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EDITORIAL

3D Ultrasound of Fetal Congenital Heart Disease: Present and Future?

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1 Introduction

Three-dimensional (3D) ultrasound has evolved from a technological novelty into a valuable extension of fetal imaging, enhancing the diagnosis of congenital anomalies. Congenital heart disease (CHD) remains the most common of congenital anomalies and an important cause of perinatal mortality. In this setting, there have been significant advancements in the quality of cardiac 3D ultrasound imaging with the advent of the software Spatio-Temporal Image Correlation (STIC) in recent decades. Using the STIC, a 'block' of images containing complete cardiac cycles (cardiac volumes) can be acquired through a single slow sweep of the fetal four-chamber view over approximately 7.5 to 15 s (with a temporal resolution of up to 150 time points per cardiac cycle) [1,2]. One well-acquired cardiac volume using STIC enables cardiac-cycle–synchronized capture of the fetal heart that can be rotated, processed with different multiplanar and rendering modes, and reviewed offline several times by multiple specialists. STIC technology can reconstruct moving images and display them in various modes, including STIC-M, inversion mode, B-flow imaging, and ultrasound tomographic imaging (TUI). Therefore, this technology enables the navigation through the cardiac chambers and their vessels, providing a detailed analysis of anatomical structures and function of the fetal heart [3]. Furthermore, STIC has opened up new possibilities for sending cardiac volumes to experts by an internet link (tele-STIC) [4].

The addition of STIC technology to two-dimensional (2D) cardiac ultrasound has enabled the acquisition of high-quality images, to enable more accurate prenatal diagnosis of CHD and optimize the planning of delivery and cardiological procedures [5]. Sequentially, other imaging techniques have been developed, improving image quality even further. Most impressively, these techniques can be applied to STIC, providing realistic images of the fetus and its blood vessels [3,6,7]. HDlive Software, which includes HDlive Flow and HDlive Silhouette rendering modes, can be added to 3D ultrasound with STIC. HDlive technology uses a fixed virtual light source that propagates through tissue, allowing for detailed reconstruction of cardiac structures and blood flow. These modes improve the perception of vessel wall and cavity contours, valve coaptation, ventricular outflow tract flows, and venous return in normal and CHD, improving the detection of morphological abnormalities, particularly complex lesions, for both trainees and experienced sonographers/pediatric cardiologists. In this scenario, ultrasound operators can freely select a better position for the light source in order to enhance the anatomical details of the fetal cardiac structures [6,8,9].

Fetal intelligent navigation echocardiography (FINE) is another technology that utilizes cardiac volumes obtained from a four-chamber view of the fetal heart. The FINE technology, also named “5D-Heart” is an intelligent navigation technique for fetal echocardiography that facilitates the automated reconstruction of the nine standard fetal echocardiographic views. The software guides the examiner in marking seven strategic cardiac anatomical points (=intelligent navigation): descending aorta, crux cordis, pulmonary valve, superior vena cava, and transverse aorta. Sequentially, this technology provides the automatic reconstruction of the nine fetal echocardiographic views. This technology reduces examination time and minimizes operator-dependent variations [10,11]. Recently, artificial intelligence (AI) software called HeartAssist$^{\mathrm{TM}}$ has recognized fetal cardiac structures, performs automatic measurements (anatomical and functional), and can issue alerts about the possible presence of CHD. Preliminary studies suggest high sensitivity and specificity for detecting inadequate cardiac views and identifying suspected CHD, suggesting that AI-assisted analysis may improve screening performance, reduce operator dependency, and serve as a quality control tool in fetal echocardiography [12].

2 Clinical Perspective

From a clinical perspective, these technologies have different but complementary applications. STIC is primarily used for volumetric acquisition and offline analysis of the fetal heart. HDlive rendering improves anatomical visualization and spatial perception, being particularly useful for understanding complex structural relationships and for teaching purposes. FINE facilitates standardized reconstruction of cardiac planes and is especially useful in screening examinations and in centers with less experience in fetal echocardiography. AI tools are designed for automated image evaluation, quality control, and early detection of suspected CHD.

Indeed, the most promising developments in fetal heart imaging technology may be embodied by the following: the advent of tangible 3D prints, immersive virtual navigation, and the translation of prenatal images into collaborative spaces enabled for the metaverse [13,14]. The physical and virtual 3D reconstruction of the fetal heart can be created from cardiac volumes acquired by STIC. To perform this process, volumes stored in volumetric format (vol.) undergo conversion to Nearly Raw Raster Data (nrrd). The subsequent step involves the importation of the data into the 3D Slicer software (Birmingham, UK). Following this, segmentation is performed, a process in which the cardiac structures are properly separated and identified by different colors. Upon completion of the segmentation process, the models are exported to either an Elucis software (Realize Medical, Ottawa, ON, Canada) or a mesh reconstruction program, Meshlab 2023.12 (Pisa, Italy), generating virtual models. To create physical 3D resin models, the segmented data is transferred to a 3D printer. The physical 3D resin models can be used in various settings, including cardiac anatomy classes, prenatal parental counseling, and birth planning [13–16]. This approach aims to enhance the understanding of heart disease among multidisciplinary teams, facilitating collaborative decision-making and improved patient care. Virtual navigation has been employed in other medical specialties for surgical training and, in fetal cardiology, it represents a promising tool due to its ability to facilitate the training of teams on the learning curve by expert teams at a distance, avoiding travel (shortening distances), for planning postnatal surgical procedures in a virtual simulation room and for didactic teaching (practical training of students specializing in cardiac surgery) [13,14] (Fig. 1). Future developments will likely focus on the integration of imaging, segmentation techniques, physical and virtual modeling, and AI-assisted workflows. These developments are set to create an ecosystem in which prenatal diagnosis, parental counselling, surgical planning, and training occur within a continuous 3D space [15,16]. The translation of these promising tools into better outcomes for babies and their families, for the multidisciplinary healthcare team caring for patients with CHD, and for the teaching of cardiac anatomy and heart disease will be determined by careful validation, equitable access, and well-planned governance [17]. The training of teams in cardiac surgery techniques by those with greater expertise, and the selection of the most appropriate surgical procedure for each case in a virtual environment, has been demonstrated to reduce distances, decrease time, and facilitate collaboration among professionals from various regions of the world [14,18]. Similarly, employing resin models to replace formal ones in the instruction of cardiac anatomy within a virtual environment holds considerable promise to enhance the learning experience of healthcare professionals in the field of cardiovascular anatomy [18]. The outline of the future of 3D imaging technologies is visible today in 3D prints, 3D virtual navigation projects, and metaverse pilot efforts. Now, we owe it to patients to convert potential into responsible practice.

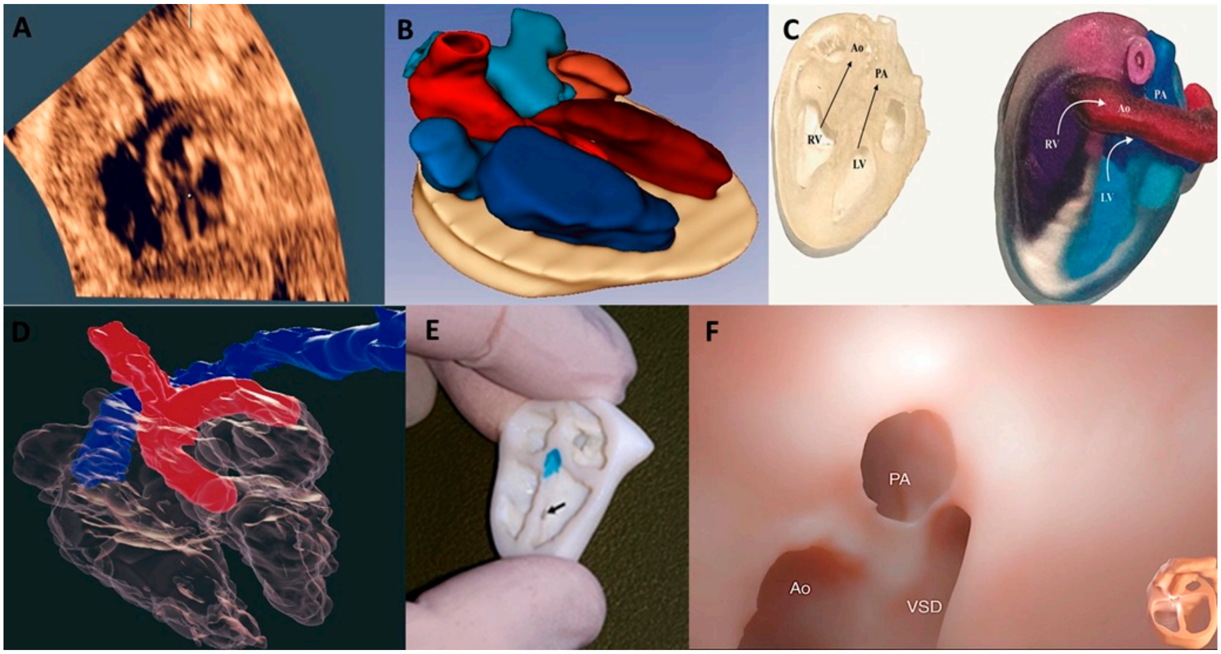

Figure 1: 3D models of the fetal heart. A, B, C and D illustrate a case of transposition of the great arteries (TGA). Note the 3D ultrasound with Spatio-Temporal Image Correlation (**A**), the segmentation process (**B**), and the reconstruction of the 3D physical (**C**) and virtual models (**D**) of a fetal heart with TGA. Images E and F demonstrate two different types of ventricular septal defect (VSD): a 3D physical model of a muscular VSD (**E**) and 3D virtual navigation in double committed VSD (**F**). Ao: aorta; PA: pulmonary artery; LV: left ventricle; RV: right Ventricle.

3 Challenges

Despite these promising advances, important barriers to implementation must be acknowledged. The integration of 3D imaging, AI, and immersive virtual platforms into routine clinical practice raises challenges related to data security, patient privacy, and regulatory governance. In addition, the high cost of advanced software, hardware, and 3D printing technologies may limit accessibility, particularly in low-resource settings, potentially exacerbating existing disparities in prenatal care. The effective adoption of these tools also depends on structured training programs and technical expertise, which are not yet widely available. Ethical considerations must also be addressed, including the responsible use of AI, transparency of automated decision-making processes, and the need to maintain clinician oversight. Therefore, while these technologies hold substantial potential, their implementation should be guided by robust validation, equitable access, and clear ethical and regulatory frameworks.

Nonetheless, several challenges persist in implementing 3D fetal echocardiography in routine clinical practice. The quality of STIC volume acquisition continues to be contingent on fetal position, fetal movements, and maternal factors, including obesity, which have the capacity to compromise image quality and limit adequate cardiac reconstruction. Moreover, the expense of advanced software, 3D printing technologies, and virtual simulation platforms, in addition to the necessity for specialized training, continues to limit the accessibility of these technologies in numerous centers. The overcoming of these limitations is imperative in ensuring equitable access and broader clinical implementation.

In summary, 3D ultrasound has already redefined how we view the fetal heart: surface realism, enhanced flow representation, and offline volumetric review have increased diagnostic confidence and improved communication. The future of fetal cardiology will be defined not only by better imaging, but also by the integration of advanced technologies into diagnosis, simulation, and multidisciplinary decision-making processes to improve outcomes for children with CHD. Ultimately, the translation of these innovations into improved clinical outcomes will require careful validation, responsible implementation, and a commitment to equitable access.

Conflicts of Interest: The authors declare no conflicts of interest.

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