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REVIEW

Three-dimensional echocardiography in the assessment of ventricular function in children: pros, cons, and hopes

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Abstract

The accurate assessment of ventricular function is crucial in paediatric cardiology because its results affect the diagnosis and clinical management. Children with cardiovascular problems require frequent evaluation of ventricular function parameters; therefore, three-dimensional echocardiography may be the perfect modality to address that issue and a valuable supplement to cardiac magnetic resonance imaging. In the present article we review the literature in search of strengths and limitations of quantitative three-dimensional echocardiography for its clinical use in paediatric cardiology.

Key words: cardiac magnetic resonance, children, left ventricular function, right ventricular function, three-dimensional echocardiography

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INTRODUCTION

The accurate assessment of ventricular function in children is one of the most prominent challenges in paediatric cardiology, especially in the case of complex geometry of the right ventricle (RV). Cardiac magnetic resonance (CMR) is considered the gold standard for ventricular volume and systolic function analysis — unmatched so far by any other modality. However, its routine use in everyday clinical practice is limited by low accessibility, high costs, and long duration of the procedure. With regard to two-dimensional echocardiography (2D-ECHO), depending on geometric assumptions, the results offered by this method lack accuracy, although feasibility, low cost, and short time of acquisition are its huge advantages. Three-dimensional echocardiography (3D-ECHO) seems to combine the benefits of both methods while overcoming their limitations. It offers accuracy, feasibility, and high reproducibility and therefore may be considered a perfect tool for regular assessment of ventricular function in patients requiring frequent follow-up [1–3].

Despite fast evolution of 3D-ECHO and its universally accepted role in quantitative cardiac assessment in adults, the clinical role of this method in the paediatric population is still not well established.

The ultimate validation of 3D-ECHO accuracy in ventricular function assessment can be obtained by its comparison with CMR, which is the method of reference. So far, multiple studies have approached the subject; however, those addressing the paediatric population are far less numerous [2–7].

In a recently published expert consensus document of the European Association of Cardiovascular Imaging and the American Society of Echocardiography on the role of 3D-ECHO in the assessment of patients with congenital heart disease (CHD), the recommendations for 3D-ECHO chamber quantification highlight its repeatability, underlining, however, that the volumetric results tend to be underestimated in comparison to CMR, and that geometric algorithms designed for healthy hearts should not be applied to CHD patients without critical validation [8].

It is worth noting that the left and right ventricles are two distinct structures with very different geometric morphologies, and they generate different problems in volumetric and functional assessment. Therefore, in many studies they are addressed separately, which is also the strategy adopted in this article.

LEFT VENTRICULAR FUNCTION

The ellipsoid morphology of the left ventricle (LV) may be considered relatively easy to embrace for quantification, even if we decide to use geometric assumptions, as in standard 2D-ECHO, or automatic 3D-ECHO algorithms offering results

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in real-time imaging. However, while left ventricular ejection fraction (LVEF) assessed in 3D-ECHO shows good agreement with CMR measurements according to many authors, the consistency of volumetric results is less conclusive, even if still well enough correlated.

So far two meta-analyses have been published on this subject. The first one, by Shimada and Shiota [9], addresses the sources of bias in LV function measurements in 3D-ECHO. Based on 95 published studies (3055 patients, mostly adults), the analysis showed excellent agreement with CMR in the case of LVEF, revealing at the same time significant underestimation of left ventricular end-diastolic (LV-EDV) and end-systolic volumes (LV-ESV) (–9.9 mL and –4.7 mL, respectively), especially for enlarged chambers. Among the factors reducing bias, the use of matrix-array transducer and semiautomated tracking of endocardial border were listed. The second meta-analysis, by Dorosz et al. [10], involved 23 studies (comprising only adults; 1638 echocardiograms) comparing the measurements performed by 3D-ECHO and CMR, proving yet again significant underestimation of volumes, but in this case — also of LVEF, although the authors only offered its overall pooled bias (–0.6% ± 11.8%).

Nevertheless, owing to the evolution of 3D-ECHO techniques and improvement of volumetric algorithms, many subsequent publications postulated good agreement between this modality and CMR in terms of left ventricular measurements, including LV-EDV and LV-ESV [11–13].

In the authors' experience, the closest agreement with CMR is obtained by using high-contrast monitor settings for off-line 3D-ECHO data analysis, which enables one to lose visual artefacts and trace the most evident line of endocardium. Moreover, all the trabeculae should be enclosed in the chamber cavity, as in CMR analysis. In the case of enlarged or deformed ventricles, the best strategy is to use more short-axis views for tracing, mimicking the method of disk summation adopted in CMR. The graphic presentation of LV function quantitative analysis by 3D-ECHO is shown in Figure 1.

The literature on the accuracy of quantitative assessment of the LV in children is still scarce. Although many authors postulate good agreement between 3D-ECHO and CMR, the acquired methodology and patients' characteristics are quite different between the studies. Those discrepancies include factors like ultrasound system, software, and geometric algorithms used for analysis, automatic vs. manual endocardial tracing, or the number of consecutive heart beats chosen for 3D image acquisition [5, 6, 14–16].

The majority of published studies enrolled small populations of children, and so far no meta-analysis dedicated exclusively to the paediatric population has been published. Table 1 presents the most recent studies on 3D-ECHO assessment of LV function validated by methods of reference [14–18].

One of the most important clinical issues concerns reference values for volumetric and functional LV parameters in 3D-ECHO, which have not yet been agreed upon; with many publications advocating different values for the paediatric population [19–23]. Even LVEF was found to be disputable in this regard. The paper by Krell et al. [23] based on 3D-ECHO results obtained from 370 healthy children proposed mean LVEF values ranging from 61.5% ± 5.1% to 62.7% ± 5.9%, depending on the software used for analysis (QLab by Philips, Amsterdam, Netherlands and Image Area by TomTec, Unterschleissheim, Germany). Kuebler et al. [22] have recently proposed a lower LVEF limit (51%), which seems to be logical considering the consistency of 3D-ECHO results with CMR adopting similar ranges. However, the only meta-analysis addressing the subject so far, published by Buccheri et al. [19] (including four studies on paediatric populations with a total of 365 patients), advocates a higher value (61%) as the lower LVEF threshold. The discrepancy between volumetric quantification is even more pronounced and still debated without valid consensus.

RIGHT VENTRICULAR FUNCTION

The complex crescent-like morphology of the RV is much more challenging for quantitative analysis than that of its left ovate counterpart. It cannot be embraced or adequately represented by single-plane imaging; it also escapes simplifications offered by geometrical algorithms, especially in the case of deformation or enlargement of the chamber cavity. Because the assessment of RV volume and function is critical in the course of many cardio-pulmonary diseases, the search for the perfect imaging modality for that purpose might be compared to the "quest for the Holy Grail" [24–27].

Again, to analyse the accuracy of 3D-ECHO in that capacity, we should compare it to the modality of reference — CMR imaging. Among many studies published on the subject, the majority address the adult population [28–35]. Studies that were performed in children mostly enrolled small or specific populations of patients [36, 37].

The only meta-analysis published so far, by Shimada et al. [38], comparing 3D-ECHO and CMR in terms of RV measurements, involved 23 studies, among which eight addressed children and four of those enrolled the very same population of 28 patients. The results of this analysis showed significant underestimation of end-diastolic and end-systolic volumes of the right ventricle (RV-EDV and RV-ESV, respectively) and right ventricular ejection fraction (RVEF) by 3D-ECHO, especially in the case of RV enlargement and — to point out specifically — in children. The bias was not reported to be reduced by matrix-array transducer or automated, semiautomated, or manual endocardial tracking, which was proven relevant in LV analysis by the same authors [9]. Table 2 presents the most recent studies comparing 3D-ECHO and CMR for RV quantification in children [36, 37, 39].

One of the prominent limitations of RV 3D-ECHO analysis seems to be suboptimal quality of real-time visualisation and recorded data sets. This issue especially concerns enlarged

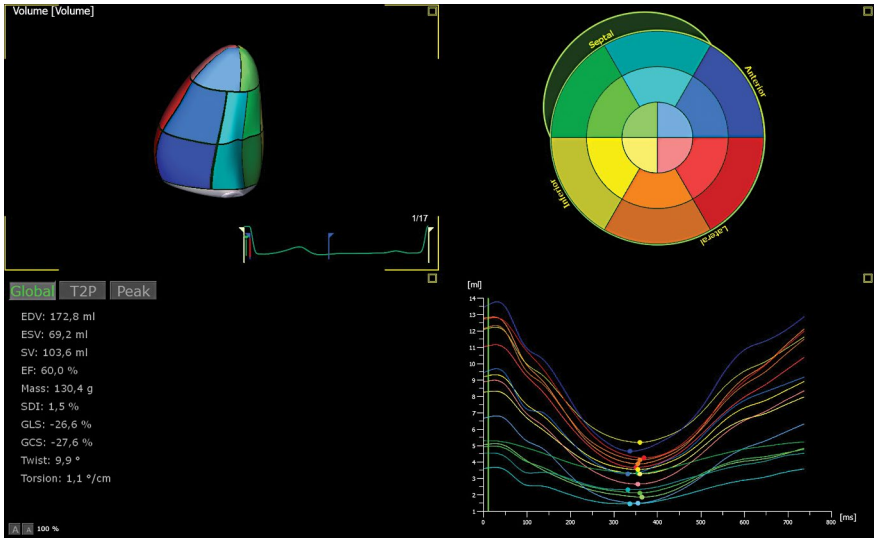

Figure 1. Analysis of left ventricular function by three-dimensional echocardiography (own material)

Table 1. The most recent (published in the last 10 years) studies comparing three-dimensional echocardiography and cardiac magnetic resonance (CMR)/angiography for quantitative analysis of the left ventricle in children

Study	Year	N	Age [years]	Diagnosis	Modality of reference	Correlation with modality of reference (r)		
						LV-EDV	LV-ESV	LVEF
Riehle et al. [15]	2008	12	1–33 (mean 15.9)	Various CHDs	CMR	0.99	0.93	0.69
Lu et al. [16]	2008	19	10.6 ± 2.8	Healthy	CMR	0.96	0.93	0.88
Friedberg et al. [14]	2010	35	< 4 (mean 0.8)	Various CHDs	CMR	0.96	0.90	0.75
Laser et al. [17]	2010	49	Mean in sub-groups: 12.6/7.3	Healthy/ /TOF	CMR	0.95	0.91	–
Abdel Aziz et al. [18]	2016	40	3.0 ± 1.8	TOF	Angiography	0.97	–	–

CHD — congenital heart disease; LV-EDV — left ventricular end-diastolic volume; LVEF — left ventricular ejection fraction; LV-ESV — left ventricular end-systolic volume; TOF — tetralogy of Fallot

Table 2. The most recent (published in the last 10 years) studies comparing three-dimensional echocardiography and cardiac magnetic resonance (CMR) for quantitative analysis of the right ventricle in children

Study	Year	N	Diagnosis	Method	Correlation with CMR (r)		
					RV-EDV	RV-ESV	RVEF
Lu et al. [36]	2008	17	Healthy	Disks summation	0.98	0.96	0.85
Khoo et al. (total of four studies) [37]	2009	28	CHD	Various (here — semi-automated)	0.91	0.90	0.76
Dragulescu et al. [39]	2012	36	Repaired TOF	Semi-automated	0.98	0.98	0.85

RV-EDV — right ventricular end-diastolic volume; RVEF — right ventricular ejection fraction; RV-ESV — right ventricular end-systolic volume; other abbreviations — see Table 1

ventricles (often observed in children with tetralogy of Fallot, before or after repair, pulmonary hypertension, arrhythmogenic right ventricular cardiomyopathy, or hypoplastic left heart syndrome), because in most semi-automatic tracking software both ventricles need to fit in the analysed field. To assess proper spatial orientation of the RV, the apical and mitral

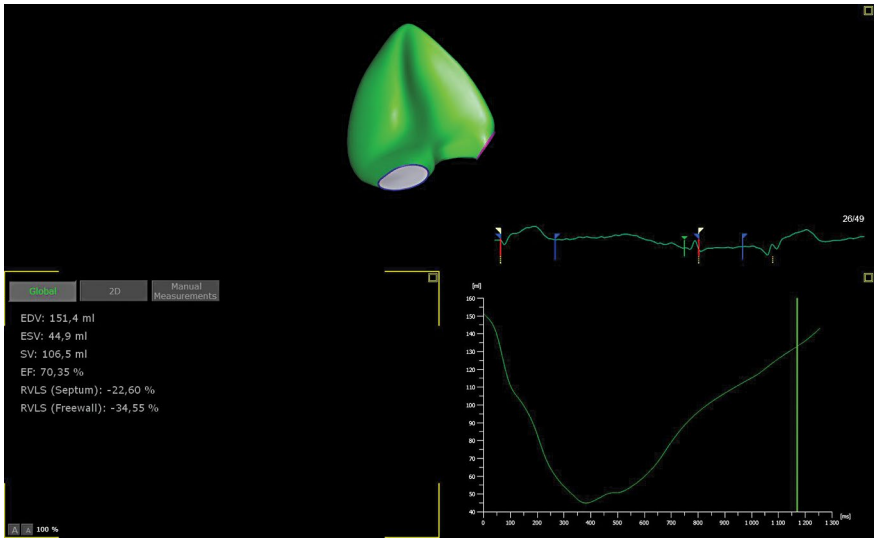

Figure 2. Analysis of right ventricular function by three-dimensional echocardiography (own material)

markers from the LV are also required. When RV chambers are enlarged, it is impossible to accommodate into focus anything else, so the LV often stays outside the acquisition area.

In the study published by Khoo et al. [37] on 54 patients (adolescents and young adults) with various heart defects affecting the RV and causing its enlargement, 3D-ECHO data were considered adequate for analysis in only 28 patients.

In our experience the key point in RV assessment is accommodating the whole chamber in a full dataset, even at the cost of losing the LV from view. During subsequent analysis the required LV markers may be placed outside the analysed field, which still enables RV orientation and allows further steps in the analysis. A 3D-ECHO analysis of the RV function is presented in Figure 2.

As mentioned earlier, the difficulty in obtaining accurate RV quantification seems to lie in the lack of an optimal geometric algorithm for the analysis. For that reason, new methods of calculation were proposed, inspired by the CMR disk summation technique [24, 25, 32, 40]. The strategy is based on manual contouring of the endocardial border in many short-axis RV views from the tricuspid valve level to the apex, and therefore not depending on the assumed ventricular geometry. The method was praised by many authors for offering better agreement with CMR, although it is much more time-consuming than automated or semi-automated tracing [28, 36, 37].

Although the novel approaches to 3D-ECHO methodology seem to at least partly overcome RVEF underestimation, RV volume assessment cannot altogether escape this tendency, especially in patients with enlarged or deformed chambers [29, 31, 41–44].

We can use 3D-ECHO for regular RV assessment in children, either in follow-up or as an addition to the CMR evaluation, but the question remains regarding the reference limits for this modality. It is a challenge to define even the lower cut-off values for RVEF. The only paper published on the subject so far, by Gopal et al. [45], concerning normal values of RV size and function assessed by 3D-ECHO in the adult population (based on 71 healthy patients), proposes lower limits of RVEF as low as 29.9% for men and 38% for women. It seems, however, that at present, when there is better agreement between 3D-ECHO and CMR in terms of RVEF calculation, we may opt for higher values accepted in clinical practice (45%), even if no consensus in the literature has been reached [46–48].

SUMMARY AND FUTURE DIRECTIONS

Three-dimensional echocardiography is a promising method for the assessment of ventricular function in children, especially in patients requiring regular follow-up. It offers good, constantly improving agreement with CMR imaging for LV volume and LVEF assessment and its accuracy in terms of RV measurements is improving; however, it still tends to underestimate ventricular volumes.

Nevertheless, even considering those limitations, the high reproducibility of 3D-ECHO results, exceeding by far 2D-ECHO, makes it a perfect tool for frequent assessment in children requiring regular follow-up. In many heart defects, cardiomyopathies, or arrhythmias the most important part of the evaluation is the assessment of ventricular function changes in a single patient, rather than concentrating on raw quantitative data. For that reason, 3D-ECHO may successfully complement CMR in everyday clinical practice.

With rapid evolution of novel imaging techniques, we hope the accuracy of 3D-ECHO results improves. Further studies are required, both in the population of healthy children and in groups suffering from cardiovascular pathologies, for full recognition of the benefits of 3D-ECHO in paediatric cardiology.

Conflict of interest: *none declared*

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