Evaluation of left ventricular function and volume by two-dimensional echocardiography in a pediatric population: Correlation with cardiac magnetic resonance imaging

Suneet Bhansali[1], Ella Tokar[1], Sunil Saharan[1], Ramzi Khalil[1], Puneet Bhatla[1,2]
[1]Department of Pediatrics, Division of Pediatric Cardiology, NYU Langone Health, New York, NY, USA, [2]Department of Radiology, NYU Langone Health, New York, NY, USA

ABSTRACT

Background: **Echocardiographic quantification of left ventricular (LV) volume and ejection fraction (EF) is widely used in the pediatric population. However, there is no consensus on the most accurate method of quantifying ventricular volumes and systolic function.**

Purpose: **The purpose of this study is to compare two commonly used echocardiographic methods for the evaluation of LV volume and quantification of EF, the five-sixth area-length (5/6 AL) and the modified biplane Simpson (BS), to cardiac magnetic resonance (CMR) imaging in children.**

Methods: **CMR studies were paired with echocardiograms and retrospectively analyzed in children 18 years of age and younger. Studies performed more than 3 months between modalities, patients with congenital heart disease, and patients who had changes in medication regimen between corresponding CMR and echocardiograms were excluded. LV volumes and EF were calculated using the 5/6 AL and BS methods and compared to volumes and EF measured on corresponding CMR studies. Subgroup analyses were conducted based on LV function, pathology, and weight.**

Results: **We retrospectively analyzed 53 CMR and corresponding echocardiogram studies (23 studies for myocarditis and 30 studies for cardiomyopathy) in 46 patients. LVEF derived by both echocardiographic methods showed a good correlation to CMR (5/6 AL r = 0.85 and BS r = 0.82). However, both echocardiographic methods overestimated LVEF and underestimated LV volumes when compared to CMR.**

Conclusion: **Left ventricular volumes and EF, as measured by echocardiography, correlate well with CMR measurements. Echocardiography underestimates LV systolic and diastolic volumes and overestimates LVEF. While echocardiography is a good surrogate for estimating LVEF, CMR should be considered in patients for whom accurate measurements are needed for critical clinical decision-making.**

Keywords: Cardiac magnetic resonance, echocardiography, pediatric heart disease

Access this article online

Quick Response Code:

Website: https://journals.lww.com/aopc

DOI: 10.4103/apc.apc_199_23

How to cite this article: Bhansali S, Tokar E, Saharan S, Khalil R, Bhatla P. Evaluation of left ventricular function and volume by two-dimensional echocardiography in a pediatric population: Correlation with cardiac magnetic resonance imaging. Ann Pediatr Card 2024;17:28-35.

Address for correspondence: Dr. Puneet Bhatla, Department of Pediatrics, Division of Pediatric Cardiology, and Department of Radiology, NYU Langone Health, 403 E 34th St, 4th Floor, New York, NY 10016, USA.
E-mail: puneet.bhatla@nyulangone.org

Submitted: 28-Dec-2023 **Revised:** 02-Apr-2024 **Accepted:** 03-Apr-2024 **Published:** 24-May-2024

INTRODUCTION

Estimating left ventricular (LV) systolic function, or ejection fraction (EF), is a vital component of any echocardiographic examination in patients with acquired or congenital heart disease. Diagnosis, management, and prognosis of sick children oftentimes depend on appropriate and accurate quantification of LV volumes and systolic function.[1,2] Cardiac magnetic resonance (CMR) imaging is the current gold standard for assessment of ventricular size and systolic function.[3] CMR allows direct measurements of cardiac chambers from high-resolution imaging obtained without limitations of acoustic windows and eliminates the need for geometric assumptions regarding chamber shape, thus providing an accurate cardiac assessment.[4] Although CMR is a desirable reference, echocardiography is much more accessible and routinely utilized for cardiac evaluation. Various echocardiographic two-dimensional (2D) imaging planes are utilized to obtain ventricular dimensions and area by planimetry at end-diastole and end-systole. Volumetric estimation of the LV can then be performed using the five-sixth area-length (5/6 AL) and modified biplane Simpson (BS) method of disc summation, both of which are dependent on geometrical assumptions. While the reproducibility of each method has been extensively reported, data on the accuracy of these two methods are lacking in the pediatric-age population.[5] Therefore, we conducted a single-center retrospective analysis comparing these two common 2D echocardiographic measures for ventricular size and systolic function against the gold standard of CMR among children with acquired heart diseases.

METHODS

The study was approved by our Institutional Review Board (s20-01511, approved October 14, 2020). Being a retrospective study, patient consent was waived by the Institutional Review Board. Echocardiographic measurements were performed retrospectively by an experienced echocardiographer who was blinded to the results of CMR. CMR measurements were performed retrospectively by a pediatric cardiologist experienced in CMR and blinded to echocardiography results.

Population

Children younger than 18 years of age who underwent a CMR study between January 2015 and February 2021 were identified. CMR studies with corresponding echocardiograms were included for analysis from 31 hospital-admitted patients and 22 from nonadmitted patients, all with segmentally normal hearts. All corresponding echocardiographic studies were performed under the same anesthetic conditions as CMR studies. Children with congenital heart disease, suboptimal echocardiographic or CMR images, and CMR studies that did not have a corresponding echocardiogram within 3 months were excluded. Subjects were also excluded if a change in inotropic or heart failure medication regimen was made between the CMR and the corresponding echocardiographic study [Supplementary Figure 1].

Echocardiography

Echocardiographic studies were performed using either an IE33 or Affinity (Phillips Medical Systems, Andover, MA) ultrasound machine using multiple frequency transducers. All data were digitally stored using Syngo Dynamics Software (Siemens Healthineers, Munich, Germany). Echocardiographic measurements were retrospectively performed by an experienced echocardiographer (ET) using Syngo Dynamics workstation. Each echocardiographic study chosen was closest in time to the corresponding CMR study. Images required for systolic function and volumetric analysis were obtained from the standard 2D parasternal short axis at the mid-LV (papillary muscle) level, 2D apical four-chamber, and 2D apical two-chamber (A2C) views [Figures 1a-d and 2a-d]. Studies were excluded if endocardial borders were unable to be detected for accurate measurements, appropriate apical or parasternal views were not obtained, or A2C views were not obtained. Left ventricular end-diastolic volume (LVEDV) and LV end-systolic volume (LVESV) were calculated using the 5/6 AL and the modified BS methods, as recommended by the American Society of Echocardiography.[6] Volumes and EF were calculated using the following equations:[6,7]

$$\text{LV volume (mL) by modified BS method} = \frac{\pi}{4} * \sum (ai\ x\ bi) * \frac{L}{n}$$

$$\text{LV volume (mL) by 5/6 AL} = \frac{5}{6} * \left(LV\ short\ axis\ endocardial\ area\ (cm^2) * LV\ length\ (cm) \right)$$

$$\text{LVEF (\%)} = \frac{\left[LVEDV\ (mL) - LVESV\ (mL) \right]}{LVEDV\ (mL)} * 100\%$$

Cardiac magnetic resonance imaging

CMR imaging was performed on a Siemens 1.5T magnetic resonance imaging machine (Avanto; Siemens Medical Systems, Germany) with ECG gating. Briefly, our CMR protocol for ventricular size and systolic function, details of which have been described previously, was a standard short-axis cine balanced steady-state free precession acquisition during expiratory breath holding or respiratory suspension (if under general anesthesia).[8,9] The endocardial borders of the LV at each slice were traced at end-diastole and end-systole to calculate LVEDV and LVESV utilizing standard manual offline analysis using CVI software (Circle Cardiovascular Imaging, Alberta, Canada). The compacted myocardium

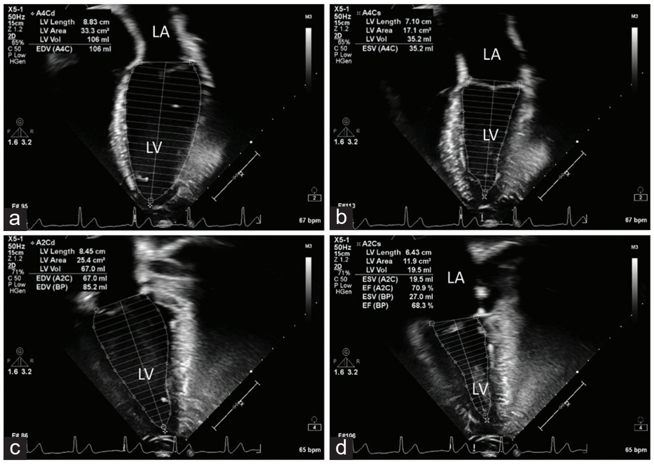


Figure 1: (a-d) Echocardiographic measurements using the modified biplane Simpson method. (a) Left ventricular end-diastolic volume in apical four-chamber view, (b) Left ventricular end-systolic volume in apical four-chamber view (c) Left ventricular end-diastolic volume in orthogonal apical two-chamber view, (d) Left ventricular end-systolic volume in apical two-chamber view and calculated ejection fraction. LV: Left ventricle, LA: Left atrium

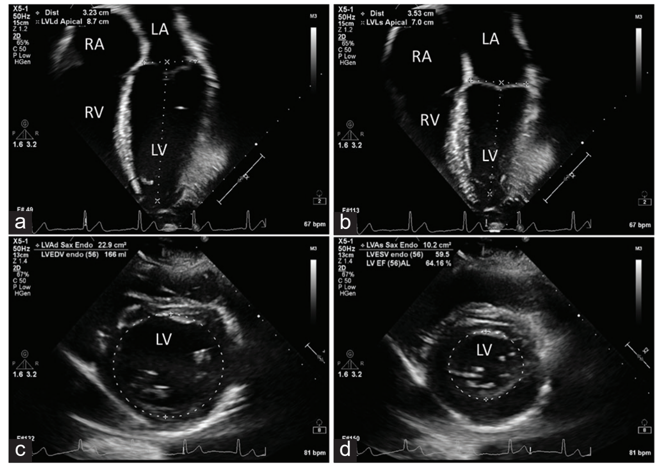


Figure 2: (a-d) Echocardiographic measurements using the five-sixth area-length method. (a) Left ventricular end-diastolic length in apical four-chamber view, (b) Left ventricular end-systolic length in apical four-chamber view, (c) Left ventricular end-diastolic endocardial area by parasternal short-axis view, (d) Left ventricular end-systolic endocardial area by parasternal short-axis view and calculated ejection fraction. RA: Right atrium, RV: Right ventricle, LV: Left ventricle, LA: Left atrium

was used to calculate volumes; papillary muscles and trabeculations were excluded. All CMR measurements were performed retrospectively by a single pediatric cardiologist experienced in CMR (PB) who was blinded to the echocardiographic measurements.

Statistical analysis

Statistical analysis was performed using Microsoft 365 Excel (Microsoft Corporation, 2020, Redmond, WA, USA) and IBM Statistical Packages of the Social Sciences Program for Windows, version 26.0 (IBM Corporation, Armonk, NY, USA). LVEDV and LVESV measured by echocardiography were compared to corresponding volumes measured by CMR. LVEF was calculated based on the 5/6 AL method and modified BS method and compared to corresponding LVEF by CMR. Subgroup analysis was conducted for patients based on LV dysfunction, pathology, and weight cutoffs. Pearson correlation coefficient and Bland–Altman methods were used to compare LVEF, LVEDV, and LVESV by two echocardiographic methods versus CMR. To account for the wide range of ages and, therefore, vastly differing ventricular volumes, bias was calculated and reported as a mean percent difference for Bland–Altman analysis for LVEDV and LVESV. LVEF results are shown as an absolute difference.

RESULTS

Subjects

Forty-six subjects with normal segmental cardiac anatomy who underwent CMR met the inclusion criteria. Of these, 20 subjects were diagnosed with myocarditis, and 26 had cardiomyopathy. A total of 53 CMR studies and corresponding echocardiograms were analyzed. Of the 53 echocardiographic studies, 40 had adequate A2C images to obtain volumes by the modified BS method. In aggregate, the median age at the time of CMR was 15.5 years (interquartile range = 12.6–17.5), and the mean age was 13 years. On average, the CMR study was completed within 7 days of the corresponding echocardiographic study in patients being evaluated for myocarditis and within 12 days in patients being evaluated for cardiomyopathy; median times for each were 1 day. Patient demographics are summarized in Table 1.

Comparison of left ventricular systolic function

LVEF was overestimated by both echocardiographic methods [Table 2 and Figure 3]. Compared to CMR, the modified BS and the 5/6 AL methods overestimated LVEF by a mean difference of 8.3% and 7.0%, respectively. Good correlations were observed using both the 5/6 AL and modified BS methods [Supplementary Figure 2 and Table 2].

Comparison of left ventricular volumes

Both echocardiographic methods significantly underestimated LVEDV and LVESV. Figures 4 and 5 show the Bland–Altman analysis using the percent difference between echocardiography and CMR for all subjects. Tables 3 and 4 show the results of the analysis separated by subgroups. The modified BS method underestimated LVEDV (bias −43.2% ±27.5%) and LVESV (bias −54.4% ±35.6%), more than the 5/6 AL method LVEDV (bias −12.0% ± 26.5%) and LVESV (bias −21.6% ± 40.1%). Better correlations were

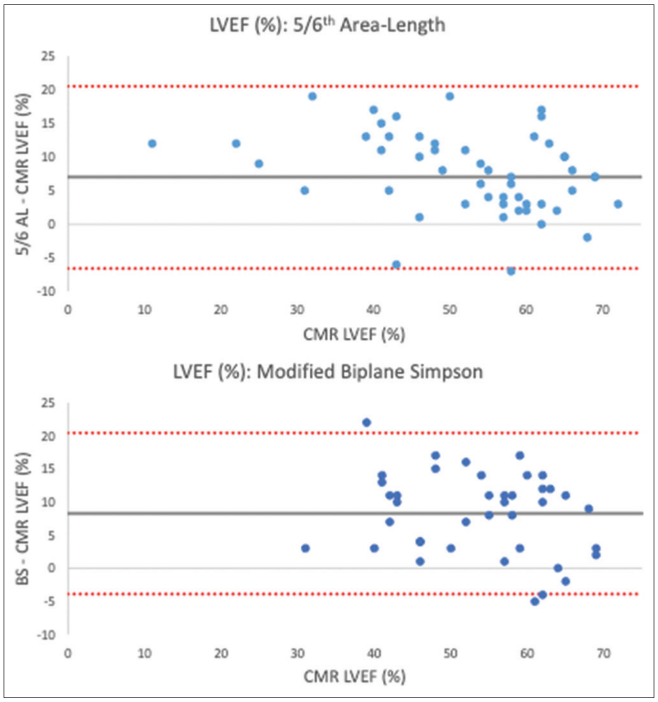


Figure 3: Bland–Altman analysis of left ventricular ejection fraction between cardiac magnetic resonance and echocardiography. Solid line represents the mean absolute bias. Dotted lines represent limits of agreement. Five-sixth area-length mean absolute bias = 7.0% ± 13.6%. Modified biplane Simpson mean absolute bias = 8.3% ± 12.2%. LVEF: Left ventricular ejection fraction, CMR: Cardiac magnetic resonance

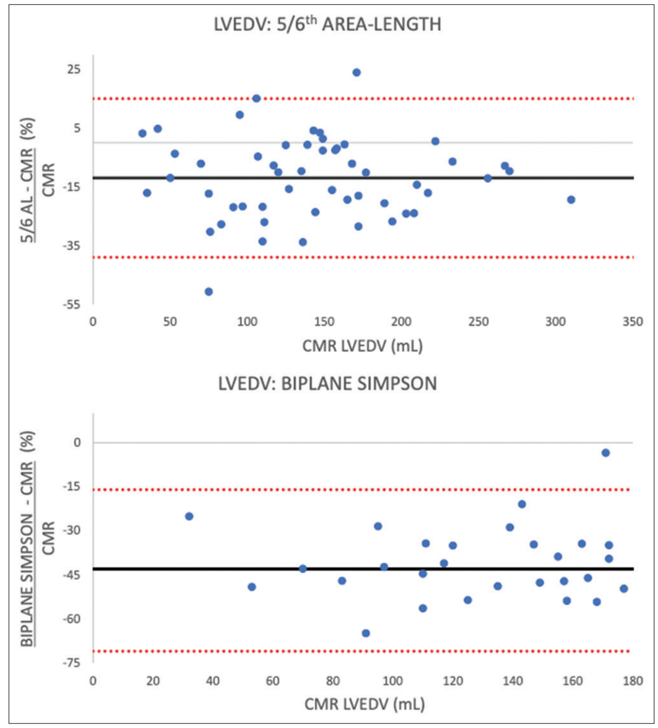


Figure 4: Bland–Altman analysis of left ventricular end-diastolic volume between cardiac magnetic resonance and echocardiography. Solid line represents the bias (average percent difference). Dotted lines represent limits of agreement. Five-sixth area-length mean bias = −12.0% ± 26.6%. Modified biplane Simpson bias = −43.2% ± 27.5%. LVEDV: Left ventricular end-diastolic volume, CMR: Cardiac magnetic resonance

observed using the 5/6 AL method for LVEDV and LVESV than the modified BS method [Supplementary Figures 3, 4 and Tables 3, 4].

Comparison of left ventricular systolic function and volumes by pathology

LVEF was overestimated by both methods in patients with myocarditis and cardiomyopathy [Table 2]. The 5/6 AL method showed better agreement with CMR than the modified BS method in the LVESV and LVEDV analysis for patients with myocarditis and cardiomyopathy. Results are shown in Tables 3 and 4.

Comparison of left ventricular systolic function and volumes by LV dysfunction

Subgroup analyses for function and volumes were conducted by separating patients with LVEF <50% and those with LVEF >50% calculated by CMR. Both echocardiographic methods overestimated function more in patients with LVEF <50% by CMR than in patients with LVEF >50% [Table 2].

Volumetric analysis by echocardiography was also affected in patients with LV dysfunction. LV volumes were better estimated by both methods in patients with LVEF <50% by CMR than in patients with LVEF >50%. The 5/6 AL method showed better agreement against CMR than the modified BS method. LVESV was more underestimated by the modified BS method than the 5/6 AL method [Tables 3 and 4].

Comparison of left ventricular systolic function and volumes by weight cutoff

Excluding patients with weight >95th percentile for age, no significant differences were noted by either the 5/6 AL method or the modified BS method in comparing LV volumes or systolic function [Tables 2-4].

DISCUSSION

Pediatric patients with heart disease require frequent cardiac evaluation to assess ventricular size and function. CMR is the noninvasive gold standard for cardiac assessment of anatomy, function, chamber size, and deformation. However, higher costs, the need for dedicated radiology and anesthesia personnel, and transportation may limit its use in children.[10,11] Due to these constraints, echocardiography has remained the mainstay for routine evaluation of cardiac chamber size and function. Both American and European echocardiography consensus groups recommend the modified BS and 5/6 AL methods for LV chamber quantification.[1,6] Both methods rely on accurately defining the endocardial border, precise orthogonal

Table 1: Demographics

	All Subjects
Total number of patients analyzed	46
Males (%)	65
Total number of CMR studies	53
Mean age of all subjects (years)	13
Median age (IQR) (years)	15.5 (12.6–17.5)
Mean number of days between CMR and echo (days)	9
Median number of days between CMR and echo (IQR) (days)	1 (0–5.5)

	Myocarditis	Cardiomyopathy
Number of patients	20	26
Number of CMR studies	23	30
Average age (years)	14.5	12.5
Median age (IQR) (years)	16.4 (13.1–17.6)	14.3 (11.9–16.8)
Age range	1–18	0–18
Median time between CMR and echocardiogram (IQR) (days)	1 (0–2)	1 (0–8)
Average LVEF by CMR (%)	50	55

IQR: Interquartile range, CMR: Cardiac magnetic resonance, LVEF: Left ventricular ejection fraction

Table 2: Left ventricular ejection fraction

	n	Bias (%)	Lower LOA (%)	Upper LOA (%)	*R*	*P*
5/6 AL versus CMR						
All subjects	53	7.0	−6.6	20.5	0.85	<0.01
Myocarditis	23	6.2	−6.0	18.4	0.82	<0.01
Cardiomyopathy	30	7.5	−7.1	22.2	0.86	<0.01
CMR LVEF <50%	19	10.3	−1.2	21.8	0.85	<0.01
CMR LVEF >50%	34	5.1	−8.3	18.5	0.51	<0.01
Weight <95th percentile	40	7.3	−7.2	21.7	0.85	<0.01
Modified BS versus CMR						
All subjects	40	8.3	−3.9	20.5	0.82	<0.01
Myocarditis	19	8.6	−3.8	21.0	0.81	<0.01
Cardiomyopathy	21	6.9	−7.4	21.2	0.83	<0.01
CMR LVEF <50%	14	9.6	−2.6	21.8	0.76	<0.01
CMR LVEF >50%	26	7.5	−4.6	19.7	0.54	<0.01
Weight <95th percentile	27	8.3	−5.1	21.6	0.83	<0.01

Number of studies analyzed (*n*). Bias (mean difference) between echocardiography and CMR. Correlation (*R*) and *P*-values. CMR: Cardiac magnetic resonance, LVEF: Left ventricular ejection fraction, LOA: Limits of agreement, BS: Biplane Simpson, 5/6 AL: Five/sixth area-length

Table 3: Left ventricular end-diastolic volumes

	n	Bias (%)	Lower LOA (%)	Upper LOA (%)	*R*	*P*
5/6 AL versus CMR						
All subjects	53	−12.0	−38.5	14.6	0.85	<0.01
Myocarditis	23	−6.8	−30.5	17.0	0.89	<0.01
Cardiomyopathy	30	−16.0	−42.2	10.3	0.89	<0.01
CMR LVEF <50%	19	−6.7	−26.5	13.2	0.96	<0.01
CMR LVEF >50%	34	−15.2	−43.5	13.2	0.80	<0.01
Weight <95th percentile	40	−11.4	−37.4	14.7	0.89	<0.01
Modified BS versus CMR						
All subjects	40	−43.2	−70.7	−15.7	0.79	<0.01
Myocarditis	19	−39.7	−74.3	−5.1	0.73	<0.01
Cardiomyopathy	21	−46.4	−64.0	−28.8	0.92	<0.01
CMR LVEF <50%	13	−42.0	−66.0	−18.0	0.84	<0.01
CMR LVEF >50%	27	−44.1	−73.7	−14.5	0.80	<0.01
Weight <95th percentile	27	−43.8	−67.5	20.1	0.86	<0.01

Number of studies analyzed (*n*). Bias (mean percentage difference) between echocardiography and CMR. Correlation (*R*) and *P*-values. CMR: Cardiac magnetic resonance, LVEF: Left ventricular ejection fraction, LOA: Limits of agreement, BS: Biplane Simpson, 5/6 AL: Five/sixth area-length

image alignment, and geometric assumptions. Given the assumption that accurate echocardiographic assessment of ventricular dimensions is prone to error, we evaluated these two echocardiographic methods of estimating LV volume and EF compared to CMR in children.

Studies in adults have compared various methods of echocardiographic LV size and functional analysis to CMR, reporting the underestimation of ventricular volumes and the overestimation of LVEF by the modified BS method.[3,6,12-17] One study in adult patients with heart failure demonstrated significant underestimations of LVEDV (bias of −133 mL) and LVESV (bias of −99 mL) measurements when compared to CMR despite relatively good correlation.[12] They reported a comparison of LVEDV and LVESV by BS method to CMR, which revealed very wide limits of agreement (52–216 ml and 11–188 ml, respectively), similar to our results.[12] Extrapolating these data to the pediatric population has limitations, given a higher prevalence of ventricular dysfunction in adults.[17] We demonstrate here the degree to which echocardiography, irrespective of the method used, systematically underestimates LV volumes and overestimates LV systolic function compared to CMR in children. To our knowledge, ours is the first pediatric study to compare the 5/6 AL and the modified BS methods to CMR and further quantify the degree to which both methods differ from CMR measurements. Our data suggest that volumes measured using the 5/6 AL method showed less bias [Figures 4 and 5] against CMR than the modified BS method. However, both methods may equally be prone to error, and neither can be used interchangeably with CMR.

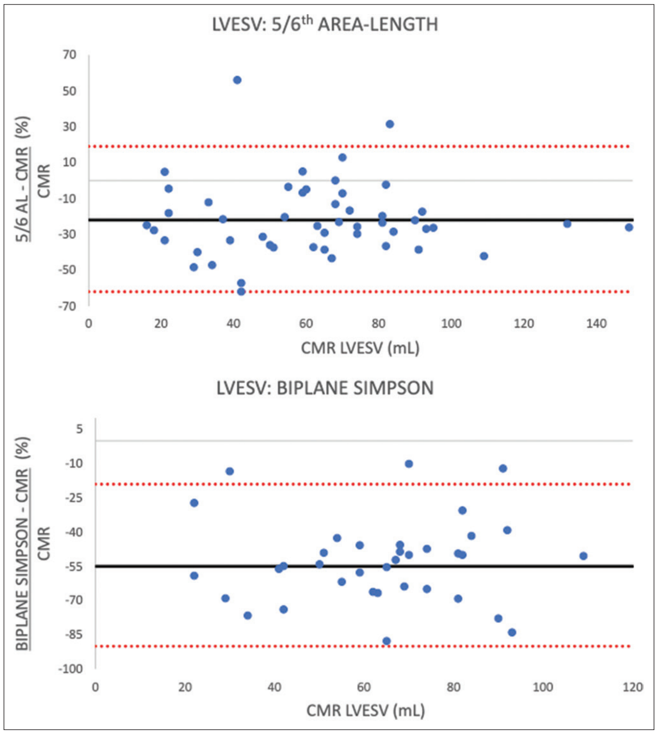


Figure 5: Bland–Altman analysis of left ventricular end-systolic volume between cardiac magnetic resonance and echocardiography. Solid line represents the bias (average percent difference). Dotted lines represent limits of agreement. Five-sixth area-length bias = −21.6% ± 40.0%. Modified biplane Simpson bias = −54.4% ± 35.6%. LVESV: Left ventricular end-systolic volume, CMR: Cardiac magnetic resonance

The reproducibility and validity of echocardiographic and CMR measures of LV size and LVEF have been extensively reported in pediatric and adult patients and, thus, were not reassessed in this study.[3,5,8,15] In keeping with findings from previous studies, however, our data also suggest that both the 5/6 AL and the modified BS method have limitations when assessing LV size and EF compared with CMR in children. Our data add to prior studies by providing the degree to which ventricular size and function may be misrepresented in children with pathology and ventricular dysfunction.[8,17] One explanation of these findings is that obtaining accurate measurements may be hindered by the inability to obtain good endocardial definition resulting from poor parasternal or apical windows. In our study, 25% of the echocardiographic studies did not have sufficient imaging to obtain measurements for the modified BS method. Furthermore, calculations for echocardiographic methods also assume that the LV shape is perfectly conical, which is not typically the case. Congenital and acquired heart disease, cardiomyopathy, abnormal hemodynamic states, infections, hydration status, drugs, and genetics may all affect the structure and geometry of the LV, leading to inaccurate 2D measurements.[18,19] Errors in LVEF or volumetric estimation may be amplified with small variations in individual 2D measurements.

Obesity is thought to result in poor acoustic windows, potentially affecting the accuracy of 2D echo measurements. Interestingly, however, we found that excluding patients with weight >95th percentile did not significantly alter our results. There was no significant

Table 4: Left ventricular end-systolic volumes

	n	Bias (%)	Lower LOA (%)	Upper LOA (%)	*R*	*P*
5/6 AL versus CMR						
All subjects	53	−21.6	−61.6	18.5	0.89	<0.01
Myocarditis	23	−16.2	−50.3	18.0	0.89	<0.01
Cardiomyopathy	30	−25.7	−68.6	17.1	0.98	<0.01
CMR LVEF <50%	19	−16.0	−57.0	25.0	0.95	<0.01
CMR LVEF >50%	34	−24.7	−64.0	14.6	0.70	<0.01
Weight <95th percentile	40	−20.3	−60.4	19.8	0.91	<0.01
Modified BS versus CMR						
All subjects	40	−54.4	−90.0	−18.8	0.62	<0.01
Myocarditis	19	−45.6	−108.8	18.2	0.49	0.03
Cardiomyopathy	21	−55.8	−83.8	−27.8	0.78	<0.01
CMR LVEF <50%	13	−55.0	−87.9	−22.1	0.60	0.02
CMR LVEF >50%	27	−54.1	−91.7	−16.5	0.54	<0.01
Weight <95th percentile	27	−57.4	−85.3	−29.7	0.72	<0.01

Number of studies analyzed (*n*). Bias (mean percentage difference) between echocardiography and CMR. Correlation (*R*) and *P*-values. CMR: Cardiac magnetic resonance, LVEF: Left ventricular ejection fraction, LOA: Limits of agreement, BS: Biplane Simpson, 5/6 AL: Five/sixth area-length change in the bias or correlation for volume or functional assessment from a clinical standpoint. We acknowledge that our sample size for patients above the 95th percentile in weight was quite small, and further studies with a larger sample size may be necessary to confirm these findings.

Recent advances in three-dimensional technology and the use of contrast-enhancing agents have opened new avenues in improving image quality and accuracy of measurements by echocardiography. One pediatric study demonstrates that LV size measured by three-dimensional echocardiography strongly correlates and agrees with CMR for LVEDV ($r = 0.8$) and LVESV ($r = 0.9$).[20] This relationship was similar to our results. However, routine use of three-dimensional echocardiography may still be limited by additional time, specific probes appropriate for patient size, and postprocessing analysis software to track the borders adequately. For these reasons, three-dimensional echocardiographic studies, similar to CMR, may not be readily accessible in all institutions and other resource-limited settings. Contrast-enhanced studies, while more widely accessible, require the placement of an intravenous catheter and carry their inherent risks. Severe allergic reaction and anaphylaxis provide an additional barrier in patients with known perflutren, sulfur hexafluoride, or blood product allergies.[21,22]

Based on our findings and those of prior reported studies,[23] it must be noted that in cases requiring accurate volumetric or functional analysis, the limitations of echocardiography should be taken into account. While our institution prefers the use of the 5/6 AL and modified BS methods to estimate ventricular volumes and function, we routinely consider the use of CMR for more accurate assessments.[24]

Limitations and future studies

The relatively small sample size limits this study, although statistically significant results were obtained. A prospective trial or larger sample size for each cohort is recommended to draw more robust conclusions. Additional cohorts of patients with congenital heart diseases that distort the LV size, muscle thickness, and shape may be considered for future studies. The concept of indexed versus nonindexed volumes may also be considered for future studies. Volumes indexed to body surface area require accurate measurements of patient height and weight. Inaccuracy in measuring either of these introduces a new potential source of measurement error. Comparison of CMR with three-dimensional echocardiography also provides additional avenues of research in the pediatric population.

CONCLUSIONS

While echocardiography is suitable for estimating left ventricular systolic function, it routinely overestimates LVEF and underestimates LV volumes as compared to CMR. Our findings suggest that CMR improves the accuracy of LV volumetric measurements, perhaps due to direct chamber measurements and the use of three-dimensional volumetric analysis. Therefore, we recommend increased scrutiny for patients in whom echocardiographic results do not support clinical findings or more accurate measurements are required.

Acknowledgment

We would like to thank James S. Babb, PhD (Associate Professor in the Department of Radiologyat NYU Grossman School of Medicine) for help with statistical analysis.

Financial support and sponsorship

Nil.

Conflicts of interest

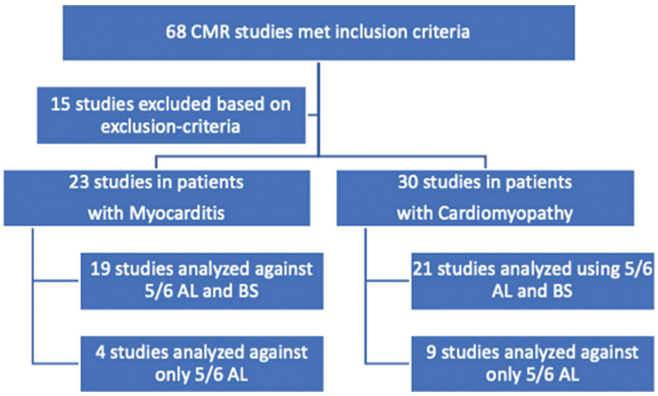
There are no conflicts of interest.

REFERENCES

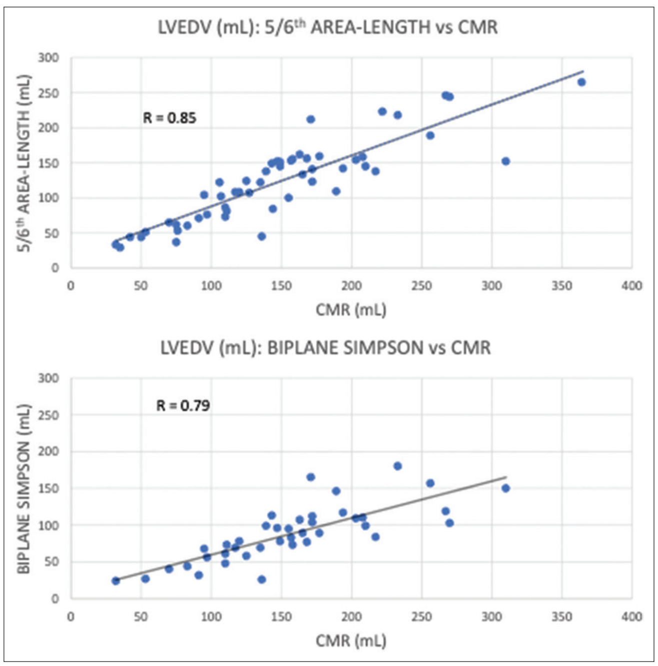
1. Cheitlin MD, Armstrong WF, Aurigemma GP, Beller GA, Bierman FZ, Davis JL, *et al*. ACC/AHA/ASE 2003 guideline update for the clinical application of echocardiography: Summary article. A report of the American College of Cardiology/American Heart Association task force on practice guidelines (ACC/AHA/ASE committee to update the 1997 guidelines for the clinical application of echocardiography). J Am Soc Echocardiogr 2003;16:1091-110.
2. Brown JM. Use of echocardiography for hemodynamic monitoring. Crit Care Med 2002;30:1361-4.
3. Buddhe S, Lewin M, Olson A, Ferguson M, Soriano BD. Comparison of left ventricular function assessment between echocardiography and MRI in Duchenne muscular dystrophy. Pediatr Radiol 2016;46:1399-408.
4. Assomull RG, Pennell DJ, Prasad SK. Cardiovascular magnetic resonance in the evaluation of heart failure. Heart 2007;93:985-92.
5. Margossian R, Chen S, Sleeper LA, Tani LY, Shirali G, Golding F, *et al*. The reproducibility and absolute values of echocardiographic measurements of left ventricular size and function in children are algorithm dependent. J Am Soc Echocardiogr 2015;28:549-58.e1.
6. Lang RM, Bierig M, Devereux RB, Flachskampf FA, Foster E, Pellikka PA, *et al*. Recommendations for chamber quantification: A report from the American Society of echocardiography's guidelines and standards committee and the chamber quantification writing group, developed in conjunction with the European association of echocardiography, a branch of the European society of cardiology. J Am Soc Echocardiogr 2005;18:1440-63.
7. Lopez L, Colan SD, Frommelt PC, Ensing GJ, Kendall K, Younoszai AK, *et al*. Recommendations for quantification methods during the performance of a pediatric

echocardiogram: A report from the pediatric measurements writing group of the American society of echocardiography pediatric and congenital heart disease council. J Am Soc Echocardiogr 2010;23:465-95.

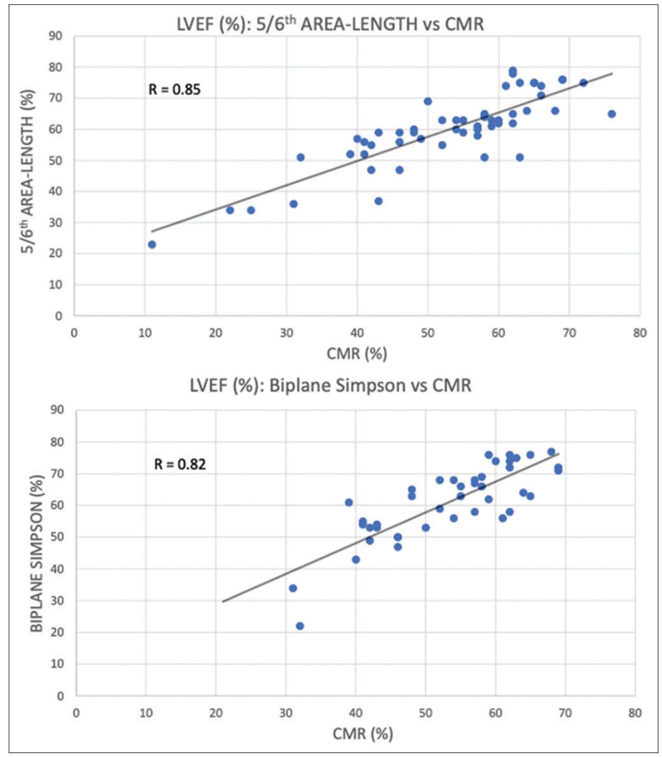
8. Chu BJ, Lee T, Gilbreth JG, Nielsen JC, Ludomirsky A, Tretter JT, *et al.* Left ventricular mass quantification by two-dimensional echocardiography in a pediatric population: Correlation with cardiac magnetic resonance imaging. Pediatr Cardiol 2019;40:412-20.
9. Nielsen JC, Lytrivi ID, Ko HH, Yau J, Bhatla P, Parness IA, *et al.* The accuracy of echocardiographic assessment of left ventricular size in children by the 5/6 areaxlength (bullet) method. Echocardiography 2010;27:691-5.
10. Picano E. Economic and biological costs of cardiac imaging. Cardiovasc Ultrasound 2005;3:13.
11. Pennell DJ, Sechtem UP, Higgins CB, Manning WJ, Pohost GM, Rademakers FE, *et al.* Clinical indications for cardiovascular magnetic resonance (CMR): Consensus panel report. Eur Heart J 2004;25:1940-65.
12. Bellenger NG, Burgess MI, Ray SG, Lahiri A, Coats AJ, Cleland JG, *et al.* Comparison of left ventricular ejection fraction and volumes in heart failure by echocardiography, radionuclide ventriculography and cardiovascular magnetic resonance; are they interchangeable? Eur Heart J 2000;21:1387-96.
13. Gutiérrez-Chico JL, Zamorano JL, Pérez de Isla L, Orejas M, Almería C, Rodrigo JL, *et al.* Comparison of left ventricular volumes and ejection fractions measured by three-dimensional echocardiography versus by two-dimensional echocardiography and cardiac magnetic resonance in patients with various cardiomyopathies. Am J Cardiol 2005;95:809-13.
14. Hoffmann R, von Bardeleben S, Ten Cate F, Borges AC, Kasprzak J, Firschke C, *et al.* Assessment of systolic left ventricular function: A multi-centre comparison of cineventriculography, cardiac magnetic resonance imaging, unenhanced and contrast-enhanced echocardiography. Eur Heart J 2005;26:607-16.
15. Malm S, Frigstad S, Sagberg E, Larsson H, Skjaerpe T. Accurate and reproducible measurement of left ventricular volume and ejection fraction by contrast echocardiography: A comparison with magnetic resonance imaging. J Am Coll Cardiol 2004;44:1030-5.
16. Devlin AM, Moore NR, Ostman-Smith I. A comparison of MRI and echocardiography in hypertrophic cardiomyopathy. Br J Radiol 1999;72:258-64.
17. Margossian R, Schwartz ML, Prakash A, Wruck L, Colan SD, Atz AM, *et al.* Comparison of echocardiographic and cardiac magnetic resonance imaging measurements of functional single ventricular volumes, mass, and ejection fraction (from the pediatric heart network fontan cross-sectional study). Am J Cardiol 2009;104:419-28.
18. Lipshultz SE, Colan SD, Gelber RD, Perez-Atayde AR, Sallan SE, Sanders SP. Late cardiac effects of doxorubicin therapy for acute lymphoblastic leukemia in childhood. N Engl J Med 1991;324:808-15.
19. Lipshultz SE, Grenier MA. Left ventricular dysfunction in infants and children infected with the human immunodeficiency virus. Prog Pediatr Cardiol 1997;324:808-15.
20. Kamińska H, Małek ŁA, Barczuk-Falęcka M, Werner B. Usefulness of three-dimensional echocardiography for assessment of left and right ventricular volumes in children, verified by cardiac magnetic resonance. Can we overcome the discrepancy? Arch Med Sci 2021;17:71-83.
21. Lindner JR, Belcik T, Main ML, Montanaro A, Mulvagh SL, Olson J, *et al.* Expert consensus statement from the American society of echocardiography on hypersensitivity reactions to ultrasound enhancing agents in patients with allergy to polyethylene glycol. J Am Soc Echocardiogr 2021;34:707-8.
22. Kutty S, Biko DM, Goldberg AB, Quartermain MD, Feinstein SB. Contrast-enhanced ultrasound in pediatric echocardiography. Pediatr Radiol 2021;51:2408-17.
23. Tretter JT, Chakravarti S, Bhatla P. Use of echocardiographic subxiphoid five-sixth area length (bullet) method in evaluation of adequacy of borderline left ventricle in hypoplastic left heart complex. Ann Pediatr Cardiol 2015;8:243-5.
24. Shimada YJ, Shiota T. A meta-analysis and investigation for the source of bias of left ventricular volumes and function by three-dimensional echocardiography in comparison with magnetic resonance imaging. Am J Cardiol 2011;107:126-38.



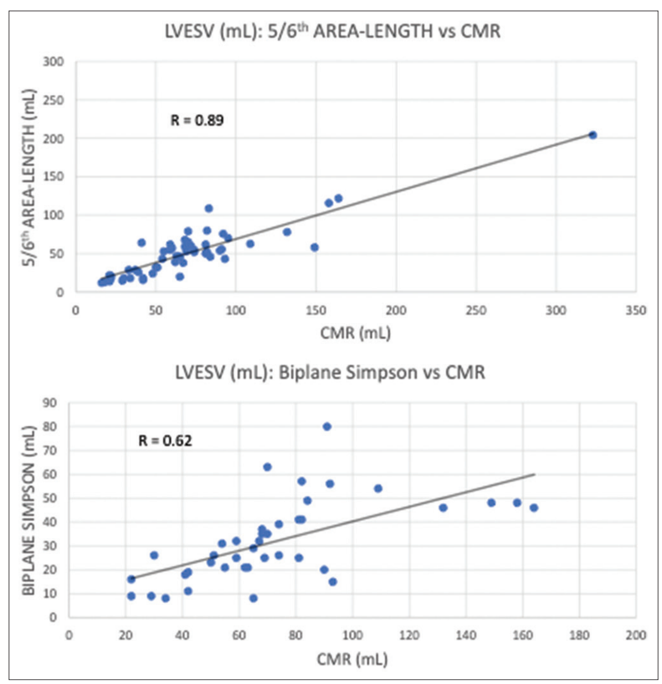
Supplementary Figure 1: Patient cohort. 5/6 AL: Five-sixth area-length, BS: Biplane Simpson, CMR: Cardiac magnetic resonance



Supplementary Figure 3: Correlation of left ventricular end-diastolic volume measured by echocardiography versus cardiac magnetic resonance (CMR). Five-sixth area-length versus CMR (r = 0.85, *P* < 0.01). Modified biplane Simpson versus CMR (*r* = 0.79, *P* < 0.01). LVEDV: Left ventricular end-diastolic volume, CMR: Cardiac magnetic resonance



Supplementary Figure 2: Correlation of left ventricular ejection fraction measured by echocardiography versus cardiac magnetic resonance (CMR). Five-sixth area-length versus CMR (r = 0.85, *P* < 0.01). Modified biplane Simpson versus CMR (r = 0.82, *P* < 0.01). LVEF: Left ventricular ejection fraction, CMR: Cardiac magnetic resonance



Supplementary Figure 4: Correlation of left ventricular end-systolic volume measured by echocardiography versus cardiac magnetic resonance (CMR). Five-sixth area-length versus CMR (r = 0.89, *P* < 0.01). Modified biplane Simpson versus CMR (r = 0.62, *P* < 0.01). LVESV: Left ventricular end-systolic volume, CMR: Cardiac magnetic resonance