Progress in Pediatric Cardiology 66 (2022) 101546

Contents lists available at ScienceDirect

Progress in Pediatric Cardiology

journal homepage: www.elsevier.com/locate/ppedcard

Assessment of ventricular septal defects by real-time three-dimensional echocardiography and comparison with surgical measurements

Ulas Karadas [a], Gül S. Saylam [a], Nuh Yilmaz [a], Mustafa Kir [a], Özgür Kizilca [a], Tülay Demircan [a], Baran Ugurlu [b], Nurettin Ünal [a], And Demir [c,*]

[a] Department of Pediatric Cardiology, Faculty of Medicine, Dokuz Eylül University, Izmir, Turkey
[b] Department of Cardiac Surgery, Faculty of Medicine, Dokuz Eylül University, Izmir, Turkey
[c] New Children's Hospital, Pediatric Research Center, University of Helsinki and Helsinki University Hospital, Helsinki, Finland

ARTICLE INFO

Keywords:
Ventricular septal defect
Three-dimensional echocardiography
Comparison with surgical measurements

ABSTRACT

Background: Three-dimensional (3D) echocardiography has facilitated evaluation of a ventricular septal defect (VSD) with its true dimensions and exact localization and improved identification of various anatomical characteristics in different types of VSDs.
Objectives: We aimed at investigating the feasibility of 3D echocardiography in assessing VSDs in comparison to two-dimensional (2D) echocardiography.
Methods: We employed both 2D and 3D echocardiography for measuring the longest diameter of VSD. The morphology, number, and size of the defect as well as its relation and distance to the tricuspid and aortic valves were analyzed by 3D echocardiography displaying the VSD from the right ventricular aspect. The size was defined in terms of maximum area, long and short axis diameters at end-diastole. The longest diameters of VSDs were compared with 2D and 3D echocardiography data in all patients as well as with the intra-operative findings in 17 patients.
Results: The mean diameters of end-diastolic VSDs measured by 3D echocardiography from the right ventricular aspect were significantly larger than those obtained by 2D echocardiography (15.6 ± 8.2 vs 10 ± 4.2 mm, $P = .02$), however, there was a good correlation between them ($r = 0.73$, $P < .001$). 3D echocardiography proved to be superior to 2D echocardiography for visualizing the shape of VSD and for measuring tissue rims from the aortic and tricuspid valves. The advantage was prominent in particular for viewing defects hidden by a ventricular septal aneurysm or a tricuspid septal leaflet, which can be erased digitally to reveal the VSD underneath. The dimensions of VSDs obtained by 3D echocardiography ($r = 0.85$, $P < .001$) correlated significantly better with actual dimensions revealed during surgery as compared to those obtained by 2D echocardiography ($r = 0.53$, $P = .03$).
Conclusions: The study demonstrated that 3D echocardiography provides more reliable information from both qualitative and quantitative aspects regarding the morphology, size, and tissue rims of VSD compared to 2D views.

1. Introduction

A ventricular septal defect (VSD) should be ideally evaluated for its exact localization, morphology, diameter and the relation with the tissues of heart such as tricuspid valve and aortic valve using echocardiography [1–5]. Although two-dimensional (2D) echocardiography with color Doppler has been the standard method for diagnosing ventricular septal defects (VSDs) as well as for reaching a clinical decision in regard to its management, it is not informative enough from the perspective of anatomic details, mainly due to the limited number of intersecting planes of the heart [6–9]. It is possible to show VSDs directly by three-dimensional (3D) echocardiography; therefore, its clinical utility has become the common practice for evaluating a VSD with true and precise dimensions [10,11]. 3D images have improved identification of various

* Corresponding author at: New Children's Hospital, Pediatric Research Center, University of Helsinki and Helsinki University Hospital, Biomedicum II, 6th floor, Tukholmankatu 8 A, FIN-00290 Helsinki, Finland.
E-mail address: drand@demir.net (A. Demir).

https://doi.org/10.1016/j.ppedcard.2022.101546
Received 25 October 2021; Received in revised form 14 June 2022; Accepted 14 June 2022
Available online 17 June 2022
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anatomical characteristics in different types of VSDs [12–15].

This study aimed at investigating the usefulness and feasibility of 3D echocardiography in assessing VSDs. Data regarding the position, size, and shape of VSDs obtained during surgical procedure, 2D echocardiography and 3D echocardiography were compared. The study also assesses clinical utility of 3D echocardiography in practice.

2. Materials and methods

This study was performed on 45 patients whose ages ranged between 1 and 198 months (mean: 34.4 ± 43.4 months) from September 2010 through June 2015 at Dokuz Eylül University, Izmir, Turkey as a prospective study. The research procedure was approved by the local ethical committee. Parents were informed about the study and each parent provided a written consent to allow their child to participate in the study.

2.1. Echocardiographic evaluations

2D echocardiographic evaluations were performed using Philips iE33 Ultrasound System and S 5-1, S 12-4 probes. Philips iE 33 Ultrasound System and X 7-2 matrix transducer were used in the evaluation of 3D echocardiography. '3D echocardiography Evaluation Protocol' developed by Nanda et al. was used to collect the data [16,17].

2.2. The analysis of 3D data

The images which were collected by real time 3D were stored in Digital Imaging and Communications in Medicine format. These images were provided by processing a 60° × 30° cake-like 3D image in real time, as the image was rotated for revealing the spatial orientation and morphologic structure of the VSD and adjacent structures more clearly along with depth perception. The full volume 3D images were then cut in order to view various dimensions at different angular aspects. These 3D echocardiography images were analyzed in an integrated software system, by cropping the images in three different color-coded (green, blue, red) intersecting planes perpendicular to each other (Fig. 1a). In addition to these intersecting planes, an additional oblique plane (purple) capable of cropping the image at any desired angulation was used (Fig. 1a). This particular plane was useful for assessment. The right ventricle free wall and right ventricle cavity were cut and the tissues in front of the septal wall were eliminated (Fig. 1b). The obtained image was rotated so that it could be viewed as "en-face" from the right ventricle (Fig. 1c). The echocardiographic images were sectioned to obtain the desired intersecting planes, after which the septal tissue was fulfilled (Fig. 1d) and separate views of the right ventricle in systolic and diastolic phases were obtained (surgery outlook) (Figs. 1e, 2a, b). Images that did not detect the ventricular septal defect in 2D mode were saved also separately. VSDs were evaluated in terms of shape, number, and localization, and measurements were obtained by using en-face right ventricle view. The relative changes in VSD area throughout the cardiac cycle were presented as end-systolic and end-diastolic VSD regions (Fig. 2c, d). The relationship between the neighbor tissues (e.g., tricuspid and aortic valves) were evaluated (Fig. 2e, f). The acquired 3D echocardiographic data sets were stored on Compact Disc in Digital Imaging and Communications in Medicine format and transferred to a separate workstation for offline data analysis. The measurement of distance, area, volumes at various angular aspects was done by using appropriate software analysis systems (QLAB Advanced Quantification software, version 3.0, Philips Ultrasound, U.S.A.).

VSDs diagnosed by 2D echocardiography were examined also using 3D echocardiography. The localization, number of VSDs, and the longest VSD diameter were detected using 2D echocardiography. The morphology, number, and size of the defect (maximum area, long and

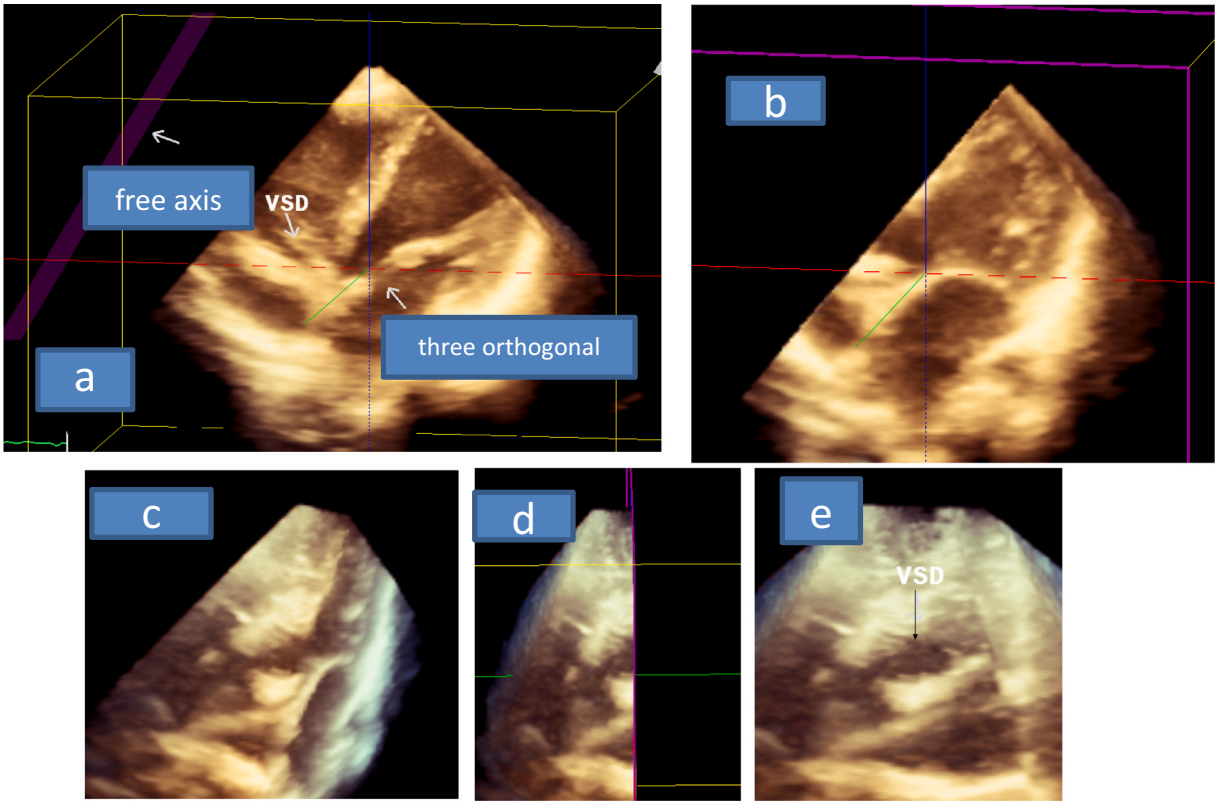


Fig. 1. The en face image of a VSD from right ventricular sight. The image of three orthogonal fixed axis and free axis (a). The selected cutting planes of right ventricular wall and right ventricular cavity (b). The rotation stages (c–d). The en face image of a VSD (e). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

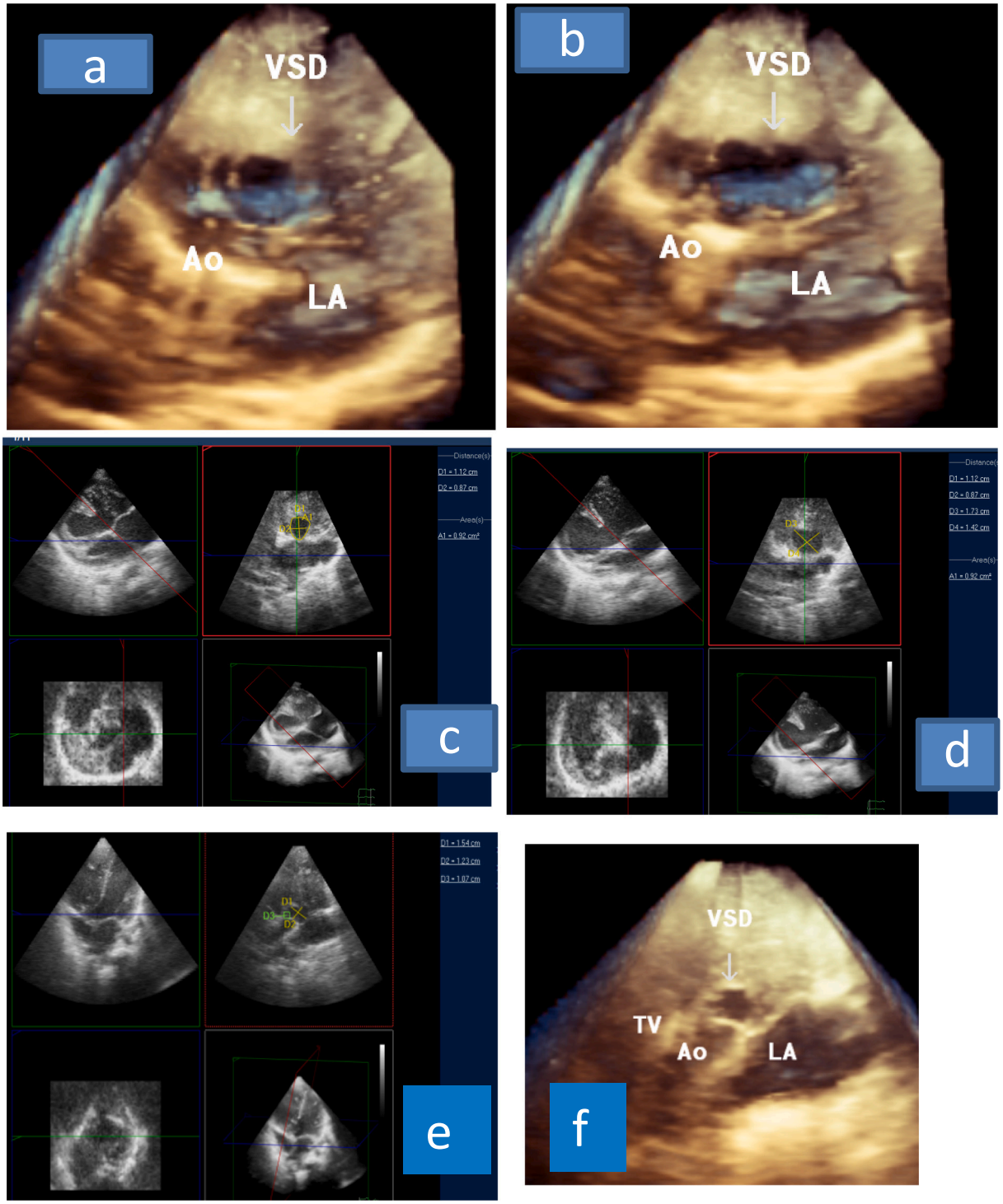


Fig. 2. The systolic (a) and diastolic (b) phase of a VSD image from right ventricular sight. The end-systolic (c) and end-diastolic (d) long and short axis and area measurements with Q LAB analysis software. The relationships between the neighbor tissues (tricuspid and aortic valve) (e–f). Ao: aorta, LA: left atrium, TV: tricuspid valve.

short axis diameters at end-diastole), its relation and distance to the tricuspid and aortic valves (at end-diastole) were analyzed using 3D echocardiography, displaying the VSD in facing views from the angular aspect of the right ventricle. The 2D and 3D echocardiography data obtained from all patients were compared in terms of localization and the number of VSDs as well as the longest diameter of the VSD. VSD measurements in 17 of the 28 patients were performed during surgery. The evaluation was executed on the right ventricle of the heart which was stopped by applying cold cardioplegia under cardiopulmonary bypass, without echocardiographic measurements. The surgeon describing and measuring the VSD was blinded to the 3D data. The intraoperative results were compared with the 2D and 3D echocardiography findings in 17 patients.

The analysis was performed using SPSS (Statistical Package for Social Sciences) 17.0. The mean values and standard deviations of digital values were calculated, and all values were expressed as means ± 2SD.

Mann-Whitney *U* test was used for the groups which were not homogenous. The correlations between the variables were analyzed using Spearman's correlation test. Correlation ratios (r) from 0.75 to 1.00 were regarded as very good correlations and the findings were accepted significant if p was under 0.05.

3. Results

Forty-five patients (24 girls, 21 boys) were enrolled in the study. Twenty-two of them (49 %) were above 1 year of age. The mean weight and height of the patients were 11.4 ± 9.3 kg, and 80.6 ± 26 cm, respectively. Real-time 3D echocardiography was performed on 44 (98 %) of the 45 patients. One 12-year-old girl was excluded from the study because of a poor acoustic window secondary to obesity and inadequate 3D echocardiographic images.

Although 51 % of the patients were at or below 1 year of age, all 3D images were proper for evaluation despite persistent respiratory and cardiac artifacts. A total of 45 VSDs were detected in 45 patients using 2D and 3D echocardiography, among which 20 (44 %) had perimembranous VSD, 9 (20 %) had a perimembranous-outlet VSD, 14 (31 %) had a perimembranous-inlet VSD and 2 (5 %) had a muscular VSD. No significant difference in localization of the VSD (perimembranous, muscular, doubly committed) was found between the results obtained by 2D and 3D echocardiography.

3.1. The data of 3D echocardiography images

The time of data acquisition was 4.1 ± 1.5 (2.1–10, in 29 patients) minutes. While the mean acquisition time was 4.6 ± 1.5 min in infants, it was 3.7 ± 0.6 min in children over 1 year of age. The mean heart rate during the 3D echocardiography imaging was 122 ± 22 (78–150) per minute. The 3D image acquisition time was not influenced by heart rate ($P = .63$) and age ($P = .50$). While the mean 3D echocardiography evaluation time was 20 ± 10.5 min (7–60 min, in 36 patients), it would be 16.5 ± 3.9 (7–24) min if the first five patients were excluded (reserved for the purposes of learning) from the study for the evaluation time got shorter ($r = -0.78$, $P < .001$) as the study progressed (Fig. 3).

3.2. 3D echocardiography analysis

The mean end-diastole maximum diameter of VSD measured with 2D and 3D echocardiography were 10 ± 4.2 mm (median: 9, interval: 4–22) and 15.6 ± 8.2 mm (median: 14, interval: 6.4–48) respectively ($P = .02$); which showed a positive correlation ($r = 0.73$, $P < .001$) (Fig. 4).

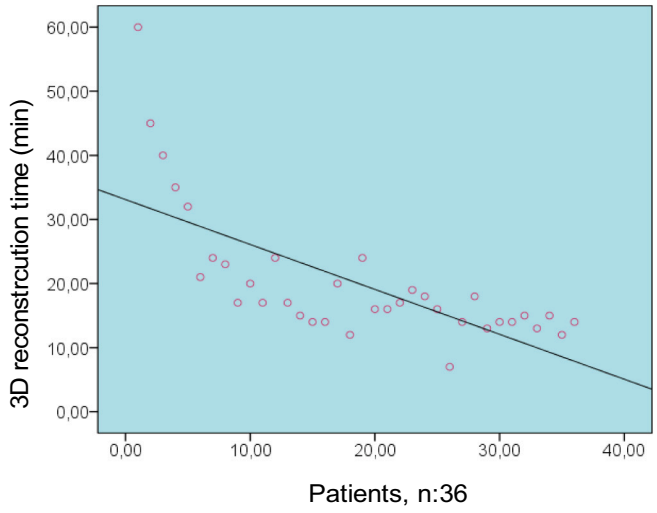


Fig. 3. Learning curve of RT 3D-TTE reconstruction time of 36 consecutive patients.

The mean end-systolic maximum diameter measured with 3D echocardiography was 13.4 ± 7.3 mm (4.8–41.4), end-systolic and end-diastolic area measurements were 1.8–6.5 (mean: 1.07 ± 1.39, median: 0.67) cm^2 and 0.29–9.78 (mean: 1.7 ± 2.03, median: 1.04) cm^2 respectively. The mean end-systolic and end-diastolic area measurements were significantly different ($P = .01$).

The measurements of end-diastolic maximum diameter measurements with 2D echocardiography showed a positive correlation with end-diastolic maximum diameter measurements, end-systolic maximum area measurements, end-diastolic maximum area measurements with 3D echocardiography (Table 1).

Tricuspid and aortic valve relationships of 34 patients with perimembranous VSD were investigated with 3D echocardiography. The mean distance of tricuspid valve to VSD was 7.3 ± 6.4 mm, and the mean distance of aortic valve to VSD was 5.1 ± 7.9 mm (Fig. 2e–f). VSD was completely or partially covered with tricuspid valve in 10 patients and ventricular septal aneurysm formation was seen in 3 patients. In these patients, the right ventricular free wall as well as the tricuspid valve and ventricular septal aneurysm tissue can be clearly identified by the morphological structure, shape and the elongation in ventricular septum shown in digital image (Fig. 5).

The VSD shapes were examined on en-face view of right ventricular of interventricular septum. The VSDs had irregular shape in %98 of patients (Fig. 6a–d). Only in one patient the VSD was in round shape (Fig. 6e, f). Perimembranous VSDs had a special morphology (rectangular shape, sunken in the middle) in 3D echocardiography (Fig. 6a–d).

The 3D echocardiographic VSD measurements of 17 patients showed similar results to the findings of the surgery and the VSD shapes were irregular in both. The VSD shapes were not as regular as it had been thought prior to the study. The VSD measurements during the surgery correlated more with the 3D echocardiography measurements ($r = 0.85$, $P < .001$) than 2D-echocardiography measurements ($r = 0.53$, $P = .03$) (Table 1) (Fig. 4).

4. Discussion

This study provides the optimal images of VSDs obtained by using 3D echocardiography in which their morphologies can be exactly seen from right ventricle. The study showed that surgical findings about VSD diameters had a better correlation with 3D echocardiography measurements compared to 2D measurements.

The 3D echocardiography made a slow progress at the beginning due to the difficult and time-consuming image acquisition quality, poor image quality resulting from the artefacts, and the inconvenient steps of making the resulting images into 3D data sets [10]. The lack of real-time evaluation possibility and the length of the evaluation (analysis) duration limit the use of this technique. The small heart structure and high heart rate in children are the other factors that make it difficult to obtain images by using this technique [11,18,19]. Great technological advances have been achieved regarding the 3D echocardiography in the past two decades [10]. In real-time 3D echocardiography, the use of a matrix array transducer and the reduction of 3D probes resulted in better imaging; and the development of online measuring in time increased the usability of this technique [2,20–22].

In our study, it was observed that the duration of acquisition of 3D echocardiography images of patients was short and that this was not affected by heart rate or age of the patient. Optimal 3D images could be obtained in 97 % of the patients using 3D echocardiography and none of the 3D images were classified as inadequate due to respiratory and cardiac artifacts despite 44 % of the patients being under 1 year of age. It was shown also in another study that the average 3D acquisition time was as short as 6.0 ± 2.0 min, and that this was not affected by age [18]. In the same study, adequate 3D images were obtained in 30 (88 %) of the 34 patients with 3D echocardiography [18].

In our study, it was observed that there was a certain learning period

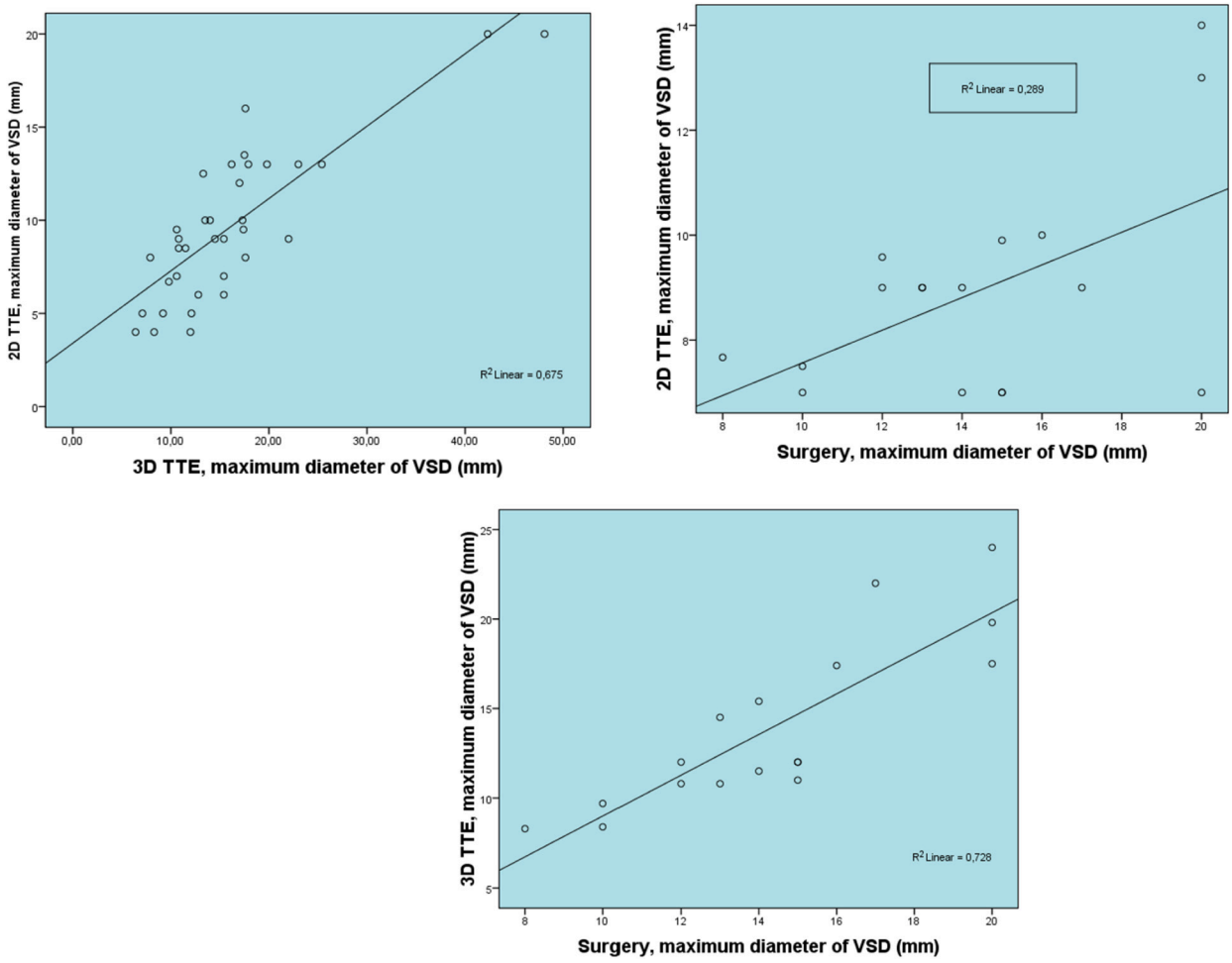


Fig. 4. Correlations between maximal diameters of VSDs measured by 2-dimensional (2D) transthoracic echocardiography (TTE) and real time 3D-TTE; also between the values obtained by 2D-TTE and surgery as well as between those obtained by 3D-TTE and surgery.

Table 1
The correlations among ventricular septal defect measurements obtained by 2D and 3D echocardiography and those obtained during surgery.

Compared measurements	r	*P* value
Maximum end-diastolic diameter measurements obtained by 2D and 3D echocardiography	0.79	<.001
Maximum end-diastolic diameter measurement obtained by 2D-echocardiography and end-diastolic area measurement obtained by 3D-echocardiography	0.80	<.001
Maximum end-diastolic diameter measurement obtained by 2D-echocardiography and end-systolic area measurement obtained by 3D-echocardiography	0.76	<.001
Maximum end-systolic and end-diastolic diameters obtained by 3D-echocardiography	0.93	<.001
End-systolic and end-diastolic diameters obtained by 3D-echocardiography	0.88	<.001
Maximum end-diastolic diameter measurements obtained by 3D-echocardiography and those measured at surgery	0.85	<.001
End-diastolic diameter measurements obtained by 3D-echocardiography and those measured at surgery	0.53	.03

for the evaluation of 3D images and the evaluation time got significantly shortened as the study progressed (r = −0.78), supporting the similar findings in earlier studies [5,23]. Van Den Bosch et al. had reported reduction in analysis period from 45 min in the first patient to 8 min in the last [18].

These findings indicate that the 3D echocardiography system used in our study is more advanced compared to the older 3D systems in terms of optimal image acquisition rate and feasible levels of analysis time, indicating its suitability for routine clinical use.

It has also been shown that a certain rate of limitation is inevitable in routine clinical use of 3D echocardiography due to the longer durations of analysis exceeding 12 min or as a consequence of the inability to analyze images at the time of shooting.

The largest diameters measured by 2D and 3D echocardiography in our study correlated well (r = 0.79); however, those obtained during surgery correlated significantly better with those obtained by 3D echocardiography (r = 0.85) than 2D echocardiography (r = 0.53). The reason for this could be the blockage of the en-face view in 2D echocardiography, presenting as an inability to expose the wider, irregularly shaped (elliptical-like) morphologies, particularly in wide septal defects. Similarly, the correlation between the largest diameters of VSDs obtained by 2D and 3D echocardiography was reported as 0.74 [24]. An earlier study also confirmed that the 3D echocardiography results showed better correlations with surgical findings than those obtained by 2D echocardiography [18].

Due to the recently prevailing use of transcatheter closure of VSDs with surgical treatment, evaluation of morphology, diameter, and adjacent tissues, especially at different angular aspects has become increasingly important in patient selection [23,25–29]. However, with 2D echocardiography, en-face views of the defect cannot be obtained, thus definition of the morphology and relationship of the defect with surrounding tissues remains relatively poor when compared with 3D echocardiography [23].

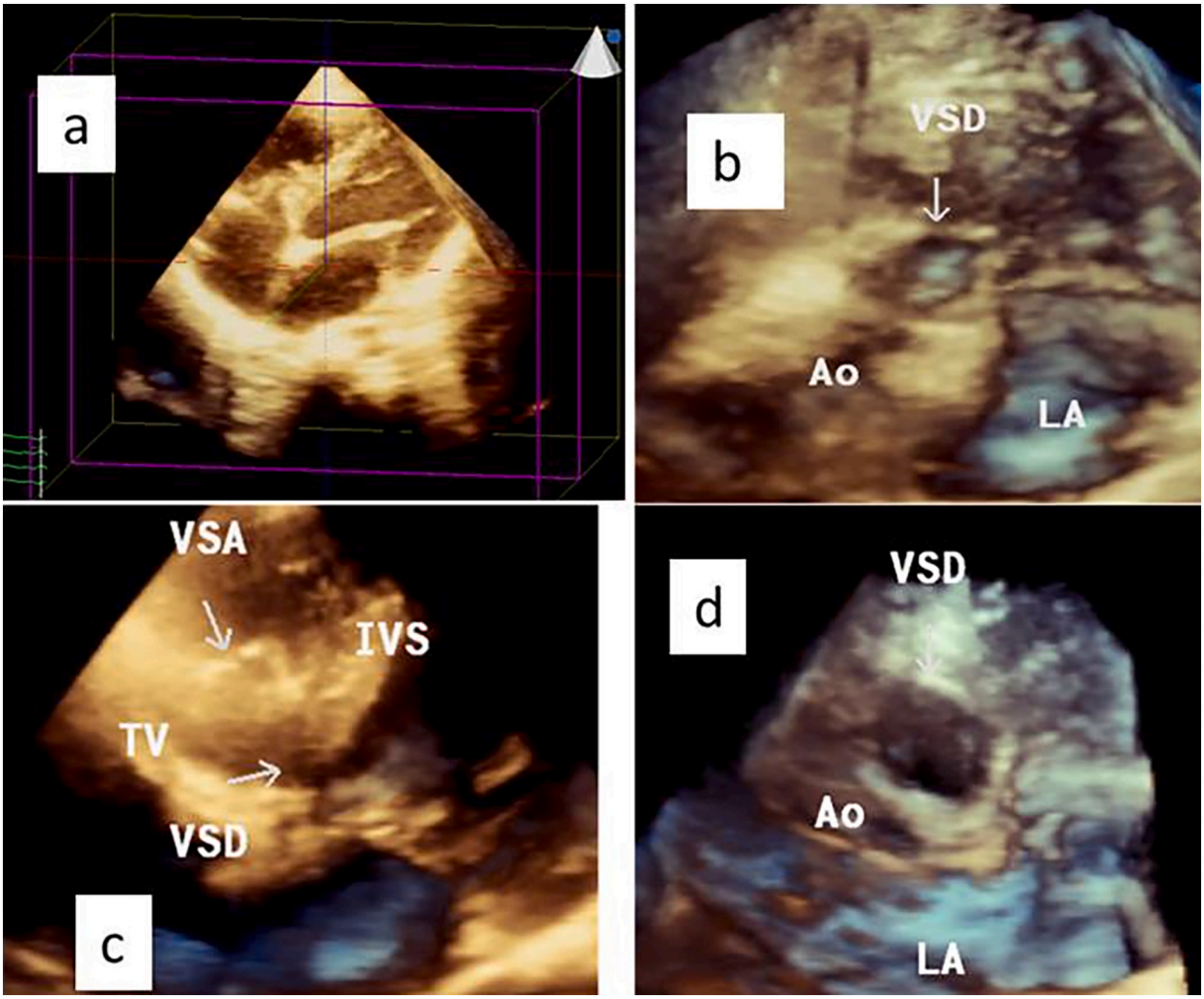


Fig. 5. Tricuspid valve (a) and ventricular septal aneurysm tissue (c) can be identified clearly according to morphological structure, shape, and the elongation in ventricular septum (b–d).

For reasons mentioned above, clinical utility of 3D echocardiography has become increasingly important in preoperative evaluation in regard to patient selection for transcatheter closure [26–30]. The most important finding of our study in this context was that the acquisition of 3D echocardiographic en-face images of VSDs via the right ventricle has significantly improved the revelation of the underlying morphology. We have demonstrated also that relation of the defect to neighboring tissues can be best demonstrated by defining the proximity of the perimembranous VSDs to the tricuspid valve and aortic valves. In addition, our study revealed that 3D echocardiographic evaluation of VSDs is important in observing dynamic morphological changes during heart cycle. In an earlier study conducted using 3D echocardiography, the difference between systolic and diastolic field values of VSDs was found to be significant and it was argued that the dynamic process changes should be taken into account in the evaluation of VSDs [24].

Perimembranous VSDs may be difficult to visualize because they may be covered with tricuspid leaflets, ventricular septal aneurysm tissues, or both [31]. In such cases, although transesophageal echocardiography is the preferred method for detailed evaluation, 3D echocardiography may be useful as well [32]. Indeed, our study revealed that 3D echocardiography can be used to clearly demonstrate the morphological structures of VSDs covered with tricuspid leaflets or aneurysm tissues, confirming the findings of earlier studies [18,19].

These findings in our study demonstrate the feasibility of 3D echocardiographic evaluation of VSDs and that the shape of the VSDs is different than linear measurements of 2D echocardiography. In this regard, the recommendations about three-dimensional echocardiography in congenital heart disease mentioned in the Expert Consensus Document from the European Association of Cardiovascular Imaging and the American Society of Echocardiography [33] should be followed also by the surgical community for obtaining more accurate measurements compared to those from 2D echocardiography.

Besides, 3D echocardiography renders it possible to define any VSD with its largest diameter as a circle or an ellipse, demonstrate the dynamic features during heart cycle and evaluate the en-face view the defect as well as the neighboring tissues thereof. Indeed, it has been demonstrated in several earlier studies that data obtained from 2D, or 3D echocardiography could be used successfully in selecting patients for interventional therapy and that 3D echocardiography could be used as a guide during interventional therapy [34–39]. Our study results further confirm that patient candidates for transcatheter closure can be selected using 3D echocardiography, which can be utilized further in the surgical or interventional stages of the treatment also.

The limitations of our study are the relatively small sample size and the single center design of the study. As the usage of 3D echocardiography becomes more commonplace in clinical practice, its role before trans-catheter management and surgery will be better understood. Outcomes of surgical repair of certain types of VSDs should be observed and published in a future study with a larger population of subjects. This may help introduce specific indications for 3D echocardiography in particular forms of VSDs, which may illustrate the greatest utility for 3D echocardiography. Also, comparisons to cardiac magnetic resonance

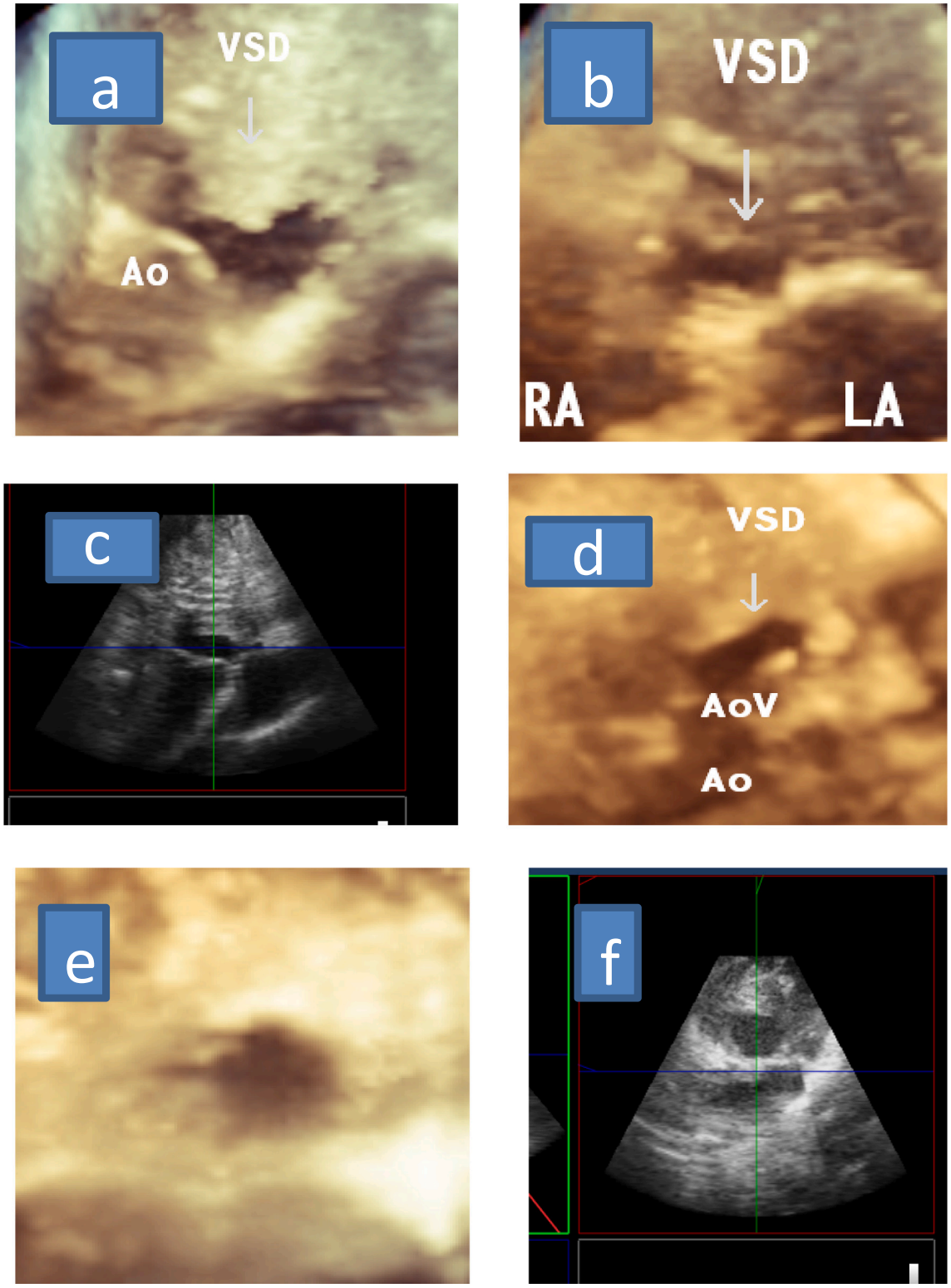


Fig. 6. The irregular shapes of VSDs (a–d). The image of only one patient whose VSD was in round shape (e–f). The typical image of a perimembranous outlet VSD (c–d). Aov: aortic valve, RA: right atrium.

imaging (cMRI) should be included in future studies since increasing number of pediatric cardiology noninvasive imaging centers use cMRI as well. Despite these shortcomings, the current study contributes to the literature by demonstrating that several morphological features of VSDs (the en-face view of VSD, morphology, the maximum diameter and area measurements, dynamic changings, and the relationship with neighbor tissues) can be investigated in more detail using 3D echocardiography compared to its 2D counterpart. It should be noted also that the current generation of real time 3D echocardiography provides adequate images with a short acquisition time and acceptable reconstruction time.

5. Conclusion

We conclude that 3D echocardiography can serve as a feasible and valuable tool in the clinical assessment and surgical interventions of VSDs and should be method of choice for obtaining reliable qualitative and quantitative information regarding the morphology, shape, size, and tissue rims of these defects before surgery.

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CRediT authorship contribution statement

All authors have accepted responsibility for the entire content of this manuscript and approved its submission.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors would like to express gratitude to the patients and their parents or custodians for their understanding and cooperation in this study.

Research funding

None declared.

Informed consent

Informed consent was obtained in written from all parents or custodians as well as children of 6 year age or above.

Ethical approval

The study protocol was approved by the ethics committee of the hospital. The study has complied with the 1964 World Medical Association Declaration of Helsinki and its later amendments and comparable standards regarding ethical conduct of research involving human subjects. The study does not involve any procedure on animals.

References

[1] Addetia K, Muraru D, Badano LP, Lang RM. New directions in right ventricular assessment using 3-dimensional echocardiography. JAMA Cardiol 2019;4:936–44. https://doi.org/10.1001/jamacardio.2019.2424.

[2] Chan KL, Liu X, Ascah KJ, Beauchesne LM, Burwash IG. Comparison of real-time 3-dimensional echocardiography with conventional 2-dimensional echocardiography in the assessment of structural heart disease. J Am Soc Echocardiogr 2004;17:976–80. https://doi.org/10.1016/j.echo.2004.05.005.

[3] Espinola-Zavaleta N, Munoz-Castellanos L, Attie F, Hernandez-Morales G, Zamora-Gonzalez C, Duenas-Carbajal R, et al. Anatomic three-dimensional echocardiographic correlation of bicuspid aortic valve. J Am Soc Echocardiogr 2003;16:46–53. https://doi.org/10.1067/mje.2003.30.

[4] German C, Nanda NC. Three-dimensional echocardiographic assessment of atrial septal defects. Ann Card Anaesth 2015;18:69–73. https://doi.org/10.4103/0971-9784.148324.

[5] Lu X, Xie M, Tomberlin D, Klas B, Nadvoretskiy V, Ayres N, et al. How accurately, reproducibly, and efficiently can we measure left ventricular indices using M-mode, 2-dimensional, and 3-dimensional echocardiography in children? Am Heart J 2008;155:946–53. https://doi.org/10.1016/j.ahj.2007.11.034.

[6] Dall'Agata A, Cromme-Dijkhuis AH, Meijboom FJ, McGhie JS, Bol-Raap G, Nosir YF, et al. Three-dimensional echocardiography enhances the assessment of ventricular septal defect. Am J Cardiol 1999;83(1576–9):A8. https://doi.org/10.1016/s0002-9149(99)00155-1.

[7] Ishii M, Hashino K, Eto G, Tsutsumi T, Himeno W, Sugahara Y, et al. Quantitative assessment of severity of ventricular septal defect by three-dimensional reconstruction of color doppler-imaged vena contracta and flow convergence region. Circulation 2001;103:664–9. https://doi.org/10.1161/01.cir.103.5.664.

[8] Rivera JM, Siu SC, Handschumacher MD, Lethor JP, Guerrero JL, Vlahakes GJ, et al. Three-dimensional reconstruction of ventricular septal defects: validation studies and in vivo feasibility. J Am Coll Cardiol 1994;23:201–8. https://doi.org/10.1016/0735-1097(94)90521-5.

[9] Shirazi S, Golmohammadi F, Tavoosi A, Salehi M, Larti F, Sardari A, et al. Quantification of aortic valve area: comparison of different methods of echocardiography with 3-D scan of the excised valve. Int J Cardiovasc Imaging 2021;37:529–38. https://doi.org/10.1007/s10554-020-02035-9.

[10] Kleijn SA, Kamp O. Clinical application of three-dimensional echocardiography: past, present and future. Neth Heart J 2009;17:18–24. https://doi.org/10.1007/BF03086210.

[11] Vogel M, Losch S. Dynamic three-dimensional echocardiography with a computed tomography imaging probe: initial clinical experience with transthoracic application in infants and children with congenital heart defects. Br Heart J 1994;71:462–7. https://doi.org/10.1136/hrt.71.5.462.

[12] Balzer J, van Hall S, Rassaf T, Boring YC, Franke A, Lang RM, et al. Feasibility, safety, and efficacy of real-time three-dimensional transoesophageal echocardiography for guiding device closure of interatrial communications: initial clinical experience and impact on radiation exposure. Eur J Echocardiogr 2010;11:1–8. https://doi.org/10.1093/ejechocard/jep116.

[13] Franke A, Kuhl HP, Rulands D, Jansen C, Erena C, Grabitz RG, et al. Quantitative analysis of the morphology of secundum-type atrial septal defects and their dynamic change using transesophageal three-dimensional echocardiography. Circulation 1997;96. II-323-7 PMID: 9386118.

[14] Handke M, Schafer DM, Muller G, Schochlin A, Magosaki E, Geibel A. Dynamic changes of atrial septal defect area: new insights by three-dimensional volume-rendered echocardiography with high temporal resolution. Eur J Echocardiogr 2001;2:46–51. https://doi.org/10.1053/euje.2000.0064.

[15] Hofmann T, Franzen O, Koschyk DH, Von Kodolitsch Y, Goldmann B, Meinertz T. Three-dimensional color doppler echocardiography for assessing shunt volume in atrial septal defects. J Am Soc Echocardiogr 2004;17:1173–8. https://doi.org/10.1016/j.echo.2004.06.030.

[16] Nanda NC, Kisslo J, Lang R, Pandian N, Marwick T, Shirali G, et al. Examination protocol for three-dimensional echocardiography. Echocardiography 2004;21:763–8. https://doi.org/10.1111/j.0742-2822.2004.218001.x.

[17] Yagel S, Cohen SM, Rosenak D, Messing B, Lipschuetz M, Shen O, et al. Added value of three-/four-dimensional ultrasound in offline analysis and diagnosis of congenital heart disease. Ultrasound Obstet Gynecol 2011;37:432–7. https://doi.org/10.1002/uog.8867.

[18] van den Bosch AE, Ten Harkel DJ, McGhie JS, Roos-Hesselink JW, Simoons ML, Bogers AJ, et al. Feasibility and accuracy of real-time 3-dimensional echocardiographic assessment of ventricular septal defects. J Am Soc Echocardiogr 2006;19:7–13. https://doi.org/10.1016/j.echo.2005.07.009.

[19] van der Zwaan HB, Helbing WA, McGhie JS, Geleijnse ML, Luijnenburg SE, Roos-Hesselink JW, et al. Clinical value of real-time three-dimensional echocardiography for right ventricular quantification in congenital heart disease: validation with cardiac magnetic resonance imaging. J Am Soc Echocardiogr 2010;23:134–40. https://doi.org/10.1016/j.echo.2009.12.001.

[20] Chen GZ, Huang GY, Tao ZY, Liu XQ, Lin QS. Value of real-time 3-dimensional echocardiography sectional diagnosis in complex congenital heart disease evaluated by receiver operating characteristic analysis. J Am Soc Echocardiogr 2008;21:458–63. https://doi.org/10.1016/j.echo.2007.08.040.

[21] Jenkins C, Bricknell K, Chan J, Hanekom L, Marwick TH. Comparison of two- and three-dimensional echocardiography with sequential magnetic resonance imaging for evaluating left ventricular volume and ejection fraction over time in patients with healed myocardial infarction. Am J Cardiol 2007;99:300–6. https://doi.org/10.1016/j.amjcard.2006.08.026.

[22] Krishnamoorthy VK, Sengupta PP, Gentile F, Khandheria BK. History of echocardiography and its future applications in medicine. Crit Care Med 2007;35:S309–13. https://doi.org/10.1097/01.CCM.0000270240.97375.DE.

[23] Mehmood F, Miller AP, Nanda NC, Patel V, Singh A, Duncan K, et al. Usefulness of live/real time three-dimensional transthoracic echocardiography in the characterization of ventricular septal defects in adults. Echocardiography 2006;23:421–7. https://doi.org/10.1111/j.1540-8175.2006.00239.x.

[24] Cheng TO, Xie MX, Wang XF, Wang Y, Lu Q. Real-time 3-dimensional echocardiography in assessing atrial and ventricular septal defects: an echocardiographic-surgical correlative study. Am Heart J 2004;148:1091–5. https://doi.org/10.1016/j.ahj.2004.05.050.

[25] Chen FL, Hsiung MC, Nanda N, Hsieh KS, Chou MC. Real time three-dimensional echocardiography in assessing ventricular septal defects: an echocardiographic-surgical correlative study. Echocardiography 2006;23:562–8. https://doi.org/10.1111/j.1540-8175.2006.00277.x.

[26] Chessa M, Carminati M, Cao QL, Butera G, Giusti S, Bini RM, et al. Transcatheter closure of congenital and acquired muscular ventricular septal defects using the amplatzer device. J Invasive Cardiol 2002;14:322–7. PMID: 12042624.

[27] Cossor W, Cui VW, Roberson DA. Three-dimensional echocardiographic en face views of ventricular septal defects: feasibility, accuracy, imaging protocols and

reference image collection. J Am Soc Echocardiogr 2015;28:1020–9. https://doi.org/10.1016/j.echo.2015.05.014.
[28] Guo W, Li Y, Yu J, Li J, Sun L, Shi J, et al. Transcatheter closure of perimembranous ventricular septal defect with aneurysm: radiologic characteristic and interventional strategy. J Interv Cardiol 2020;2020:6646482. https://doi.org/10.1155/2020/6646482.
[29] Hijazi ZM. Device closure of membranous ventricular septal defects in adults: an alternative to surgical closure. Acute Card Care 2007;9:60–1. https://doi.org/10.1080/17482940600885477.
[30] Suematsu Y, Takamoto S, Kaneko Y, Ohtsuka T, Takayama H, Kotsuka Y, et al. Beating atrial septal defect closure monitored by epicardial real-time three-dimensional echocardiography without cardiopulmonary bypass. Circulation 2003;107:785–90. https://doi.org/10.1161/01.cir.0000047210.07839.7b.
[31] Soto B, Ceballos R, Kirklin JW. Ventricular septal defects: a surgical viewpoint. J Am Coll Cardiol 1989;14:1291–7. https://doi.org/10.1016/0735-1097(89)90430-0.
[32] Yim D, Mertens L, Honjo O, Nield LE. Intraoperative echocardiographic coronary artery imaging in congenital and acquired heart disease. Cardiol Young 2020;30:153–61. https://doi.org/10.1017/S1047951120000116.
[33] 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;30:1–27. https://doi.org/10.1016/j.echo.2016.08.022.
[34] Acar P, Dulac Y, Roux D, Rouge P, Duterque D, Aggoun Y. Comparison of transthoracic and transesophageal three-dimensional echocardiography for assessment of atrial septal defect diameter in children. Am J Cardiol 2003;91:500–2. https://doi.org/10.1016/s0002-9149(02)03261-7.
[35] Acar P, Roux D, Dulac Y, Rouge P, Aggoun Y. Transthoracic three-dimensional echocardiography prior to closure of atrial septal defects in children. Cardiol Young 2003;13:58–63. https://doi.org/10.1017/s1047951103000118.
[36] Charakida M, Qureshi S, Simpson JM. 3D echocardiography for planning and guidance of interventional closure of VSD. JACC Cardiovasc Imaging 2013;6:120–3. https://doi.org/10.1016/j.jcmg.2012.10.012.
[37] Guo Z, Zhang S, Zhu M, Jiang X, Guo W, Feng J, et al. Value of echocardiography for mini-invasive per-atrial closure of perimembranous ventricular septal defect. Int J Cardiovasc Imaging 2021;37:117–24. https://doi.org/10.1007/s10554-020-01967-6.
[38] Parisi V, Ratto E, Silvestri C, Pastore F. Ventricular septal defect: the three-dimensional point of view. Transl Med UniSa 2013;6:41–2. PMID: 24251244 PMCID: PMC3829796.
[39] Zhang C, Li Z, Xu J. Real-time three-dimensional transesophageal echocardiography is useful for percutaneous closure of multiple secundum atrial septal defects. Hellenic J Cardiol 2014;55:486–91. PMID: 25432200.