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DEVELOPMENT OF A VIRTUAL REALITY TRAINER FOR THE PRENATAL DETECTION OF CONGENITAL HEART DISEASE

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Abstract

The Virtual Reality Trainer for the Prenatal Detection of Congenital Heart Disease and Associated Malformations project addresses the need to improve specialized training in prenatal diagnosis through immersive technologies. Its theoretical module "My Friend the Lung" gamifies learning about fetal cardiovascular anatomy through 3D puzzles, timed challenges, and badges, achieving good results in its pilot test, is noteworthy. The practical module simulates ultrasounds with haptic devices, reducing diagnostic errors and enabling the generation of personalized ultrasounds. A database with 1,200 labeled studies was consolidated as a fundamental source of information. The implementation aims to initially reduce clinical errors, with the potential to decrease perinatal mortality. This project fuses technological innovation, medical rigor, and interactive pedagogy, positioning gamification as an essential tool in medical education and laying the groundwork for its expansion to other specialties.

Keywords*: virtual reality, congenital heart disease, gamification, prenatal diagnosis, medical training, clinical simulation.*

INTRODUCTION

Congenital heart defects are one of the leading causes of perinatal and infant mortality worldwide, with an incidence of 6 to 8 cases per 1,000 live births. In Cuba, these anomalies are the second leading cause of death in children under one year of age, highlighting the need to improve the training of specialists in prenatal diagnosis. Fetal echocardiography is the technique of choice for identifying these pathologies; however, its training requires years of experience and access to real-life cases, limiting its reach in regions with limited resources.

Faced with this challenge, the joint Cuba-Russia 2025 project emerged, whose objective is to develop a virtual reality (VR) trainer for the prenatal detection of congenital heart disease and associated malformations. This initiative seeks to integrate emerging technologies, such as VR and gamification, to create an accessible and standardized continuing education system. The project is based on the experience of the William Soler Cardiocenter in Cuba and on collaboration with academic and technological institutions in both countries, promoting innovation in medical education and reducing disparities in healthcare.

RELATED WORKS

Ultrasound is the imaging technique of choice for fetal studies. Intrauterine, and echocardiography is irreplaceable for the identification of cardiac structures and the analysis of fetal physiology. The fundamental purpose of prenatal diagnosis is obtain genetic, anatomical, biochemical, and physiological information about the fetus, and analyze whether any abnormalities are expected that will impact both the fetal and postnatal periods. However, there is no non-imaging-based test, whether genetic or biochemical, capable of diagnosing congenital heart disease. To date, it is the only method for identifying the specific type of cardiovascular malformation.

Beginning in 1982, interest in the application of echocardiography to the study of congenital heart disease began in Cuba, and its inclusion in some departments across the country, particularly the William Soler Pediatric Teaching Hospital. With exemplary modesty on the part of its professionals, in the Cardiology Department of this hospital, and initially self-taught, the first diagnoses were made in children with congenital malformations and acquired heart diseases, primarily rheumatic carditis. This was followed by courses and training both within and outside the country, thus ushering in the second great cardiological revolution of the 20th century, and with it, the era of echocardiography.

The progressive decline in infant mortality, which had already been achieved by those years thanks to a series of factors, such as improved living conditions and nutritional status, the drastic reduction in diarrheal and acute respiratory diseases, and the eradication of numerous infectious diseases through immunization, led to a radical change in the epidemiological profile, with other more relevant causes now taking a

significant role in infant mortality. Congenital malformations have since become the second leading cause of death in children under one year of age, half of which are cardiovascular. The incidence of these malformations ranges between 6 and 8 per 1,000 live births, of which 25% are complex, difficult to treat, and have a poor prognosis.

Since its inception, the Cuban program has attracted the attention of other international centers in France, Great Britain, and the United States. Although they all share the inclusion of four-chamber imaging in routine obstetric examinations as a factor in suspecting heart disease, the Cuban program is the only one in which 100% of pregnant women could be screened, thanks to the organization of its National Public Health System. This led to the creation of a large database of cases that were properly diagnosed and digitized in multiple formats. This program addressed the problems arising from the Comprehensive treatment of heart disease, including morphological examination of the heart, treatment of fetal arrhythmias, monitoring of high-risk pregnant women, and genetic counseling by the prenatal diagnostic team, comprised of pediatric cardiologists, obstetricians-gynecologists, geneticists, embryologists, ultrasound technicians, and pediatricians. This phase lasts for a decade, and begins another phase requiring greater use of information and communications technologies (ICTs).

In the last 5 decades, prenatal diagnosis has been perfected and has achieved an impact favorably in sensitive health indicators such as perinatal and infant mortality. The Cuban center is requesting specialized training of greater scope and accessibility from different parts of Latin America. At the same time, progress continues to be made not only in diagnosis, but also in other important areas, such as physiology, the dynamics of placental circulation and its impact on pregnancy outcomes, cardiac rhythm disorders, fetal pharmacology (about which almost nothing is known), and the treatment of fetal heart disease, whether pharmacological, through interventional catheterization, or fetal surgery. In a context where knowledge products are important sources of income for countries, the Cuban program is advancing the intensive use of computer technology to strengthen training and diagnostic systems as high- quality professional services. In this regard, progress is being made in the development of joint projects with the University of Informatics Sciences.

The Interactive Technologies Center (VERTEX) belonging to the University of Computer Sciences has specialized for 12 years in products associated with video

games, virtual reality and augmented reality. In this context, it has participated in the creation of car driving simulators [1], virtual laboratories [2] and serious video games for the rehabilitation of different disabilities [3, 4]. Since 2016, collaboration relations began with the MediaLab center, belonging to the Institute of Information Systems and Intelligent Systems of the Kazan Federal University, Russia. It has extensive experience in the application of virtual reality for the training of surgeons and in platforms for the creation of multi-user simulators with immersion in virtual environments for cooperative learning. In the period 2016–2024, there has been a cooperative contribution to the development of trainers for appendectomy surgeries [5, 6] and more recently to a trainer for the birthing process which uses emerging technologies such as interaction through hand gestures [7].

Echocardiography has different procedures that involve a complex learning curve. Manual dexterity, pattern recognition and image interpretation are necessary skills to achieve an effective diagnosis. The use of echocardiography simulators has evolved from mannequins [8] to the use of virtual reality [9]. Its use has proven to be effective in the training of specialists with demonstrated levels of effectiveness [10]. This technology is already recognized as fundamental in medical training and in the case of echocardiography, recent studies summarize a path of success in its application [11]. However, in relation to prenatal echocardiography, no trainers of this type have been identified, mainly due to the complexities and current state of medical research.

RESULTS

The Virtual Reality Trainer for Prenatal Detection of Congenital Heart Disease and Associated Malformations project works in several directions, from the creation of innovative technological tools to the validation of their impact on medical training. Below are several results achieved so far, with special emphasis on the theoretical gamification module “My Friend the Pulmonary,” designed to revolutionize the learning of fetal cardiovascular anatomy.

Integrated Clinical Case Database

A database with more than 1,200 prenatal ultrasound studies was consolidated, Compiled from the historical archive of the “William Soler” Cardiocenter (1982–2025). Each case includes:

- Video classification: Types of heart disease (e.g., tetralogy of Fallot, ventricular septal defect) and associated malformations (e.g., Holt-Oram syndrome) were segmented.
- Clinical metadata: Gestational age, postnatal findings, treatments applied and long-term outcomes.
- Collaborative labeling: This was performed by pediatric cardiologists and prenatal diagnosticians, ensuring accurate classification.

An accessible search engine was configured using a smart search interface that allows users to filter cases by complexity, frequency of occurrence, or clinical relevance, serving as an educational and reference resource for future research.

Theoretical Module My Friend the Pulmonary

This module, a pioneer in the gamification of fetal cardiovascular anatomy, focuses on teaching the layout of the pulmonary arteries and cardiac structures through immersive game mechanics. The layout of the pulmonary vessels and arteries is presented as personal, with varying levels of relationship to conditions. A visual-textual and visual-textual association approach seeks to reinforce comparative associative learning. The layout of the pulmonary artery, aorta, and vena cava is analyzed based on size and position. Different combinations of these allow for prediagnosis of most known pathologies.

Gamified Narrative: Users take on the role of “medical explorers” who must identify the correct anatomy of the vascular structures of a virtual heart affected by malformations. The narrative is structured into missions (minigames), with each level corresponding to a specific heart condition.

- 3D Puzzles: Reconstruction of pulmonary arteries and cardiac chambers by dragging anatomical components.
- Time Challenges: Rapid identification of anomalies in rotating 3D models, with scoring based on accuracy and speed.
- Achievements and Badges: Badges awarded for completing challenges (e.g., Valve Master for mastering aortic stenosis identification). Each progression in the minigames unlocks relevant aspects of the Knowledge Catalog, which can be

converted into general-purpose or customized resources for improved system performance.

Complementing the theoretical module is the ultrasound training process. This focuses on simulating ultrasound imaging in a realistic virtual environment with interaction through haptic devices. The main components are:

- Immersive 3D Environment: Virtual patient models with anatomical variations (e.g., fetal position, maternal obesity) that affect image acquisition.
- Haptic Devices: Simulation of resistance when moving the virtual transducer, replicating the sensation of a real exam.
- Calculation of correspondence between real ultrasound and virtual movement: A neural network guides the visualization of a study using the movements of the virtual transducer as input.
- Performance Indicators: Real-time metrics on transducer angle, imaging depth, and accurate diagnosis.

CONCLUSIONS

The development of the Virtual Reality Trainer for Prenatal Detection of Congenital Heart Disease represents a significant advance in specialized medical training, integrating immersive technologies and gamification to address critical challenges in prenatal diagnosis. The theoretical module, “My Friend the Lung,” proved transformative, increasing anatomical knowledge retention and reducing the time to identify anomalies in pilot tests with residents. Its gamified design, based on interactive mechanics such as 3D puzzles and timed challenges, not only improves user motivation but also facilitates the intuitive understanding of complex cardiac structures. These results underscore the potential of virtual reality to democratize access to high-quality training, especially in resource-constrained regions, while establishing a replicable model for other medical specialties.

The Cuba–Russia collaboration, based on clinical experience with the Cardiocenter “William Soler” and the technological expertise of the University of Computer Sciences and Kazan Federal University have set a precedent in educational innovation in healthcare. The implementation of the beta version of the trainer in medical centers in Latin America and Russia not only suggests an opportunity to improve birth rates but

also opens the door to commercializing this technology as a global service. Future research should expand the database with international cases and evaluate the long-term impact on perinatal mortality.

REFERENCES

1. *Coca Bergolla Y., Guzmán Montoto J.I.* Traffic control in a car driving simulator: Master Thesis // University of Informatics Sciences. 2007. 65 p.
URL: https://repositorio.uci.cu/handle/ident/TD_0960_07 (In Spanish).

2. *Reyes H.L.N., Tellez O.F.* Laboratorio Virtual como herramienta para potenciar las competencias de Física en estudiantes de Bachillerato // Serie Científica de la Universidad de las Ciencias Informáticas. 2022. Vol. 15. No. 5. P. 145–165.

3. *Correa Madrigal O.* Virtual Relax, System of Virtual Reality for Relaxation Therapy // NeuroRehabana. 2010.
URL: https://promociondeeventos.sld.cu/neurorehabana2010ingles/section-2sciences-and-disciplines-involved-in-theneurore-habilitation/

4. *Valdés Fernández D.* VirtualRelax, plataforma para integrar módulos de entornos virtuales, para apoyar a los especialistas en el tratamiento del estrés: Bachelor Thesis //University of Informatics Sciences. 2015. 78 p.
URL: https://repositorio.uci.cu/handle/123456789/8010

5. *Kugurakova V.V., Khafizov M.R., Correa Madrigal O. et al.* Virtual surgery system with realistic visual effects and haptic interaction // Proc. of The International Conference on Artificial Life and Robotics (ICAROB 2017, Japan). 2017. P. 86–89.

6. *Véliz Vega A., Correa Madrigal O., Kugurakova V.V.* Aprendizaje adaptativo basado en Simuladores de Realidad Virtual // Revista Cubana de Ciencias Informáticas. 2021. Vol. 15. No. 2. P. 138–157.

7. *Correa Madrigal O., Muhamethanov I.R., Kugurakova V.V.* A methodological overview about hand tracking and cognitive influences in virtual reality // HCI-COLLAB 2024, Colombia: Springer.

8. *Shakil O., Mahmood F., Matyal R.* Simulation in Echocardiography: An Ever-Expanding Frontier // Journal of Cardiothoracic and Vascular Anesthesia. 2012. Vol. 26. No. 3. P. 476–485. https://doi.org/10.1053/j.jvca.2012.01.019

9. *O'Sullivan D.M., Foley R., Proctor K. et al.* The Use of Virtual Reality Echocardiography in Medical Education // Pediatr Cardiol. 2021. Vol. 42. P. 723–726.

https://doi.org/10.1007/s00246-021-02596-z

10. *Khoche S., Maus T.* The reality of virtual reality in echocardiography education? //Journal of Cardiothoracic and Vascular Anesthesia. 2023. Vol. 37. No. 2. P. 306–307.

11. *Bouraghi H. et al.* Virtual reality and cardiac diseases: A systematic review of applications and effects // Journal of Healthcare Engineering. 2023. Vol. 2023. No. 1. P. 8171057. https://doi.org/10.1155/2023/8171057

РАЗРАБОТКА ТРЕНАЖЕРА ВИРТУАЛЬНОЙ РЕАЛЬНОСТИ ДЛЯ ПРЕНАТАЛЬНОЙ ДИАГНОСТИКИ ВРОЖДЕННЫХ ПОРОКОВ СЕРДЦА

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Аннотация

Проект разработки тренажера виртуальной реальности для пренатального выявления врожденных пороков сердца и сопутствующих заболеваний направлен на улучшение специализированной подготовки в области пренатальной диагностики с помощью иммерсивных технологий. Особенно заслуживает внимания теоретический модуль «Мой друг – легкое», который позволяет в игровой форме изучать анатомию сердечно-сосудистой системы плода с помощью 3D-головоломок, заданий на время и бейджей, добиваясь хороших результатов в ходе пилотного тестирования. Практический модуль имитирует УЗИ с помощью тактильных устройств, снижая количество диагностических ошибок и позволяя создавать пер-

сонализированные УЗИ. В качестве основного источника информации была собрана база данных с 1200 маркированными исследованиями. Реализация проекта направлена на первоначальное снижение количества клинических ошибок, что может привести к снижению перинатальной смертности. Этот проект объединяет технологические инновации, медицинскую строгость и интерактивную педагогику, позиционируя геймификацию как важный инструмент в медицинском образовании и закладывая основу для его распространения на другие специальности.

***Ключевые слова**: виртуальная реальность, врожденные пороки сердца, геймификация, пренатальная диагностика, медицинское обучение, клиническое моделирование.*

СПИСОК ЛИТЕРАТУРЫ

1. *Coca Bergolla Y., Guzmán Montoto J.I.* Traffic control in a car driving simulator: Master Thesis // University of Informatics Sciences. 2007. 65 p.
URL: https://repositorio.uci.cu/handle/ident/TD_0960_07 (In Spanish).

2. *Reyes H.L.N., Tellez O.F.* Laboratorio Virtual como herramienta para potenciar las competencias de Física en estudiantes de Bachillerato // Serie Científica de la Universidad de las Ciencias Informáticas. 2022. Vol. 15. No. 5. P. 145–165.

3. *Correa Madrigal O.* Virtual Relax, System of Virtual Reality for Relaxation Therapy // NeuroRehabana. 2010.
URL: https://promociondeeventos.sld.cu/neurorehabana2010ingles/
section-2sciences-and-disciplines-involved-in-theneurore-habilitation/

4. *Valdés Fernández D.* VirtualRelax, plataforma para integrar módulos de entornos virtuales, para apoyar a los especialistas en el tratamiento del estrés: Bachelor Thesis //University of Informatics Sciences. 2015. 78 p.
URL: https://repositorio.uci.cu/handle/123456789/8010

5. *Kugurakova V.V., Khafizov M.R., Correa Madrigal O. et al.* Virtual surgery system with realistic visual effects and haptic interaction // Proc. of The International Conference on Artificial Life and Robotics (ICAROB 2017, Japan). 2017. P. 86–89.

6. *Véliz Vega A., Correa Madrigal O., Kugurakova V.V.* Aprendizaje adaptativo basado en Simuladores de Realidad Virtual // Revista Cubana de Ciencias Informáticas. 2021. Vol. 15. No. 2. P. 138–157.

7. *Correa Madrigal O., Muhamethanov I.R., Kugurakova V.V.* A methodological overview about hand tracking and cognitive influences in virtual reality // HCI-COLLAB 2024, Colombia: Springer.

8. *Shakil O., Mahmood F., Matyal R.* Simulation in Echocardiography: An Ever-Expanding Frontier // Journal of Cardiothoracic and Vascular Anesthesia. 2012. Vol. 26. No. 3. P. 476–485. https://doi.org/10.1053/j.jvca.2012.01.019

9. *O'Sullivan D.M., Foley R., Proctor K. et al.* The Use of Virtual Reality Echocardiography in Medical Education // Pediatr Cardiol. 2021. Vol. 42. P. 723–726. https://doi.org/10.1007/s00246-021-02596-z

10. *Khoche S., Maus T.* The reality of virtual reality in echocardiography education? //Journal of Cardiothoracic and Vascular Anesthesia. 2023. Vol. 37. No. 2. P. 306–307.

11. *Bouraghi H. et al.* Virtual reality and cardiac diseases: A systematic review of applications and effects // Journal of Healthcare Engineering. 2023. Vol. 2023. No. 1. P. 8171057. https://doi.org/10.1155/2023/8171057

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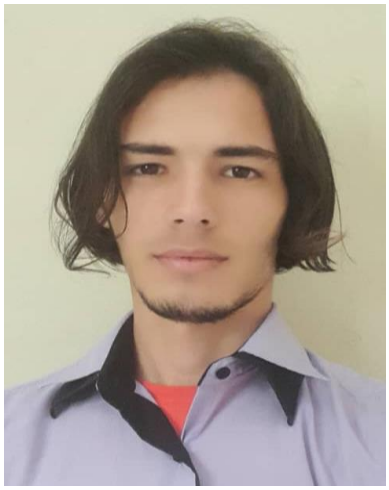

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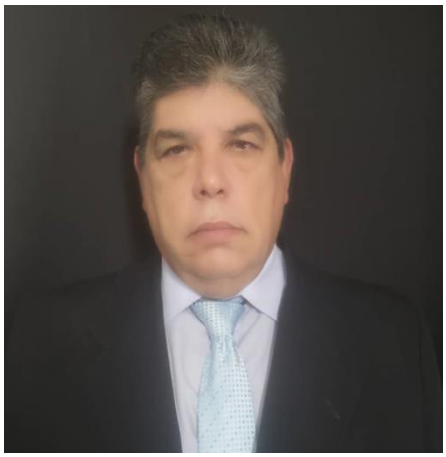

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