered by an AI knowledge graph as its foundational engine, the system employs virtual simulation and AR interaction for practical training, with intelligent assessment forming a feedback loop. This achieves comprehensive coverage from structured theoretical knowledge construction to autonomous clinical skill development. The system comprises three layers: The application service layer incorporates a virtual simulation engine and an intelligent assessment engine, enabling automated scoring based on rules and data analysis. The interactive presentation layer utilizes mobile AR devices such as smartphones and AR glasses for personalized interactive training, combined with naked-eye 3D displays for group instruction and demonstrations, thereby achieving a closed-loop “cognition-interaction-presentation” process.

1.3 Core Module Construction

1.3.1 AI Knowledge Graph-Based Intelligent Theoretical Learning System

This system addresses fragmented knowledge and passive learning. By integrating natural language processing (NLP) with domain expert rules, it structures vast amounts of unstructured knowledge—including anatomy, physiology, pathology, and nursing related to lacrimal duct irrigation—into an interconnected structured knowledge graph. Each node in the graph dynamically links to relevant resources such as 3D models, videos, literature, and complications. It also offers intelligent interactive Q&A and personalized content delivery. Learners can pose questions anytime using natural language.

The system interprets query intent, performs intelligent retrieval and reasoning within the knowledge graph, and precisely delivers relevant 3D model animations, key literature excerpts, or standard procedure videos. This shifts the paradigm from “people seeking knowledge” to “knowledge finding people,” enabling inquiry-based, personalized learning.

1.3.2 Virtual Simulation Training System for Multimodal Interaction

Empowered by knowledge graphs, this module provides trainees with a highly immersive and realistic skill training environment, addressing the challenges of “hesitation to perform and lack of proficiency.” It comprises two submodules: instructional demonstration and simulated practice.

1.3.2.1 Instructional Demonstration Module：This module tackles cognitive challenges of “incomprehension and retention difficulties” by enabling trainees to rapidly establish accurate operational mental models through highly immersive experiences. The system incorporates high-precision, interactive 3D models of the ocular and lacrimal systems. Trainees can rotate, zoom, adjust transparency, or perform layered dissection using gestures to examine the tear duct's spatial orientation, physiologically narrow segments, and relationships with surrounding tissues from any angle. This eliminates comprehension barriers inherent in two-dimensional diagrams and verbal descriptions. Additionally, it incorporates animated demonstrations of Standard Operating Procedures (SOPs). These animations, presented from either a first-person perspective or a third-person follow-along view, comprehensively and coherently showcase the entire process: from pre-procedure preparation (hand washing, verification, patient positioning, instrument preparation) through the procedure itself (needle insertion angle, advancement depth, irrigation technique) to post-procedure management (outcome assessment, documentation, instrument disposal). Animations support frame-by-frame playback, slow motion, and looping of specific steps, accompanied by text annotations and voice-over commentary highlighting critical action points and common pitfalls. They also visually demonstrate potential consequences of improper technique—such as false tract formation, tissue damage, and bleeding—while analyzing error causes to reinforce trainees' risk awareness and motivation for standardized practice.

1.3.2.2 Simulation Practice Module：This module addresses the challenge of skill transfer—overcoming hesitation and achieving proficiency—by providing a safe, repeatable, high-fidelity training environment. It offers diverse practice modes and scenarios, featuring a guided step-by-step training approach that breaks down complete procedures into critical sub-steps. Trainees progress through procedures guided by AR cues—such as virtual arrows indicating needle insertion direction and floating text prompts for next actions. The system provides real-time force feedback simulation or visual cues to replicate tactile sensations like the “hollow feeling” encountered during actual needle insertion. Free practice mode allows trainees to perform complete, independent procedures after mastering basic steps, reinforcing skills and developing operational fluency and continuity. Multiple simulated clinical scenarios include pre-set virtual cases of varying difficulty, such as lacrimal duct obstruction, common lacrimal duct obstruction, and dacryocystitis. Trainees must select corresponding diagnoses within the system based on different irrigation results, thereby training clinical diagnostic reasoning.

1.3.3 Data-Driven Intelligent Assessment and Teaching Management System

This module utilizes knowledge graphs to define assessment dimensions, achieving objectivity and data-driven evaluation and management. It aims to resolve the challenges of “inaccurate and unclear assessments” in teaching evaluations, enabling objective and data-driven skill assessments. The system's backend incorporates a quantitative scoring algorithm that performs multidimensional, fully automated evaluations of the entire trainee operation process. Assessment metrics include: Operation Time: Total duration and time spent on each step. Operational Accuracy: Correct instrument selection, precise needle angle and depth, avoidance of sterile field contact, and standardized flushing technique. Process Completeness: Omission of critical steps. Correctness of outcome judgment: Ability to provide accurate diagnoses based on irrigation findings. Error frequency: Records of serious errors like creating false passages or contamination. Upon completion, the system automatically generates a visual assessment report containing total scores, sub-scores, and radar charts. Trainees and instructors can review the entire procedure, with the system highlighting exemplary and problematic steps in different colors and providing specific improvement suggestions for precise feedback. The system backend tracks each trainee's learning trajectory, practice duration, assessment scores, and areas of weakness, forming personalized learning profiles. Instructors can monitor overall training progress in real-time, enabling personalized, data-driven teaching management.

2. System Application and Effectiveness Evaluation

2.1 Research Subjects

This study employs a multi-phase application validation design to conduct systematic evaluations across three critical components of the ophthalmic nursing education system. The subjects encompass the entire career progression from students to clinical nurses. Specifically, Application Group A comprises 30 ophthalmology interns from the 2023 and 2024 cohorts at a university; Application Group B consists of 36 newly hired ophthalmology nurses from two hospitals in 2023; and Application Group C includes 28 practicing ophthalmology specialty nurses. Parallel control groups using traditional teaching models were established for each group.

2.2. Intervention Protocol

During the teaching process, this study developed a progressive training and assessment plan tailored to the three distinct professional development stages of nursing personnel.

2.2.1 Ophthalmology Intern Intervention Protocol (Application Group A)

Application Group A undergoes a 5-day, 40-hour pre-service immersive intensive training program. During the initial phase, trainees gain an in-depth understanding of the spatial configuration of lacrimal duct anatomy through interactive 3D models under systematic guidance. They also learn standard procedures and key points for managing complications using knowledge graphs. After mastering anatomical structures, trainees undergo step-by-step guided hands-on practice on physical models using AR devices, with the system providing real-time visual cues and corrective feedback. Following foundational skill acquisition, trainees independently complete diverse case simulations in a virtual environment, where the system records their operational pathways, angular deviations, and decision-making processes. At the training conclusion, trainees undergo a comprehensive AI-powered assessment, generating automated reports for group debriefing and personalized feedback. The research team tracks learning behavior data through the system's backend and collects pre- and post-training data on theoretical scores, procedural ratings, and confidence scales to evaluate short-term learning outcomes and psychological preparedness.

2.2.2 Intervention Protocol for Newly Hired Ophthalmic Nurses (Application Group B)

Application Group B integrates the system into a three-month standardized training program divided into foundational, proficiency, and certification phases. During the first month, nurses must complete the system's theoretical modules and achieve predetermined proficiency thresholds in guided training. The second month focuses on comprehensive application across diverse pathological scenarios, requiring stable procedural performance within specified attempt limits. In the third month, nurses must pass the system's rigorous final assessment and complete a clinical skills evaluation supervised by a preceptor to obtain independent practice authorization. The research team records trainees' phased achievement data and practice curves within the system. For three months after their independent deployment, clinical operational safety data is continuously tracked via the hospital's adverse event reporting system. The system also quantifies the direct instructor time saved, enabling a comprehensive evaluation of its value in enhancing training efficiency, ensuring clinical safety, and optimizing resource allocation.

2.2.3 Intervention Plan for Practicing Ophthalmic Specialty Nurses (Application Group C)

Application Group C primarily utilizes the system's intelligent assessment module as an objective evaluation tool for annual skill recertification and hierarchical promotion. Prior to assessment, the system provides personalized review content targeting historical data-identified weaknesses. During formal assessments, nurses independently manage complex, randomly selected comprehensive cases in an unassisted environment. The system automatically collects and quantifies performance scores. The generated evaluation reports serve as key evidence for individual promotions while providing data support for developing advanced training plans for subsequent phases.

2.2.4 Parallel Control Group

The control group employs conventional teaching methods. Interns and newly hired nurses receive traditional instruction of equivalent duration, including large-class theory lectures, instructional video viewing, and practice using physical models. Current nurses undergo traditional practical assessments scored by examiners through subjective observation. Data for the control group is collected using the same evaluation tools at the same time points as the intervention group.

2.3 Evaluation Criteria

2.3.1 Theoretical Assessment Scores

Following the intervention, a standardized closed-book examination was administered. The content covered lacrimal duct anatomy, the sequence of lacrimal duct irrigation procedures, complication identification, and complex case analysis. The test comprised 40 objective questions and 2 scenario analysis questions, totaling 100 points. Scoring employed a dual-review model. The performance grading criteria were as follows:85 points and above: Excellent (Complete Mastery) 75–84 points: Good (Basic Mastery), 60–74 points: Pass (Partial Mastery), Below 60 points: Fail.

2.3.2 Procedural Skill Assessment Pass Rate

The procedural skills assessment is conducted in a standardized simulated environment, evaluating dimensions including aseptic technique, needle insertion angle, procedural integrity, and clinical judgment accuracy. Each dimension has specific scoring criteria and weightings, with a total score of 100 points. The pass criteria require a score of at least 80% in each dimension and a total score of 85 points. The entire assessment process is video-recorded and automatically scored by the system.

2.3.3 Clinical Error Rate

Actual performance of newly hired nurses during their initial independent practice period is tracked. Complications related to tear duct irrigation procedures are collected through the hospital's adverse event reporting system. Data is gathered over a 90-day period following independent practice commencement. Standardized statistics are calculated using the incidence rate per 100 procedures, with risk variance analysis conducted against historical data from the same period.

2.3.4 Training Efficiency

Measures the number of practice sessions and training duration required to meet assessment standards. Key metrics include total virtual training time needed to reach the procedural assessment threshold and the number of practice sessions from the first attempt to achieving three consecutive passing assessments. Cumulative effective training duration and total practice sessions per trainee are recorded. Efficiency improvement percentages are calculated by comparing these metrics with control group data.

2.3.5 Psychological Readiness

The Self-Rating Anxiety Scale (SAS)[14]is used to assess trainees' psychological anxiety prior to their first clinical operation. This 20-item scale employs a 4-point scoring method (1–4 points), with ≥ 50 points indicating anxiety. Higher SAS scores reflect greater anxiety severity.

2.3.6 Satisfaction

A structured satisfaction assessment tool was employed, comprising 10 core evaluation items. Each item corresponded to a specific descriptive statement, requiring trainees to rate their actual experience on a scale from “Strongly Disagree” (1 point) to “Strongly Agree” (5 points). Core items encompass three dimensions: system usability, learning effectiveness, and willingness to promote. A score ≥ 4.0 for each item indicates positive endorsement. Overall satisfaction is considered satisfactory when the total average score ≥ 4.0.

2.4 Statistical Methods

Data analysis was performed using SPSS 26.0 software, with statistical methods selected based on data characteristics. Quantitative data are presented as mean±standard deviation. Paired t-tests were used for within-group pre-post comparisons, while analysis of variance (ANOVA) was employed for multi-group comparisons. Qualitative data are expressed as frequency and percentage, analyzed using chi-square (χ^2) tests. Inter-rater reliability was assessed via Kappa tests. All statistical tests set $P < 0.05$ as the threshold for statistical significance.

3. Application Effect Evaluation

3.1 Application Group A

A controlled study involving 30 ophthalmology interns revealed that Application Group A, which underwent pre-service training using this system, significantly outperformed the traditional teaching group across multiple metrics. The average number of practice sessions required for Application Group A to meet operational assessment standards was 5.5 ± 1.8, representing a 45% reduction compared to the control group's 10.0 ± 2.0 sessions ($t = 9.16$, $P < 0.001$). Regarding total training duration, Group A completed 12.0 ± 3.0 hours, representing a 40% reduction compared to the control group's 20.0 ± 4.0 hours ($t = 8.76$, $P < 0.001$). Theoretical assessment scores showed that the mean score for Group A was 92.5 ± 4.2 points, representing a significant 18.1% improvement compared to the control group's 78.3 ± 6.8 points ($t = 9.73$, $P < 0.001$). In psychological readiness assessment, Group A's pre-clinical operation anxiety self-assessment score (SAS) was 36.±5.2, significantly lower than the control group's 51.5 ± 6.8 ($t = 9.40$, $P < 0.001$). The results of the operational skills assessment showed that the pass rate for Group A after training was 93.3% (28/30), significantly higher than the 66.7% (20/30) in the control group ($\chi^2 = 6.67$, $P = 0.010$). This indicates that Group A demonstrated superior performance in procedural compliance, process integrity, and clinical judgment accuracy.

3.2 Application Group B

During the standardized training of 36 newly recruited nurses, this system demonstrated excellent clinical translation outcomes. Application Group B required an average of 6.2 ± 1.5 practice sessions to meet procedural assessment standards, representing a 46.1% reduction compared to the historical control group's 11.5 ± 2.8 sessions (t = 10.02, P < 0.001). Regarding total training duration, Group B required 14.0 ± 3.2 hours, significantly lower than the control group's 24.0 ± 5.0 hours (approximately 41.7% reduction, t = 9.55, P < 0.001). Theoretical assessment scores showed that the mean score in Group B was 90.8 ± 4.5 points, representing a significant 20.1% improvement compared to the control group's 75.6 ± 7.0 points (t = 10.64, P < 0.001). In psychological readiness assessment, Group B's pre-clinical operation anxiety self-assessment score (SAS) was 38.2 ± 5.6, significantly lower than the control group's 52.8 ± 6.4 (t = 9.87, P < 0.001). The procedural assessment pass rate reached 94.4% (34/36), representing a 30.6% increase compared to the historical control group's 72.2% (26/36) (χ^2=6.4, P = 0.011). The complication rate within three months post-deployment was 2.8% (1/36) in Group B, significantly lower than the control group's 13.9% (5/36) (χ^2=2.91, P = 0.088). Resource efficiency analysis indicated a reduction of 8 ± 2 teaching hours per instructor (t = 12.33, P < 0.001), demonstrating significantly optimized faculty-to-output ratio. These findings validate the system's comprehensive value in enhancing training quality, ensuring patient safety, and optimizing resource allocation.

3.3 Application Group C

During the annual competency assessment of 28 specialty nurses, the intelligent assessment system exhibited high efficiency and precision. For practical skills assessments, Group C achieved an average score of 88.6 ± 5.2 points, representing an approximately 11.6% improvement (t = 4.82, P < 0.001) over the previous year's traditional assessment score of 79.4 ± 7.8 points. Scores in both “standardization of operational procedures” and “anatomical localization accuracy” exceeded 90%. Theoretical assessment results showed that Group C achieved an average score of 91.3 ± 4.0 points, representing a 10.4% increase (t = 5.64, P < 0.001) compared to the previous year's theoretical assessment score of 82.7 ± 6.5 points. The average time per assessment was 14.2 ± 2.5 minutes, representing a 50% efficiency improvement compared to the previous year's theoretical assessment score of 28.4 ± 3.1 points (t = 19.32, P < 0.001). Assessment data revealed common skill weaknesses: the “fine-tuning technique at the lacrimal duct bend” item achieved an average score rate of 76.3%, while the “judgment of outcomes under different obstruction scenarios” item scored 81.5%. Analysis of agreement between system scoring and expert evaluation yielded a Kappa value of 0.87 (P < 0.001), indicating strong reliability of assessment outcomes. Quantitative data-driven group competency profiles provided clear direction for targeted continuing education, facilitating a shift from “outcome evaluation” to “process improvement” in assessment models.

3.4 Teaching Satisfaction and System Performance

In Application Group A, system satisfaction averaged 4.28 ± 0.49 points, with “depth of anatomical understanding” (4.50 ± 0.41) receiving highest recognition. Average training duration per session was 38.2 ± 10.5 minutes, with a weekly active rate of 85.6%, and abnormal exit rate was 0.7%. Open-ended feedback frequently highlighted “3D visualization aids anatomical comprehension” and “real-time

guidance reduces operational anxiety" as most valuable features. Application Group B reported a satisfaction score of 4.35 ± 0.52, with "Enhanced Procedural Confidence" (4.52 ± 0.40) receiving particularly high ratings. Training duration averaged 34.8 ± 11.7 minutes, weekly activity rate was 83.1%, and abnormal exit rate was 0.6%. Feedback consistently highlighted that "multiple case simulations" and "visualization of error consequences" significantly aided clinical adaptation. Suggestions included "adding rare cases" and "optimizing force feedback realism." Application Group C reported a satisfaction score of 4.33 ± 0.50, with the highest rating for "objectivity of assessment" (4.48 ± 0.42). Training duration averaged 33.8 ± 9.5 minutes, weekly activity rate was 78.5%, and abnormal exit rate was 0.9%. Open feedback highlighted "detailed intelligent assessment reports" and "historical data tracking" as valuable continuing education tools, while expressing expectations for "system integration with hospital case databases" and "enhanced advanced complication simulation modules." All trainees rated the system 4.32 ± 0.51 points (on a 5-point scale). The overall average single training session duration was 35.6 ± 12.3 minutes, with a weekly activity rate of 82.4% and an abnormal exit rate of 0.73%. All metrics met the preset performance standards. In learner feedback, "3D visualization effects" and "real-time error correction mechanisms" were widely regarded as the most valuable features; "force feedback realism" and "case database richness" were the primary areas for improvement.

4. Discussion

4.1 This system significantly enhances trainees' theoretical mastery, operational proficiency, and clinical safety.

For ophthalmology interns, the system's educational efficacy manifests in dual improvements: cognitive construction and skill transfer. Research data indicates that the experimental group achieved an 18.1% higher score on theoretical assessments compared to the control group, while the number of practice sessions required to meet skill proficiency standards decreased by 45%. This suggests that an immersive 3D learning environment effectively facilitates the spatial cognitive transformation of anatomical knowledge. The high-fidelity, zero-risk virtual simulation environment provides unlimited opportunities for repeated practice, promoting the formation of muscle memory and operational confidence[15]. Previous studies indicate that under traditional two-dimensional teaching models, trainees typically require 4–6 weeks of clinical observation to establish three-dimensional cognition of the lacrimal duct[16]. This system compresses this process to completion within 2 days. The core mechanism behind this efficiency gain lies in the system's simultaneous delivery of "visual cognition" and "muscle memory training." Learners can practice spatial operations while understanding anatomical structures, eliminating the temporal separation between cognition and operational training in traditional teaching. This makes abstract knowledge intuitive and tangible[17]. Training data for newly hired nurses further validates the system's clinical translation capabilities. The procedural assessment pass rate reached 94.4%, a 30.6% improvement over traditional methods, while clinical complication rates dropped to 2.8%. This reflects the standardized advantages of system-based training: AI knowledge graphs ensure theoretical completeness, AR guidance guarantees procedural standardization, and multi-case

simulations enhance complexity management. Additionally, the system reduced direct instructor guidance time by an average of 8 class hours, demonstrating how intelligent systems effectively share foundational skill training tasks. This allows faculty to focus on cultivating more complex clinical reasoning, achieving structured optimization of teaching resources[18].

4.2 The System Effectively Addresses the Triple Challenge of Teaching Resources, Operational Safety, and Standardized Assessment

By integrating AI knowledge graph technology, this system successfully consolidates fragmented professional knowledge to establish a hybrid virtual-physical intelligent teaching pathway. In ophthalmology intern training, it demonstrates clear advantages: experimental group trainees achieved procedural competency standards with 45% fewer practice sessions, reduced total training duration by 40%, and improved theoretical assessment scores by an average of 18.1%, effectively resolving knowledge gaps and low learning efficiency[19].Addressing the cognitive bottleneck of “invisibility and intangibility” caused by hidden structures in traditional teaching, the system employs high-precision 3D visualization and AR overlay technology to achieve intuitive presentation of anatomical structures and real-time guidance during procedures [20]. This not only significantly enhances trainees' spatial cognition but directly translates into increased procedural confidence. Trainees in the experimental group exhibited significantly lower anxiety levels before their first clinical procedure compared to the control group, demonstrating effective translation from cognitive understanding to procedural competence. In addressing the core challenge of limited clinical practice opportunities versus patient safety risks, the system's high-fidelity, zero-risk simulation environment plays a pivotal role [21]. In standardized training for newly hired nurses, trainees using the system achieved a 94.4% pass rate in procedural assessments. Within three months of employment, their complication rate was only 2.8%. These data confirm that the system effectively enhances the intensity and efficiency of skill training while optimizing teaching resource allocation, all while ensuring patient safety. To further address the issues of subjective and delayed teaching feedback, the system enables full-process data collection and intelligent analysis. In specialty nurse competency assessments, the intelligent evaluation system not only reduces per-person assessment time by over 50% but also achieves a high consistency rate of 0.87 (Kappa value) with expert reviews. It precisely identifies common skill weaknesses, such as “fine-tuning technique at the bend of the lacrimal duct,” driving the transformation of teaching evaluations toward an objective, accurate, and traceable model. Furthermore, by simulating diverse complex pathological scenarios, the system compensates for the limited case types encountered during clinical rotations.

4.3 Virtual-Physical Empowerment: Establishing a New Paradigm for Digital-Intelligent Tear Duct Irrigation Training

This system deeply integrates AI and multimodal technologies, achieving a systematic transformation in teaching methodologies. Its built-in AI knowledge graph for tear duct irrigation care constructs a structured, interconnected “domain expert system.” This system not only guides trainees on “how to perform procedures” but also explains “why these steps are necessary,” shifting learning from passive imitation to deep understanding and independent exploration. Simultaneously, leveraging high-precision 3D reconstruction and AR overlay technology, the system creates a multimodal immersive learning environment. Trainees can observe three-dimensional anatomical structures from multiple angles, achieving precise registration between virtual models and physical space, effectively overcoming the spatial cognition limitations of traditional two-dimensional teaching. The further integration of a high-fidelity physics engine simulates real-world mechanical feedback and pathological dynamics during procedures, providing trainees with a safe, infinitely repeatable environment for honing precise skills [22]. Through comprehensive data collection and intelligent analysis, the system enables quantitative assessment of operational metrics and personalized feedback, elevating teaching evaluation from subjective experience to data-driven objectivity and forming a complete precision teaching loop [23]. The integrated hardware-software solution employing “mobile AR + naked-eye 3D” ensures precise virtual-reality overlay while significantly reducing deployment costs. This grants the system outstanding scalability and adaptability, enabling broad coverage across diverse training settings—from large hospitals to primary care units—and truly aligning with China's urgent need for large-scale, high-quality nursing talent development.

4.4 Limitations

While validating the system's effectiveness, this study also identifies areas requiring further refinement. The knowledge graph's coverage depth remains limited, primarily focusing on standard operating procedures and common complications. It currently lacks sufficient inclusion of rare cases, individual variations, and the latest clinical guidelines, which somewhat impacts the system's reasoning and adaptability in complex clinical scenarios. Additionally, the system's multimodal interaction experience has room for improvement. The current force feedback mechanism lacks deep integration with the tissue mechanics parameters in the knowledge graph, resulting in discrepancies between simulated tactile sensations and the elastic differences of real tissues under various pathological conditions. This gap diminishes the realism and immersion of the training experience [24]. Furthermore, the breadth and depth of pedagogical validation require strengthening. Current research relies solely on single-center, short-term teaching experiments with limited sample sizes, lacking long-term tracking of trainees' skill retention. These factors constrain the generalizability of research conclusions.

Future progress should focus on two directions: technological refinement and validation expansion. The core technical challenge lies in achieving organic integration between knowledge graphs and multimodal perception. This can be achieved by developing intelligent simulation instruments equipped with high-precision sensors to collect real-time mechanical data and dynamically correlate it with tissue characteristics in the knowledge graph. This enables the construction of force feedback models that accurately reflect different pathological states. Building upon this foundation, knowledge graphs and

trainees' full-process operational data can be leveraged to create personalized learner capability profiles[25]. Intelligent algorithms can then dynamically adjust learning paths in real time, ultimately forming an adaptive, precision-oriented smart teaching system. To validate effectiveness, multi-center, large-sample, long-term teaching efficacy studies are required. These should systematically evaluate the sustained impact of this training model on clinical operational competence, safety awareness, and long-term skill retention. This will provide more robust and comprehensive evidence-based support for system optimization and widespread adoption, driving the continuous advancement of nursing skills training toward intelligent, personalized, and standardized approaches.

5. Results

The AI knowledge graph-based ophthalmic tear duct irrigation intelligent teaching system developed in this study, integrated with AR/naked-eye 3D technology, effectively combines cutting-edge information technology with nursing education requirements. It achieves a deep integration of systematic theoretical knowledge construction, immersive practical skill training, and data-driven teaching evaluation. Preliminary applications demonstrate that this system significantly enhances teaching efficiency and quality, reduces clinical training risks, and improves nurses' job competency. Beyond providing an innovative tool for specialized ophthalmic nursing talent development, its technical framework—combining knowledge graphs, multimodal interaction, and intelligent assessment—offers a replicable paradigm for intelligent training of other high-risk, high-precision operational skills in medical education, presenting broad prospects for promotion and application.

Declarations

Human Ethics and Consent to Participate

This study involving human participants (ophthalmology interns, newly hired nurses, and specialized nurses) was reviewed and approved by the Ethics Committee of the First Affiliated Hospital of Air Force Medical University (Ethics Approval Reference Number: 2024-YX-032). All participants were fully informed of the study’s objectives, procedures, potential risks, and voluntary participation rights prior to enrollment. Written informed consent was obtained from each participant. The study was conducted in strict accordance with the Declaration of Helsinki (2013 revision) and the ethical guidelines for medical education research in China.

Funding Declaration

This study received no specific funding from any funding agency in the public, commercial, or not-for-profit sectors.

Consent for publication

This manuscript does not contain any individually identifiable data (e.g., names, contact information, clinical records, or visual materials) of the study participants. No participant images or personal details are included. Therefore, consent for publication is not applicable.

Availability of data and materials

The minimal dataset generated and/or analysed during the current study (including theoretical assessment scores, procedural skill scores, training duration, error rates, satisfaction ratings, and anxiety levels) is not publicly available to protect participant privacy and comply with the institutional data management policies of Air Force Medical University. However, the dataset is available from the corresponding author (Mengyao Wang) on reasonable request for non-commercial research purposes. The AI knowledge graph and AR/naked-eye 3D intelligent teaching system developed in this study (including core modules and evaluation protocols) is also available from the corresponding author on reasonable request for educational and non-commercial research use.

Competing interests

The authors declare that they have no competing interests (financial or non-financial) related to this work.

Authors' contributions

MW (Mengyao Wang) conceived and designed the study, led the development of the AI/AR intelligent teaching system, drafted the initial manuscript, and coordinated the study implementation.

MZ (Meixia Zhang) supervised the study, revised the manuscript critically for important intellectual content, and provided expertise in nursing education methodology.

LC (Lina Cheng) and AZ(Ajuan Chen) were responsible for participant recruitment, intervention delivery, and primary data collection.

LZ (Lingli Zhao) managed data entry, verification, and preliminary analysis.

XB (Xue Bai) contributed to the validation of the teaching system and assisted with manuscript revision.

All authors read and approved the final manuscript and agreed to its submission to BMC Medical Educatio.

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Clinical trial number

not applicable

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