Curr Treat Options Cardio Med (2018) 20: 9
DOI 10.1007/s11936-018-0599-x

Recent Advances and Trends in Pediatric Cardiac Imaging

Wadi Mawad, MD
*Luc L. Mertens, MD, PhD**

Address
*Cardiology, The Hospital for Sick Children, University of Toronto, 555 University Avenue, Toronto, ON, M5G 1X8, Canada
Email: luc.mertens@sickkids.ca

Published online: 21 February 2018

This article is part of the Topical Collection on *Pediatric and Congenital Heart Disease*

Keywords Pediatric cardiac imaging · Echocardiography · Magnetic resonance imaging · Congenital cardiac imaging · Cardiac MRI

Abstract

Cardiac imaging is central to today's pediatric cardiology practice not only to diagnose structural congenital defects and delineate cardiac and extracardiac anatomy but also for determining the hemodynamic impact of the structural defects and acquired pediatric diseases. Not so long ago, clinicians had to heavily rely on angiography as the main cardiac imaging modality to visualize the heart. Particularly, the development of echocardiography in the 1970s and 1980s together with the development of magnetic resonance imaging (MRI) and computed tomography (CT) resulted in a non-invasive diagnostic revolution with diagnostic catheterization becoming obsolete apart for very specific indications. The continuous improvements in non-invasive imaging modalities allow an unprecedented level of understanding of cardiac morphology and function. Over the last few years, the specific roles of the three imaging modalities and their complementary roles in diagnosis and treatment have become well established resulting in a multimodality approach to specific congenital lesions. Recently, multimodality guidelines were published for postoperative tetralogy of Fallot and patients with transposition of the great arteries (Cohen et al. J Am Soc Echocardiogr. 2016;29(7):571–621, Valente et al. J Am Soc Echocardiogr. 2014;27(2):111–41). In this paper, we aim to highlight some of the most significant advances and highlight some emerging trends in pediatric cardiac imaging.

Introduction

Brief historical perspective of echocardiography

Inspired by its use to determine ocean depths as suggested by Behm in 1921, the idea to use ultrasound as a means of imaging organs and structures within the body was first entertained in the early 1940s and required decades to be realized successfully. It was the Austrian neurologist Karl Dussik, in 1947, who successfully imaged the ventricles of the brain using ultrasound [1]. The pioneering work of Elder and Hertz in the 1950s, motivated by the need to diagnose mitral valve disease in the setting of highly prevalent rheumatic fever, brought forth the first echocardiographic images of the heart using M-mode. The advent of B-mode and Doppler echocardiography deeply changed the face of structural cardiology. Currently for many forms of congenital heart disease, echocardiography is the first-line imaging modality and adequately provides all anatomical and hemodynamic information allowing for surgical or interventional treatment planning for many lesions. After demonstrating a close relationship between the images and pathologic specimens, an increasing number of surgeries are performed based on echocardiographic images only, especially in infants and children. For specific indications, additional imaging using MRI and CT may be needed and more rarely invasive diagnostic catheterization is required pre-operatively. The addition of transesophageal (TEE) and later intracardiac [2] echocardiography (ICE) further impacted the field as TEE allowed immediate post-bypass assessment in the operating room impacting peri-operative management and significantly reducing the number of reoperations [3]. TEE and ICE have become important techniques for monitoring interventional procedures in the catheterization laboratory such as ASD closure. As the heart is a three-dimensional structure, the utilization of two-dimensional imaging for visualizing structural defects is challenging and requires extensive training. With the development of matrix array probes as well as increasing computational processing power, real-time 3D echocardiography (3DE) became possible. For pediatric heart disease, currently only transthoracic 3D echocardiography is available. The introduction of 3D TEE was a major breakthrough in the diagnosis and treatment of adult structural disease but is not available for use in children < 20–25 kg [4]. Other more recent technological evolutions in echocardiography include myocardial deformation imaging based on speckle-tracking echocardiography, high-frequency ultrasound, and more recently high frame-rate echocardiography.

3D echocardiography (3DE) in congenital heart disease

While 2D echocardiography still plays a dominant role in congenital echocardiography, the development of 3D echocardiography allowed for real-time 3D visualization of cardiac structures providing additional diagnostic information on valves and spatial relationship of specific cardiac structures [5, 6]. Especially for transthoracic 3D imaging, the lower spatial and temporal resolution still limits the diagnostic value of the technique, and the post-processing of the acquired 3D images requires a good understanding of the morphology by the operator. Presenting the images in a surgical orientation is useful in peri-operative imaging as it facilitates communication between the echocardiographer and the surgeon.

Current 3DE acquisitions can be obtained by four modes: real-time 3DE, ECG-gated multi-beat acquisition, multiplane mode, and 3DE color-Doppler mode. Each mode had its advantages and disadvantages, and the selected mode of acquisition should aim to obtain the required clinical information. The American Society of Echocardiography has recently published a consensus document on the use of 3DE in congenital heart disease [7••]. This document highlighted the added value of 3DE in the assessment of complex morphologic structures which can be difficult to image adequately using 2D echocardiography, including structures like atrioventricular valves, outflow tracts, aortic valve, and the atrial and ventricular septa.

A specific area of interest in recent years has been the use of 3DE of the right ventricle in the assessment of RV function. Despite its importance in different types of congenital heart defects, imaging the right ventricle by transthoracic echocardiography remains challenging. The retrosternal anterior position and more complex variable geometry contribute to the difficulty of 2D imaging. Given adequate acoustic windows, 3DE acquisition allows volumetric and functional RV analysis. After full volumetric acquisition, RV volumes and ejection fraction can be calculated using semi-automated post-processing softwares. Initially, post-processing was based on the summation of disk method, which uses the same principle used in MRI, and is the only method devoid of geometrical assumptions. However, it suffers from poor feasibility, particularly in older patients and is labor-intensive, limiting the clinical applicability [8]. This method has largely been replaced by semi-automated border detection method. From a full 3D dataset, the RV is segmented and reconstructed in three dimensions. This has proven a more user-friendly method although the feasibility is variable and the method results in systematic underestimation of RV volumes when compared to MRI measurements which limits its clinical utility [9, 10]. This likely explains why the clinical utilization of this technology has been relatively slow. Feasibility is largely determined by echocardiographic windows, which can be problematic in post-operative patients, and in some patients with severe RV dilatation, it can be extremely challenging to include the entire RV in one single acquisition. Because of these limitations, our group explored the 2D-based 3D reconstruction method that uses 2D images localized in 3D space by attaching a magnetic tracker to the probe and using knowledge-based 3D reconstruction based on a reference database of lesion-specific right ventricular geometries. This method is more feasible and reproducible and results in RV volumes more closely related to MRI data. It, however, requires specific equipment and significant post-processing time and expertise [11]. Combining speckle-tracking techniques and 3DE [12, 13•], a promising new and more automated technique has recently become available that allows to obtain RV volumes which are much more closely correlated to those of CMR. While this automated method seems to work well for normal-sized ventricles, manual correction was needed in dilated RVs making post-processing semi-automated. Echocardiographic RV volumetric assessment still is an emerging field. Widespread clinical application is limited by vendor-specific differences and the lack of normal reference values. Intrinsic limitations like limited sector width and lower volume rates are additional problems that still should be resolved. Finally, 3D image resolution may be a limiting factor in smaller RVs especially in infants with borderline RVs.

3DE for valve assessment, especially for atrioventricular valves, remains the main area of interest where this technology can influence patient care and surgical decision-making. Automated software for detailed mitral valve analysis has been developed and is commercially available. These softwares are not applicable to the tricuspid valve and not for atrioventricular valve in the context of atrioventricular septal defects where mechanisms for valve dysfunction are different from the mitral valve.

One of the limitations of 3DE is that visualization of the 3D-datasets still is based on 2D rendering with some added depth perspective. Novel 3D rendering techniques like holography and 3D printing techniques based on echocardiographic images are likely to highly impact the field and future development of 3DE in CHD (see below).

Deformation imaging in CHD

Historically, assessment of ventricular function has been based on evaluating pump function by measuring dimensional or volumetric changes during ventricular systole. As changes in cardiac dimensions are based on myocardial thickening and shortening, it seems logical to directly investigate these changes within the myocardium. The first attempt at direct measures of myocardial function was the introduction of tissue Doppler which uses pulsed or color-Doppler techniques to measure myocardial velocities during the cardiac cycle. For the assessment of patients with CHD, this method has the advantage of being independent from ventricular morphology. Tissue Doppler velocities have been shown to be influenced by ventricular size and loading conditions and more importantly also by overall cardiac translational motion and myocardial tethering (segment-segment interactions). Tissue Doppler is currently mainly used for the assessment of ventricular longitudinal function especially in the assessment of diastolic function. To overcome the effect of translation and tethering, myocardial strain imaging was developed. This measures myocardial deformation studying longitudinal and circumferential shortening (longitudinal strain) and radial thickening (radial strain). Speckle-tracking echocardiography (STE) largely replaced the initial, tissue-Doppler-based strain measurements [14] which were angle-dependent and required extensive post-processing. Strain imaging has harbored much interest in the past decade to measure regional and global myocardial function and has been suggested to detect abnormalities at a subclinical stage in pediatric and congenital heart disease [15]. Semi-automated strain analysis software packages allow for smooth application into clinical practice. Especially in the adult population, measurement of global LV longitudinal strain was proven to be a highly reliable technique adding prognostic value to measurement of ejection. Normative values have been reported and validated in adult populations [16–18]. Different studies focused on establishing pediatric normative values [19, 20], but their methodological limitations were recently highlighted [21••], including relatively small sample sizes, heterogeneous methods of normalization, and the mixed use of TDI and STE-derived strain techniques. Normative values using Z-scores, which is the generally preferable way to express normative data in pediatrics, has been recently published for the left ventricle [22••].

Strain measurements rely on vendor-specific software packages that use different algorithms that are not standardized, proprietary and result in variability in strain values between the different vendors [23]. Different professional organizations are collaborating with the vendors to develop industry standards that reduce the variability. While the intervendor variability for global LV longitudinal strain is lower compared to other strain measurements, it seems cautious to use the same equipment for longitudinal follow-up of patients. Another limitation is that most softwares were developed specifically for assessing LV strain measurements with still limited availability of RV-specific strain packages. RV deformation is mainly longitudinal with limited contribution of a circumferential and radial components in the normal RV. RV strain analysis still has not been well standardized, and there still is a lack of well-standardized normal reference data both in adults as well as in children. Different studies have demonstrated that reduced RV longitudinal strain measurements could have important predictive values in diseases affecting the RV like pulmonary hypertension. Even less data are available on the utility of strain imaging in patients with single ventricular anatomy.

While current clinical applications are mainly developed using 2D strain imaging, 3DE-derived strain is a more recently developed emerging technique potentially superior to 2D–STE as it avoids in-plane loss of tracking. The lower temporal resolution and the more limited feasibility have been flagged as important limitations. Normal 3D strain values have been proposed [24], but so far, the technique has not been widely clinically implemented as 2D strain has been better validated and is more easily accessible with better research data supporting its clinical utility.

Strain imaging for assessment of LV function has become a routine part of a clinical functional protocol that is used in the follow-up of patients with cardiomyopathy, chemotherapy-related cardiotoxicity, post-transplant, and many other indications for functional assessment of the heart. Global longitudinal strain is calculated based on a 18-segment LV model. For the RV, we clinically use RV strain imaging for patients after tetralogy of Fallot repair (> 7 years) and pulmonary hypertension follow-up. RV free-wall lateral strain is calculated from an RV-centric 4-chamber view. Tissue Doppler and strain imaging have also been applied to study the myocardial response to exercise using exercise stress echocardiography (ESE) in children. While ESE has a clearly defined role in the adult population with specific guidelines, its role in children is less well defined. As in the adult population, the main indication for pediatric ESE has been in patients at risk of ischemic heart disease, including heart transplant recipients, post-coronary artery surgery (arterial switch, Ross procedure, ALCAPA correction), and Kawasaki disease [25, 26]. In addition, ESE can unmask dynamic outflow tract obstruction, particularly in aortic stenosis (AS) and hypertrophic cardiomyopathy (HCM) [27]. Studying myocardial reserve by applying tissue Doppler and strain echocardiography is hoped to be helpful for detecting early changes in myocardial function. Reference values have been recently published with regards to TDI and 2D-STE parameters during exercise and the LV and RV response to exercise in pediatric transplant patients was recently studied [28].

Recent developments in ultrasound

Two new technical developments will influence the future development of pediatric echocardiography. The first one is high-frame rate echocardiography. While conventional beam forming allows to acquire data up to around 200–250 frames per second the use of techniques like plane-wave imaging allows data acquisition at up to 10,000 frames per second. This technology can be used for different purposes, and two novel applications have recently been developed that still require further validation. The first one is shear-wave imaging for assessing myocardial stiffness. Shear waves are generated when an ultra-sound generated energy pulse is applied to the tissue. The speed of shear wave propagation is proportional to the stiffness of the tissue, and this technology has been proposed as a novel way to characterize mechanical tissue properties. Pernot et al. recently described that the technology can be useful in distinguishing between stunned and infarcted myocardial tissue properties [29•]. We recently investigated the shear-wave physics in pediatric myocardium though in vitro experiments and finite element simulations demonstrating some of the challenges associated with the anisotropic myocardial properties [30]. Another application related to the development of high-frame rate technology is the development of speckle-tracking techniques to visualize blood flow velocities and vectors [31, 32]. The visualization of blood flow vortices allows better characterization of physiologic flow properties and can help in understanding the hemodynamic consequences of congenital defects and their treatments. A second technological development with potential impact for pediatric imaging is high-frequency imaging. This was initially developed as techniques for small animal scanning but has recently become available clinically. This technique has very high spatial resolution but limited penetration. This technique has been proven to result in better spatial resolution for pediatric vascular imaging [33] and allowed the study of changes in the arterial walls during growth in children. Further clinical applications in very small infants are expected in the near future.

Brief historical perspective of cardiac magnetic resonance imaging

Nuclear magnetic resonance (NMR) imaging as it is known today is the result of brilliant contributions of scientists from the fields of mathematics, engineering, physics, and chemistry, spanning more than a century [34]. In 1974, Paul Lauterbur and Peter Mansfield, incognizant of each other's work, described the use of magnetic field gradients to locate the NMR signal in space [35, 36]. They were awarded the 2003 Nobel Prize in Physiology in recognition of this major discovery. In 1975, Ernst described the application of the Fourier transform to the NMR signal to reconstruct 2D images, which is still to this day, the principle behind CMR. This heralded a period of continued advances in the field, with the enticing prospect of cross-sectional imaging while avoiding ionizing radiation. Its use in congenital heart disease has evolved from static images in the 1980s [37], to moving, ECG-gated "cine" imaging [38], blood flow quantification [39, 40], and tissue characterization [41] in the 1990s and a substitute for fluoroscopy during catheter intervention in the early 2000s [42].

Most recent advances in cardiac MR

Improvements in image acquisition techniques

Apart from its more limited availability, one of the major drawbacks of CMR in the pediatric population is the relatively lengthy acquisition times when compared to echocardiography. Obtaining the volumetric, hemodynamic, and anatomic information from a pediatric CMR usually requires multiple specific sequences, breath-holding, or signal averaging over a few cardiac cycles to reduce cardiac motion related to respiration. In younger children, this requires general anesthesia. Accelerating image acquisition and reconstruction without sacrificing valuable anatomic and hemodynamic information could potentially transform the utilization of CMR in clinical practice. Multidimensional CMR is a potential game changer in the field which, in addition to 4D-flow imaging, solves the MR signal to dimensions of cardiac phase, respiratory phase, and contrast enhancement [43••] with scan times of about 10 min compared to 60 min using conventional acquisition methods. The fast acquisition results in very large CMR datasets which are challenging to post-process and require specific computational capacity. Cloud computing [44•] promises to accelerate the analysis of the datasets. Although this is promising, its widespread use in clinical practice is still limited.

Tissue characterization

A specific strength of CMR is its ability to characterize myocardial tissue using T1, T2, and T2* signals. Identification of localized or diffuse myocardial fibrosis has become feasible and has been demonstrated to have prognostic importance for specific lesions [45, 46]. Late gadolinium enhancement has been well established as a non-invasive technique to detect myocardial scar of localized fibrosis. Diffuse myocardial fibrosis can be identified by T1 mapping and is used as a promising marker of diffuse myocardial fibrosis. Extracellular volume (ECV) can be estimated when contrast (gadolinium) is used. The role of ECV in congenital heart disease is being actively pursued and studies have already shown a correlation of ECV with echocardiographic parameters of diastolic dysfunction in aortic stenosis [47] as well as arrhythmic risk in repaired TOF [48].

Lymphatic imaging

Abnormalities in the lymphatic system are recognized to play an important role in the pathogenesis of protein-losing enteropathy and plastic bronchitis after the Fontan operation and have become targets for intervention on the lymphatic system [49, 50]. Dynamic contrast-enhanced magnetic resonance lymphangiography is based on contrast injection into an inguinal lymph node followed by acquisition of time-resolved “key-hole” images where the MR signal from the contrast medium is over-sampled compared to the peripheral tissue. Particularly for patients with plastic bronchitis, this lymphatic imaging technique has been used to identify interventional targets [51]. Also, non-contrast T2-weighted MR lymphangiography can be used to image the lymphatic system. This is based on the high T2 signal produced by slow-moving lymph in comparison to low intensity signal of fast moving blood and adjacent tissues. It allows imaging the central and peripheral lymphatic systems with good spatial resolution [52].

Brief historical perspective of cardiac computed tomography imaging

Computed tomography (CT) first emerged in the 1970s, thanks to the Nobel-prize-winning work of Hounsfield and Cormak [53]. Initial cardiac applications suffered from the lack of spatial and temporal resolution. The introduction of helical CT scanning in the 1990s was a real turning point in cardiac CT imaging significantly improving temporal and spatial resolution. Continued acceleration of gantry rotation speed, multi-detector, and multi-slice technologies now result in excellent imaging quality of anatomy and function.

Most recent advances in cardiac CT

Lower radiation dose

Cardiac CT offers excellent spatial resolution for anatomic imaging of the heart, extracardiac vessels, and airway. Its broad availability combined with its ever-faster acquisition times makes it a powerful imaging modality in pediatric congenital heart disease. Its drawback has always been its use of ionizing radiation, which is related to lifetime cancer risk, especially when the exposure is in the pediatric age [54, 55]. The additional challenge specific to cardiac imaging is the necessity to account for cardiac motion, which requires ECG-gating and consequently more radiation depending on the type of acquisition (prospective, retrospective, ECG-triggered). The use of “As low as reasonably achievable” principle usually dictates the type of cardiac CT done to focus on limiting the radiation dose maximally while answering the clinical question. For example, coronary imaging, which is one of the most frequent indications for cardiac CT, requires ECG-triggering which increases radiation exposure while imaging extra-cardiac vessels usually does not require ECG-triggering. With the appearance of the newest generation of scanners with higher gantry rotation speeds, helical scanning, and multiple detectors, faster scan times are achieved with lower radiation dose [56]. Radiation dose depends on many factors [57], and many strategies exist to minimize it including reduced tube voltage, automated current modulation, minimizing coverage as well as prospective ECG-triggering and iterative reconstruction [58]. The current effective radiation related to a cardiac CT ranges from 1.6 to 3.5 mSv, compared to approximately 0.1 mSv per chest x-ray. With better control of the radiation dose, cardiac CT is increasingly used in patients with CHD. It is the preferred technique in patients with contraindications to MRI related to devices or non-MRI compatible implants. It is increasingly used for visualization of extracardiac vessels especially after stent implantation.

Newest imaging approaches

3D printing/holography

The first reported cardiac experience with 3D printing dates to the year 2000 where echocardiographic datasets were used to produce "real" 3D printed models [59]. Today, any 3D dataset can be printed in theory. However, the imaging quality at the outset determines the quality of the segmentation and the subsequent printed model. Usually, contrast-enhanced CMR or cardiac CT are the modalities of choice for 3D printing. The datasets are segmented, and selected images are exported to be printed into a 3D model using different materials [60•, 61]. Especially for complex surgical lesions, 3D printing is increasingly applied to guide surgical management and facilitate communication between imagers and surgeons. Holding a 3D model in your hands allows intuitive understanding of complex cardiac anatomy without the need for mental reconstruction. 3D models improve the surgeons' pre-operative understanding of the cardiac anatomy and facilitates surgical planning. It also is useful in training cardiac surgeons and cardiologists improving their understanding of congenital heart lesions [62]. Using softer materials, surgical trainees can practice congenital surgeries as they can cut, sew, patch in the models as they would in real situations thus acquiring these skills faster. [63]. The models can also be used in the planning of complex percutaneous interventions [64, 65]. Limitations include the current temporal and spatial resolution of CMR and cardiac CT images which are insufficient to allow adequate printing of valvar and sub-valvar apparatus. 3D printing these structures based on 3D echocardiographic datasets is increasingly used in adults for mitral valve interventions [66]. 3D printing is still is very costly process requiring expensive printers and extensive post-processing by an experienced operator. Direct 3D visualization using holography is another emerging imaging tool. Holographic representation of 3D volumetric datasets with intuitive post-processing tools have the potential to significantly impact planning of interventions and surgeries [67].

Fusion imaging

Fusion imaging cross-registers imaging obtained from two imaging modalities into a single, spatially oriented display. This approach is useful for catheter interventions as integration of 3D TEE echocardiographic images with fluoroscopic images can be helpful for guidance of complex interventions. Application of overlay technology has been shown to result in lower fluoroscopy time and radiation dose in adults and children [68]. The size of the 3D TEE probe has precluded smaller children and infants from the application of this technology. Also, imaging more anterior structures such as the pulmonary valve remains challenging using 3D TEE.

Table 1. Summary of imaging modalities

	Echocardiography	*CMR*	*Cardiac CT*
Availability and portability	++++	++	+++
Radiation risk	–	–	++++
Technical limitations	• Dependent on acoustic windows • Operator dependent • Contrast not approved for use in children	• Contraindicated in the presence of ferromagnetic devices • Claustrophobia • Gadolinium reactions	• Radiation risk • Iodine reactions
Requirement for sedation	+	++++	+
Spatial resolution	2D: ++++ 3DE: +++	+++	++++
Temporal resolution	2D: ++++ 3DE: +++ (depending on imaging mode)	+++	+++
Intracardiac anatomy	++++	++++	++++
Extracardiac vessels	++	++++	++++
Coronary imaging	++	+++	++++
Volumetric ventricular function	2D: ++ 3D: +++ (underestimates CMR values, more limited for RV)	++++	- +++ gated with more radiation dose
Pressure gradient	++++	–	–
Segmental function	++++	++++	–
Diastolic function	++++	+++	–
Flow quantification	+	++++	–
Tissue characterization	+	++++	+
Myocardial viability	+	++++	++++
Airway imaging	–	+++	++++
Multiplane reconstruction	2DE: - 3DE: ++	++++	++++
Suitability for 3D printing	+	++++	++++

Artificial intelligence and deep learning

Automation has already been part of most modalities, being applied in semi-automated segmentation and calculation of ejection fraction or strain data [69]. With advancing artificial intelligence and the ability for machine learning, extracting these quantitative data will become faster and more reproducible. Automated segmentation of coronary arteries from coronary CT has been

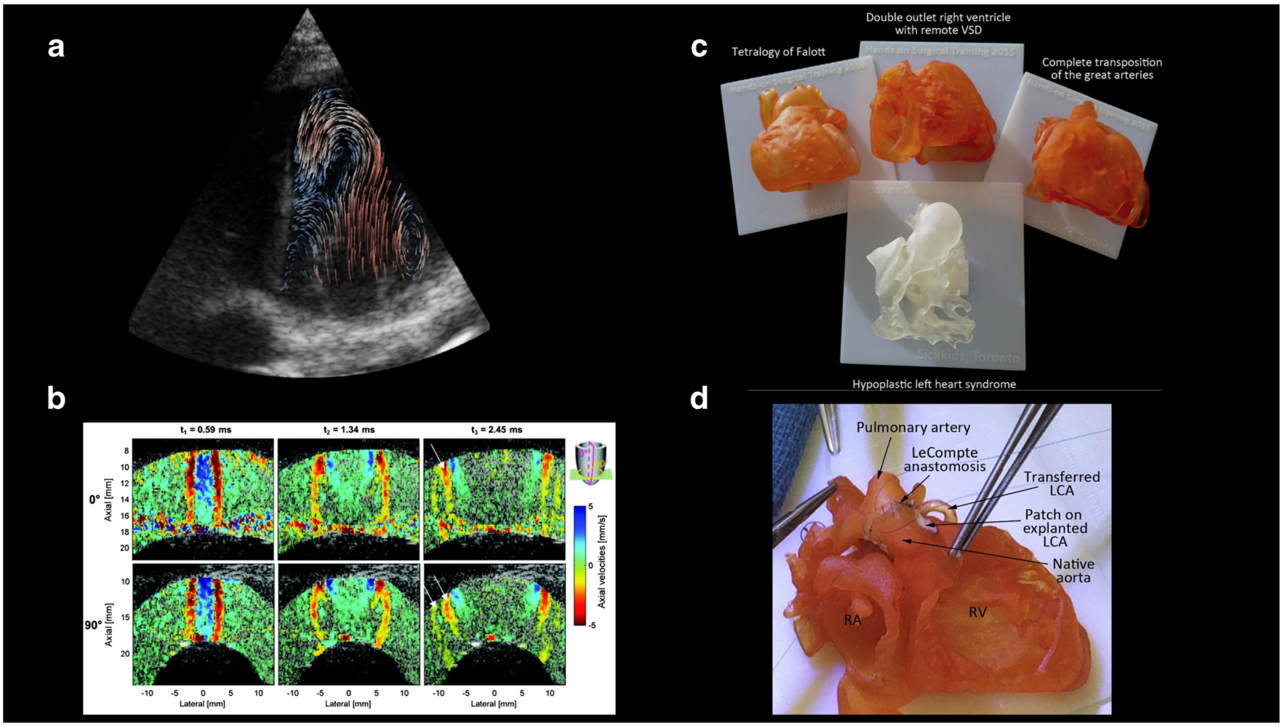

Fig. 1. Examples of advances in cardiac imaging. **a** Vortical diastolic flow imaged by high frame rate echocardiography and blood speckle tracking. **b** Comparison of shear wave propagation in the LV apical zone *(reproduced with permissions from Elsevier Caenen* et al. *Investigating shear wave physics in a generic pediatric left ventricular model* via in vitro *experiments and finite element simulations. IEEE Trans Ultrason Ferroelectr Freq Control. 2017;64(2):349–361*). **c** Printed 3D cardiac models from MRI or CT datasets. **d** Surgical practice with 3D model from flexible material *(reproduced with permissions from Elsevier from Yoo* et al. *GS. Hands-on surgical training of congenital heart surgery using 3-dimensional print models. J Thorac Cardiovasc Surg. 2017;153(6):1530–1540)*.

shown to better predict ischemic risk by estimating fractional flow reserve [70]. While relatively advanced in echocardiography, automated segmentation in CMR is an area where progress is needed and expected, as this is one of the most time-consuming stages of the CMR workflow. However, there are many obstacles such as difficult endocardial definition related to artifacts, volume-averaging, complex geometries, and the presence of trabeculations. In echocardiography, machine learning is evolving quickly and has produced some encouraging results such as in the discrimination between HCM and athlete's heart based on speckle tracking data [71]. As large datasets are required for machine learning, this may prove to be challenging for CHD given the higher variability in congenital defects. As clinical information and imaging become increasingly connected through electronic medical records, machine learning and artificial intelligence could be used to make predictions and recommendations for optimal management using real-time data.

Beyond the heart

As cardiac surgical results have improved dramatically in the past decade, the focus has shifted from maximizing survival to also optimizing other aspects of long-term outcome such as the impact of CHD on neurocognitive development. Children with congenital heart disease are known to be at a higher risk for neuro-developmental abnormalities. The mechanisms are actively being investigated as early as during fetal life. The use of fetal cardiac and brain MRI has shown reduced cerebral oxygen consumption and reduced brain size and growth in fetuses with congenital heart disease [72]. Pre- and post-operative brain MRI are aimed to investigate the effects of congenital heart disease and its management on brain structure and function.

Summary

Cardiac imaging has known exceptional advances (Fig. 1), which parallel those of miniaturization of electronic components and computational power. While echocardiography remains the main modality in pediatric cardiac imaging, no single imaging modality is perfect and all have complementary roles to play in the understanding of anatomy and physiology (Table 1). The broader scope of cardiac imaging now includes the brain, as there is a need to address the heart-brain connection in our patients who are at particularly high risk of neuro-developmental problems. The wealth of data which can now be extracted from the different modalities is exceeding the processing power of conventional computers, which has brought on the emergence of cloud computing as well as artificial intelligence in our field. These will undoubtable play major roles in the near future but there remains value in the experienced imaging specialist to choose the most appropriate modality, and to choose and reformat the imaging in a way that connects with all involved in the patient care. The future of imaging specialist will likely require them to have detailed knowledge of the different modalities, which will likely affect the structure and length of their training.

Compliance with Ethical Standards

Conflict of Interest
Wadi Mawad and Luc L. Mertens each declare no potential conflicts of interest.

Human and Animal Rights and Informed Consent
This article does not contain any studies with human or animal subjects performed by any of the authors.

References and Recommended Reading

Papers of particular interest, published recently, have been highlighted as:

- • Of importance
- •• Of major importance

1. Edler I, Lindstrom K. The history of echocardiography. Ultrasound Med Biol. 2004;30(12):1565–644. https://doi.org/10.1016/S0301-5629(99)00056-3.
2. Medford BA, Taggart NW, Cabalka AK, Cetta F, Reeder GS, Hagler DJ, et al. Intracardiac echocardiography during atrial septal defect and patent foramen ovale

device closure in pediatric and adolescent patients. J Am Soc Echocardiogr. Elsevier Inc. 2014;27(9):984–90. https://doi.org/10.1016/j.echo.2014.05.017.
3. Jijeh AMZ, Omran AS, Najm HK, Abu-Sulaiman RM. Role of intraoperative transesophageal echocardiography in pediatric cardiac surgery. J Saudi Hear Assoc. King Saud University. 2016;28(2):89–94. https://doi.org/10.1016/j.jsha.2015.06.005.
4. Simpson JM. Real-time three-dimensional echocardiography of congenital heart disease using a high frequency paediatric matrix transducer. Eur J Echocardiogr. 2008;9(2):222–4. Available from: http://www.ncbi.nlm.nih.gov/pubmed/17714999
5. von Ramm OT, Smith SW. Real time volumetric ultrasound imaging system. J Digit Imaging. 1990;3(4):261–6. https://doi.org/10.1007/BF03168124.
6. Sheikh KH, Smith SW, von Ramm O, Kisslo J. Real-time, three-dimensional echocardiography: feasibility and initial us. Echocardiography. 1991;8(1):119–25.
7.•• Simpson J, Lopez L, Acar P, Friedberg MK, Khoo NS, Ko HH, et al. Three-dimensional Echocardiography in Congenital Heart Disease: An Expert Consensus Document from the European Association of Cardiovascular Imaging and the American Society of Echocardiography. J Am Soc Echocardiogr. 2017;30(1):1–27. https://doi.org/10.1016/j.echo.2016.08.022.
Elsevier Inc; Expert review and recommendations for the use of 3DE in congenital heart disease.
8. Renella P, Marx GR, Zhou J, Gauvreau K, Geva T. Feasibility and reproducibility of three-dimensional echocardiographic assessment of right ventricular size and function in pediatric patients. J Am Soc Echocardiogr. Elsevier Inc. 2014;27(8):903–10. https://doi.org/10.1016/j.echo.2014.04.008.
9. Bell A, Rawlins D, Bellsham-Revell H, Miller O, Razavi R, Simpson J. Assessment of right ventricular volumes in hypoplastic left heart syndrome by real-time three-dimensional echocardiography: comparison with cardiac magnetic resonance imaging. Eur Heart J Cardiovasc Imaging. 2014;15(3):257–66. https://doi.org/10.1093/ehjci/jet145.
10. Selly J-B, Iriart X, Roubertie F, Mauriat P, Marek J, Guilhon E, et al. Multivariable assessment of the right ventricle by echocardiography in patients with repaired tetralogy of Fallot undergoing pulmonary valve replacement: A comparative study with magnetic resonance imaging. Arch Cardiovasc Dis. 2015;108(1):5–15. Available from: http://www.ncbi.nlm.nih.gov/pubmed/25453716
11. Hubka M, Bolson EL, McDonald JA, Martin RW, Munt B, Sheehan FH. Three-dimensional echocardiographic measurement of left and right ventricular mass and volume: in vitro validation. Int J Cardiovasc Imaging. 2002;18(2):111–8. https://doi.org/10.1023/A:1014616603301.
12. Muraru D, Spadotto V, Cecchetto A, Romeo G, Aruta P, Ermacora D, et al. New speckle-tracking algorithm for right ventricular volume analysis from three-dimensional echocardiographic data sets: validation with cardiac magnetic resonance and comparison with the previous analysis tool. Eur Hear J Cardiovasc Imaging. 2016;17(11):1279–89. Available from: https://academic.oup.com/ehjcimaging/article-lookup/doi/10.1093/ehjci/jev309
13.• Medvedofsky D, Addetia K, Patel AR, Sedlmeier A, Baumann R, Mor-Avi V, et al. Novel Approach to Three-Dimensional Echocardiographic Quantification of Right Ventricular Volumes and Function from Focused Views. J Am Soc Echocardiogr. Elsevier Inc. 2015;28(10):1222–31. https://doi.org/10.1016/j.echo.2015.06.013.
3DE echocardiographic technique compared to CMR volumetric measures.
14. Pavlopoulos H, Nihoyannopoulos P. Strain and strain rate deformation parameters: from tissue Doppler to 2D speckle tracking. Int J Cardiovasc Imaging. 2008;24(5):479–91. https://doi.org/10.1007/s10554-007-9286-9.
15. Forsey J, Friedberg MK, Mertens L. Speckle tracking echocardiography in pediatric and congenital heart disease. Echocardiography. 2013;30(4):447–59. https://doi.org/10.1111/echo.12131.
16. Amundsen BH, Helle-Valle T, Edvardsen T, Torp H, Crosby J, Lyseggen E, et al. Noninvasive myocardial strain measurement by speckle tracking echocardiography: Validation against sonomicrometry and tagged magnetic resonance imaging. J Am Coll Cardiol. Elsevier Masson SAS. 2006;47(4):789–93. https://doi.org/10.1016/j.jacc.2005.10.040.
17. Korinek J, Wang J, Sengupta PP, Miyazaki C, Kjaergaard J, McMahon E, et al. Two-dimensional strain-a Doppler-independent ultrasound method for quantitation of regional deformation: validation in vitro and in vivo. J Am Soc Echocardiogr. 2005;18(12):1247–53. https://doi.org/10.1016/j.echo.2005.03.024.
18. Bansal M, Cho GY, Chan J, Leano R, Haluska BA, Marwick TH. Feasibility and Accuracy of Different Techniques of Two-Dimensional Speckle Based Strain and Validation With Harmonic Phase Magnetic Resonance Imaging. J Am Soc Echocardiogr. Elsevier Inc. 2008;21(12):1318–25. https://doi.org/10.1016/j.echo.2008.09.021.
19. Sato Y, Maruyama A, Ichihashi K. Myocardial strain of the left ventricle in normal children. J Cardiol. Japanese College of Cardiology. 2012;60(2):145–9. https://doi.org/10.1016/j.jjcc.2012.01.015.
20. Klitsie LM, Roest AAW, Van Der Hulst AE, Stijnen T, Blom NA, Ten Harkel ADJ. Assessment of intraventricular time differences in healthy children using two-dimensional speckle-tracking echocardiography. J Am Soc Echocardiogr. Elsevier Inc. 2013;26(6):629–39. https://doi.org/10.1016/j.echo.2013.03.006.
21.•• Cantinotti M, Kutty S, Franchi E, Paterni M, Scalese M, Iervasi G, et al. Pediatric echocardiographic nomograms: What has been done and what still needs to be done. Trends Cardiovasc Med. 2017;27(5):336–49.

https://doi.org/10.1016/j.tcm.2017.01.006.
Elsevier; Review of current state of normal values in pediatric echocardiography and highlights of important shortcomings.
22.•• Dallaire F, Slorach C, Bradley T, Hui W, Sarkola T, Friedberg MK, et al. Pediatric Reference Values and Z Score Equations for Left Ventricular Systolic Strain Measured by Two-Dimensional Speckle-Tracking Echocardiography. J Am Soc Echocardiogr. 2016;29(8):786–793.e8. https://doi.org/10.1016/j.echo.2016.03.018.
Elsevier Inc.; Important normal values for 2DSTE derived strain in a pediatric population.
23. Nagata Y, Takeuchi M, Mizukoshi K, Wu VCC, Lin FC, Negishi K, et al. Intervendor variability of two-dimensional strain using vendor-specific and vendor-independent software. J Am Soc Echocardiogr. Elsevier Inc. 2015;28(6):630–41. https://doi.org/10.1016/j.echo.2015.01.021.
24. Zhang L, Gao J, Xie M, Yin P, Liu W, Li Y, et al. Left ventricular three-dimensional global systolic strain by real-time three-dimensional speckle-tracking in children: Feasibility, reproducibility, maturational changes, and normal ranges. J Am Soc Echocardiogr. Elsevier Inc. 2013;26(8):853–9. https://doi.org/10.1016/j.echo.2013.05.002.
25. Cifra B, Dragulescu A, Border WL, Mertens L. Stress echocardiography in paediatric cardiology. Eur Heart J Cardiovasc Imaging. 2015;16(10):1051–9. https://doi.org/10.1093/ehjci/jev159.
26. Chen MH, Abernathey E, Lunze F, Colan SD, Apos O, Neill S, et al. Utility of exercise stress echocardiography in pediatric cardiac transplant recipients: A single-center experience. J Int Soc Hear Lung Transplant. Elsevier Inc. 2012;31(5):1–7. https://doi.org/10.1016/j.healun.2011.12.014.
27. Magne J, Lancellotti P, Piérard LA. Exercise testing in asymptomatic severe aortic stenosis. JACC Cardiovasc Imaging. 2014;7(2):188–99. https://doi.org/10.1016/j.jcmg.2013.08.011.
28. Cifra B, Mertens L, Mirkhani M, Slorach C, Hui W, Manlhiot C, et al. Systolic and Diastolic Myocardial Response to Exercise in a Healthy Pediatric Cohort. J Am Soc Echocardiogr. Elsevier Inc. 2016;29(7):648–54. https://doi.org/10.1016/j.echo.2016.02.015.
29.• Pernot M, Lee WN, Bel A, Mateo P, Couade M, Tanter M, et al. Shear wave imaging of passive diastolic myocardial stiffness: stunned versus infarcted myocardium. JACC Cardiovasc Imaging. 2016;9(9):1023–30. https://doi.org/10.1016/j.jcmg.2016.01.022.
Important work showing the use of shear-wave imaging to characterize stunned vs infarcted myocardium.
30. Caenen A, Thabit A, Swillens A, Segers P. The Effect of Stretching on Transmural Shear Wave Anisotropy in Cardiac Shear Wave The Effect of Stretching on Transmural Shear Wave Anisotropy in Cardiac Shear Wave Elastography. 2017;(September).
31. Van Cauwenberge J, Lovstakken L, Fadnes S, Rodriguez-Morales A, Vierendeels J, Segers P, et al. Assessing the Performance of Ultrafast Vector Flow Imaging in the Neonatal Heart via Multiphysics Modeling and *In Vitro* Experiments. IEEE Trans Ultrason Ferroelectr Freq Control. 2016;63(11):1772–85. Available from: http://ieeexplore.ieee.org/document/7527648/
32. Fadnes S, Wigen MS, Nyrnes SA, Lovstakken L. In Vivo Intracardiac Vector Flow Imaging Using Phased Array Transducers for Pediatric Cardiology. IEEE Trans Ultrason Ferroelectr Freq Control. 2017;64(9):1318–26.
33. Sundholm JKM, Olander RFW, Ojala TH, Andersson S, Sarkola T. Feasibility and precision of transcutaneous very-high resolution ultrasound for quantification of arterial structures in human neonates - Comparison with conventional high resolution vascular ultrasound imaging. Atherosclerosis. Elsevier Ltd. 2015;239(2):523–7. https://doi.org/10.1016/j.atherosclerosis.2015.02.016.
34. Geva T. Magnetic Resonance Imaging: Historical Perspective. J Cardiovasc Magn Reson. 2006;8(4):573–80. https://doi.org/10.1080/10976640600755302.
35. Garrowaya N, Grannell PK, Mansfield P. Image formation in NMR by a selective irradiative process. J Phys C Solid State Phys. 1974;7(24):L457–62. https://doi.org/10.1088/0022-3719/7/24/006.
36. Sholl CA. NMR "diffraction" in solids?.
37. Hawkes RC, Hawkes RC, Holland GN, Moore WS, Roebuck EJ, Worthington BS. Nuclear magnetic resonance (NMR) tomography of the normal heart. J Comput Assist Tomogr. 1981;5(5):605–12. Available from: http://www.ncbi.nlm.nih.gov/pubmed/7298936
38. Ordidge RJ, Mansfield P, Doyle M, Coupland RE. Real time movie images by NMR. Br J Radiol. 1982;55(658):729–33. https://doi.org/10.1259/0007-1285-55-658-729.
39. van Dijk P. Direct cardiac NMR imaging of heart wall and blood flow velocity. J Comput Assist Tomogr. 1984;429–36. Available from: http://www.ncbi.nlm.nih.gov/pubmed/6725689.
40. Bryant DJ, Payne JA, Firmin DN, Longmore DB. Measurement of flow with NMR imaging using a gradient pulse and phase difference technique. J Comput Assist Tomogr. 1984;588–93. Available from: http://www.ncbi.nlm.nih.gov/pubmed/6736356.
41. Schaefer S, Malloy CR, Katz J, Parkey RW, Buja LM, Willerson JT, et al. Gadolinium-DTPA-enhanced nuclear magnetic resonance imaging of reperfused myocardium: identification of the myocardial bed at risk. J Am Coll Cardiol. 1988;12(4):1064–72. https://doi.org/10.1016/0735-1097(88)90477-9.
42. Razavi R, Hill DLG, Keevil SF, Miquel ME, Muthurangu V, Hegde S, et al. Cardiac catheterisation guided by MRI in children and adults with congenital heart disease. Lancet. 2003;362(9399):1877–82. https://doi.org/10.1016/S0140-6736(03)14956-2.
43.•• Cheng JY, Zhang T, Alley MT, Uecker M, Lustig M, Pauly JM, et al. Comprehensive Multi-Dimensional MRI for the Simultaneous Assessment of Cardiopulmonary

Anatomy and Physiology. Sci Rep. 2017;7(1):5330. Springer US; Available from: http://www.nature.com/articles/s41598-017-04676-8.
Example of multidimensional MRI acquisitions to allow fast, comprehensive studies in patients as young as 3 days.
44.• Chelu RG, Wanambiro KW, Hsiao A, Swart LE, Voogd T, van den Hoven AT, et al. Cloud-processed 4D CMR flow imaging for pulmonary flow quantification. Eur J Radiol. 2016;85(10):1849–56. https://doi.org/10.1016/j.ejrad.2016.07.018.
Elsevier Ireland Ltd; Application of multidimentional CMR with fast acquisition and reconstruction in neonatal patients including complete CMR datasets in about 10 min long acquisition.
45. Babu-Narayan SV, Kilner PJ, Li W, Moon JC, Goktekin O, Davlouros PA, et al. Ventricular fibrosis suggested by cardiovascular magnetic resonance in adults with repaired tetralogy of Fallot and its relationship to adverse markers of clinical outcome. Circulation. 2006;113(3):405–13. https://doi.org/10.1161/CIRCULATIONAHA.105.548727.
46. Wald RM, Haber I, Wald R, Valente AM, Powell AJ, Geva T. Effects of regional dysfunction and late gadolinium enhancement on global right ventricular function and exercise capacity in patients with repaired tetralogy of fallot. Circulation. 2009;119(10):1370–7. https://doi.org/10.1161/CIRCULATIONAHA.108.816546.
47. Dusenbery SM, Jerosch-Herold M, Rickers C, Colan SD, Geva T, Newburger JW, et al. Myocardial extracellular remodeling is associated with ventricular diastolic dysfunction in children and young adults with congenital aortic stenosis. J Am Coll Cardiol. 2014;63(17):1778–85. https://doi.org/10.1016/j.jacc.2013.11.066.
48. Chen CA, Dusenbery SM, Valente AM, Powell AJ, Geva T. Myocardial ECV fraction assessed by CMR is associated with type of hemodynamic load and arrhythmia in repaired tetralogy of Fallot. JACC Cardiovasc Imaging. 2016;9(1):1–10. https://doi.org/10.1016/j.jcmg.2015.09.011.
49. Rychik J. Protein-losing enteropathy after Fontan operation. Congenit Heart Dis. 1987;2(5):288–300. Available from: http://www.ncbi.nlm.nih.gov/pubmed/23396878
50. Connor FL, Hons M, Angelides S, Gibson M, Larden DW, Hons B, et al. Post-Fontan : Role of 99m Technetium-Dextran Scintigraphy. 2003;112(3).
51. Itkin MG, McCormack FX, Dori Y. Diagnosis and treatment of lymphatic plastic bronchitis in adults using advanced lymphatic imaging and percutaneous embolization. Ann Am Thorac Soc. 2016;13(10):1689–96. https://doi.org/10.1513/AnnalsATS.201604-292OC.
52. Kim EY, Hwang HS, Lee HY, Cho JH, Kim HK, Lee KS, et al. Anatomic and Functional Evaluation of Central Lymphatics With Noninvasive Magnetic Resonance Lymphangiography. Medicine (Baltimore). 2016;95(12):e3109. Available from: http://content.wkhealth.com/linkback/openurl?sid=WKPTLP:landingpage&an=00005792-201603220-00021
53. Hurlock GS, Higashino H, Mochizuki T. History of cardiac computed tomography: single to 320-detector row multislice computed tomography. Int J Cardiovasc Imaging. 2009;25(SUPPL. 1):31–42. https://doi.org/10.1007/s10554-008-9408-z.
54. Council NR. Health effects of exposure to low levels of ionizing radiation By the Committee on the Biological Effects of Ionizing Radiations of the National Research Council Washington D.C., National Academy Press, 421 pp., 1990, ISBN 0–309–03995-9, £30.00 [Internet]. Health Policy. 1990. 269 p. Available from: http://linkinghub.elsevier.com/retrieve/pii/016885109190028V.
55. Brenner DJ, Elliston CD, Hall EJ, Berdon WE. Estimated risks of radiation. AJR. 2001;176(2):289–96. https://doi.org/10.2214/ajr.176.2.1760289.
56. Marcus RP, Koerner E, Aydin RC, Zinsser D, Finke T, Cyron CJ, et al. The evolution of radiation dose over time: Measurement of a patient cohort undergoing whole-body examinations on three computer tomography generations. Eur J Radiol. Elsevier Ireland Ltd. 2017;86:63–9. https://doi.org/10.1016/j.ejrad.2016.11.002.
57. Hui PKT, Goo HW, Du J, Ip JJK, Kanzaki S, Kim YJ, et al. Asian consortium on radiation dose of pediatric cardiac CT (ASCI-REDCARD). Pediatr Radiol. 2017;47(8):899–910. https://doi.org/10.1007/s00247-017-3847-4.
58. Nie P, Li H, Duan Y, Wang X, Ji X, Cheng Z, et al. Impact of sinogram affirmed iterative reconstruction (SAFIRE) algorithm on image quality with 70 kVp-tube-voltage dual-source CT angiography in children with congenital heart disease. PLoS One. 2014;9(3):1–7.
59. Binder TM, Moertl D, Mundigler G, Rehak G, Franke M, Delle-Karth G, et al. Stereolithographic biomodeling to create tangible hard copies of cardiac structures from echocardiographic data: in vitro and in vivo validation. J Am Coll Cardiol Elsevier Masson SAS. 2000;35(1):230–7. https://doi.org/10.1016/S0735-1097(99)00498-2.
60.• Yoo S-J, Thabit O, Kim EK, Ide H, Yim D, Dragulescu A, et al. 3D printing in medicine of congenital heart diseases. 3D Print Med. 2015;2(1):3. https://doi.org/10.1186/s41205-016-0004-x.
Overview of the progress and the future role of 3D printing in congenital heart disease.
61. Meier LM, Meineri M, Qua Hiansen J, Horlick EM. Structural and congenital heart disease interventions: the role of three-dimensional printing. Netherlands Hear J. 2017;25(2):65–75. https://doi.org/10.1007/s12471-016-0942-3.
62. Costello JP, Olivieri LJ, Su L, Krieger A, Alfares F, Thabit O, et al. Incorporating three-dimensional printing into a simulation-based congenital heart disease and critical care training curriculum for resident physicians.

Congenit Heart Dis. 2015;10(2):185–90. https://doi.org/10.1111/chd.12238.

63. Yoo S-J, Spray T, Austin EH, Yun T-J, van Arsdell GS. Hands-on surgical training of congenital heart surgery using 3-dimensional print models. J Thorac Cardiovasc Surg. 2017;153(6):1530–40. Elsevier Inc; Available from: http://linkinghub.elsevier.com/retrieve/pii/S0022522317301848

64. Chaowu Y, Hua L, Xin S. Images in Cardiovascular Medicine Three-Dimensional Printing as an Aid in Transcatheter Closure of Secundum Atrial Septal Defect. Circulation. 2016;133(17):608–11. Available from: http://circ.ahajournals.org/lookup/doi/10.1161/CIRCULATIONAHA.115.020735%5Cnpapers3://publication/doi/10.1161/CIRCULATIONAHA.115.020735

65. Pellegrino PL, Fassini G, Di Biase M, Tondo C. Left atrial appendage closure guided by 3D printed cardiac reconstruction: emerging directions and future trends. J Cardiovasc Electrophysiol. 2016;27(6):768–71. https://doi.org/10.1111/jce.12960.

66. Vukicevic M, Mosadegh B, Min JK, Little SH. Cardiac 3D printing and its future directions. JACC Cardiovasc Imaging. 2017;10(2):171–84. https://doi.org/10.1016/j.jcmg.2016.12.001.

67. Bruckheimer E, Rotschild C, Dagan T, Amir G, Kaufman A, Gelman S, et al. Computer-generated real-time digital holography: first time use in clinical medical imaging. Eur Heart J Cardiovasc Imaging. 2016;17(8):845–9. https://doi.org/10.1093/ehjci/jew087.

68. Jone P-N, Ross MM, Bracken JA, Mulvahill MJ, Di Maria MV, Fagan TE. Feasibility and Safety of Using a Fused Echocardiography/Fluoroscopy Imaging System in Patients with Congenital Heart Disease. J Am Soc Echocardiogr. 2016;29(6):513–21. Elsevier Inc; Available from: http://linkinghub.elsevier.com/retrieve/pii/S0894731716002145

69. Tsang W, Salgo IS, Medvedofsky D, Takeuchi M, Prater D, Weinert L, et al. Transthoracic 3D echocardiographic left heart chamber quantification using an automated adaptive analytics algorithm. JACC Cardiovasc Imaging. 2016;9(7):769–82. https://doi.org/10.1016/j.jcmg.2015.12.020.

70. Gransar H, Achenbach S, Min JK. Angiography Non-invasively Predicts Hemodynamic Significance by Using Fractional Flow Reserve in Intermediate Coronary Lesions 1. 2015;276(2).

71. Emad O, Yassine IA, Fahmy AS. Automatic localization of the left ventricle in cardiac MRI images using deep learning. 2015 37th Annu Int Conf IEEE Eng Med Biol Soc. 2015;683–6. Available from: http://ieeexplore.ieee.org/document/7318454/.

72. Sun L, Macgowan CK, Sled JG, Yoo SJ, Manlhiot C, Porayette P, et al. Reduced fetal cerebral oxygen consumption is associated with smaller brain size in fetuses with congenital heart disease. Circulation. 2015;131(15):1313–23. https://doi.org/10.1161/CIRCULATIONAHA.114.013051.

73. Cohen MS, Eidem BW, Cetta F, Fogel MA, Frommelt PC, Ganame J, et al. Multimodality Imaging Guidelines of Patients with Transposition of the Great Arteries: A Report from the American Society of Echocardiography Developed in Collaboration with the Society for Cardiovascular Magnetic Resonance and the Society of Cardiovascul. J Am Soc Echocardiogr. Elsevier Inc. 2016;29(7):571–621. https://doi.org/10.1016/j.echo.2016.04.002.

74. Valente AM, Cook S, Festa P, Ko HH, Krishnamurthy R, Taylor AM, et al. Multimodality imaging guidelines for patients with repaired Tetralogy of fallot: A report from the American society of echocardiography: Developed in collaboration with the society for cardiovascular magnetic resonance and the society for pediatric radiol. J Am Soc Echocardiogr. Elsevier Inc. 2014;27(2):111–41. https://doi.org/10.1016/j.echo.2013.11.009.