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Computer-Based Simulation for Pediatric Cardiovascular Disease Management: A Policy Brief

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Background

Cardiovascular diseases are significant global health concerns, particularly in children, and encompass a broad spectrum of conditions from congenital heart defects to acquired heart diseases.[1,2] Despite medical advancements, treating pediatric CVDs remains complex, often requiring intricate surgeries, medications, or catheter-based procedures.[3] CHDs affect a considerable number of infants annually and complicate surgical planning due to anatomical intricacies.[4-7] Accurate diagnosis and preoperative planning heavily rely on precise depictions of the heart's anatomy and function, yet traditional imaging methods such as 2-dimensional echocardiography, have limitations in portraying the intricate 3-dimensional dynamics of the heart.[4,5,8]

In recent years, computer-based simulation (CBS) technologies have emerged as promising tools in pediatric cardiovascular care, offering innovative solutions to longstanding challenges.[9-12] These technologies, including Virtual Reality (VR), Augmented Reality (AR), Mixed Reality (MR), and 3D modeling, hold immense potential to revolutionize medical education, surgical planning, and procedural training.[6] By providing realistic virtual models of the heart, CBS offers a platform for comprehensive analysis, enhancing the understanding of complex cardiac pathologies and interventions.[11,13-20]

Recent advancements in Extended Reality (XR), particularly in VR headsets and graphics cards, have significantly enhanced user experience, making VR a prime candidate for surgical planning and diagnostics due to its immersive nature.[21] AR and MR are attractive for real-time procedural guidance as they allow surgeons to maintain real-world awareness.[21,22] However, there are several challenges including a limited visual field, resolution limitations, and the need for a regulatory approval. Clinical studies on XR's impact on procedural outcomes in pediatric structural heart disease are scarce and varied due to the complexities of patient populations. However, their results suggest the positive outcomes of using the technology which includes improving operator confidence, reducing procedural times, and enhancing anatomical understanding.[21,22]

Healthcare providers, policymakers, and medical instructors can simulate real-world scenarios and gain practical insights into how these technologies can revolutionize diagnostic accuracy, surgical planning, and medical training in this critical field.[23,24]

Pediatric CVDs management presents unique challenges due to its complexity and the limitations of conventional imaging methods. Fortunately, CBS technologies, including VR, AR, and 3D modeling, are emerging as powerful tools to improve patient care in this critical area. This policy brief explores the potential of CBS in pediatric cardiology, highlighting its impact on diagnosis, surgical planning, procedures, and training. By understanding the benefits of CBS, policymakers can create an environment that fosters its widespread adoption and integration into pediatric cardiac care practices for better health outcomes.

Policy Background

The FDA highlights how AR and VR are transforming healthcare with innovative diagnostic and treatment methods. AR and VR enhance pediatric diagnostics, pain management, mental health treatment, neurological rehabilitation, and surgical planning. They also improve ophthalmic diagnostics and expand telemedicine, making healthcare more accessible. Despite their benefits, AR/VR technologies pose risks such as cyber-sickness, physical

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strain, cybersecurity issues, potential distractions during procedures, and unknown side effects, particularly in vulnerable populations like children. As a result, the FDA regulates AR/VR medical devices and provides a periodically updated list of approved devices, ensuring careful management to mitigate these risks.[25]

In another policy brief, the European Institute for Asian Studies spotlights the growing role of digital tools in enhancing clinical outcomes, with efforts focused on digital infrastructure and emerging technologies. The policy brief indicated that adopting computer-based simulations requires policy measures for standardized protocols, data interoperability, and specialized training. It also stresses the importance of secure integration to protect patient data. Prioritizing these technologies could improve decision-making and care quality for patient's conditions while aligning with broader EU digital health strategies.[26]

Key Findings

The findings reported in this section are derived from a systematic review conducted in 2023. In this study, the applications and benefits of computer-based simulation technologies in pediatric CVDs management were investigated.

- Studies have demonstrated that VR, AR, MR, and 3D modeling technologies enhance preoperative planning for complex CHD cases.[8,27-34] These tools provide detailed visualization of cardiac anatomy, enabling surgeons to develop precise surgical strategies and reduce intraoperative adjustments.[10,27,35]
- CBS offers immersive learning experiences for medical professionals and students and facilitates understanding of complex cardiac structures and congenital defects. By integrating VR, AR, and MR into medical education curricula, healthcare providers can enhance training and skill development in pediatric cardiovascular care.[10,33,36]
- Mixed reality holographic guidance and VR imaging helps to improve accuracy in diagnosing CHD and related abnormalities. Surgeons can utilize these technologies to optimize diagnostic workflows, leading to more accurate diagnoses and informed decision-making during surgery.[8,28-30,33,34,37]
- Virtual endoscopy and other CBS applications offer high diagnostic accuracy for congenital heart defects, potentially leading to earlier intervention and better patient prognosis.[38]
- The adoption of CBS technologies has the potential to streamline diagnostic and surgical workflows, resulting in savings in time and resources. MR holograms and 3D printed models offer cost-effective alternatives for surgical planning, reducing procedural times and improving overall surgical outcomes.[28,35,39]
- Techniques such as computational fluid dynamics (CFD) simulate blood flow and hemodynamics within these models, providing insights into disease mechanisms and potential intervention outcomes.[40-42]

Policy Recommendations

This brief proposes 8 key action areas (Table 1). They aim to improve the use of CBS in pediatric cardiology care.

Table 1. Policy Recommendations for Integrating CBS in Pediatric Cardiology.

Domain	Policy recommendations
Technology adoption	• Health policymakers and health care providers should collaborate with technology providers to integrate VR, AR, MR, and 3D modeling into pediatric cardiac care. This includes securing funding for VR/AR/MR equipment, 3D printing facilities, software development, and ensuring these resources are tailored to the unique needs of healthcare providers. • Policymakers must ensure equitable access to computer-based simulation technologies, especially in underserved and rural areas. Telemedicine programs and mobile simulation units can expand access to these technologies in remote communities, guaranteeing all pediatric patients receive high-quality cardiovascular care. Holographic consultations, where patients interact with virtual specialists, can further improve access to expert advice regardless of location.
Funding, incentives and sustainability	• To help cover initial costs, promote broader use, and accelerate the adoption of computer-based simulation technologies and these technologies, policymakers should offer financial incentives, such as reimbursements, to healthcare providers and institutions. • Policymakers should prioritize long-term sustainability of computer-based simulation initiatives by providing ongoing funding for maintenance, upgrades, and staff training. Additionally, incentives for private sector investment in simulation technology development and implementation can promote widespread use and technological advancement.
Regulation and ethics	• Regulatory agencies should establish guidelines for the ethical and safe use of computer-based simulation technologies in pediatric care. Guidelines must address patient privacy, data security, and bias while ensuring ethical alignment with beneficence, non-maleficence, and justice, alongside promoting transparency to maintain stakeholder trust.
Education and training	• To improve pediatric cardiovascular care training, medical education programs can leverage computer-based simulations and explore the potential of VR/AR/MR technologies in patient care. This approach can lead to the development of immersive and interactive learning modules that enhance decision-making skills and procedural competence in a safe, controlled environment. • Establishing standardized training and certificate programs for healthcare professionals in the use of computer-based simulation technologies is essential. These programs should go beyond technical skills to encompass ethical considerations, best practices for scenario development, and effective debriefing techniques to maximize learning impact.
Collaboration	• Policymakers should encourage the formation of collaborative networks between healthcare institutions, technology developers, and regulatory agencies to foster innovation and knowledge-sharing in the field of computer-based simulation. These partnerships should focus on developing best practices and quality standards for computer-based simulation in pediatric cardiovascular care. • Creating a global network where healthcare providers can share and crowdsource simulation scenarios and solutions, can foster a collaborative approach to pediatric cardiovascular disease management.
Public awareness	• Public awareness campaigns should be launched to educate parents, caregivers, and patients about the benefits of computer-based simulation in pediatric cardiovascular care. Clear communication regarding the safety, efficacy, and potential impact of these technologies can help to alleviate concerns and promote acceptance among stakeholders.
Research and evaluation	• Continued research is needed to assess the long-term impact of computer-based simulation on pediatric cardiovascular care outcomes. Policymakers should support research initiatives that evaluate the effectiveness and cost-effectiveness of these technologies in improving patient outcomes and reducing healthcare costs. • Integrating patient data into CBS enhances the understanding and management of CVDs, enabling personalized medicine strategies and optimizing treatment outcomes.
Quality and standards	• Standardized benchmarks and accreditation are vital for simulation training centers in pediatric cardiovascular care. These programs ensure quality, prioritize patient safety, and maximize CBS training's effectiveness. Accreditation emphasizes rigorous quality assurance, fostering trust in the reliability and effectiveness of simulation-based education for both healthcare professionals and children. • Pediatric cardiology currently lacks a standardized approach for integrating CBS applications into clinical workflows, limiting their potential to improve patient care. Developing national or regional guidelines outlining best practices for integration is crucial. Explicit protocols within these guidelines can minimize the risk of errors associated with introducing new technologies into clinical settings. This initiative would ensure a smooth transition for CBS in pediatric cardiology, maximizing benefits for patients and minimizing potential risks.

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Arezoo Abasi:Writing original draft, Review & Editing. Haleh Ayatollahi: Writing, Review & Editing, Supervision.

Declaration of Conflicting Interests

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