ORIGINAL ARTICLE

THREE-DIMENSIONAL PRINTING OF MITRAL VALVE MODELS USING ECHOCARDIOGRAPHIC DATA: DOES IT ADD TO THE KNOWLEDGE OF CARDIOLOGY FELLOW PHYSICIANS IN TRAINING?

AUTHORS:
Ziad R. Bulbul[1], MD, Issam El Rassi[2], MD, Lamya Atweh[3], MD, Ramsey F. Hamade[4], Ph.D., Hani Tamim[5], Ph.D., and Fadi Bitar[1], MD
1. Department of Pediatrics and Adolescent Medicine, 2. Department of Surgery, 3. Department of Diagnostic Radiology, 4. Department of Mechanical Engineering, Department of Biostatistics. American University of Beirut Medical Center. Beirut, Lebanon

Corresponding Author:
Ziad Bulbul, MD. Department of Pediatrics and Adolescent Medicine,American University of Beirut Medical Center, P.O. Box 11-0236, Riad El-Solh Beirut 1107 2020, Lebanon. Phone: 00(961) 76 793838. Fax: 00(961) 1 370781. Ziad.bulbul@aub.edu.lb. ORCID ID 0000-0002-0893-0435

Conflicts of interest: The authors declare that they have no conflict of interest, due to either financial or personal relationship, that might have affected or biased their work.
Funding: All 3D models were printed in the Department of Engineering at the American University of Beirut by Dr. Hamadeh and his group, funded by the National Council for Scientific Research (Grant Research Program 2017 award number 103288).

https://doi.org/10.55634/1.3.4

ABSTRACT

Background: three-dimensional mitral valve models (3D MVM) printed from echocardiography are currently being used in preparation for surgical repair. We hypothesize that printed 3D MVM could improve the understanding of cardiologists in training of normal mitral valve anatomy and pathology.
Methods: 16 fellows in pediatric and adult cardiology training were recruited. 3D echocardiography (3DE) video clips of 6 MVs were displayed. Following that, three still images of each of 3D MVMs in different projections, corresponding to the same MVs seen in the clips were presented on a screen. Fellows were asked to answer a questionnaire aimed at assessing whether the 3D MVM has improved their understanding of MV. Finally, a printed 3D MVM of each of the previously projected valves was handed out, and the same questionnaire was re-administered.
Results: the correct diagnosis of prolapsing segments using the 3DE video clip of the MV was attained only by 45% of the study participants. Both pediatric and adult trainees, demonstrated improved understanding of the anatomy of MV after observing the latter's MVM image. Further improvement in the participants' understanding was noted after they had seen and physically examined the printed MVM.
Conclusion: printed 3D MVM has a beneficial impact on the cardiology trainees' understanding of MV anatomy and pathology as compared to 3DE images.
Keywords: Echocardiography, Three-Dimensional, Mitral valve, Printing, Educational, Cardiology Trainees

INTRODUCTION

Since its initial introduction in the 1980s, 3D printing of radiographic based imaging has gained momentum as a clinical tool over the last few years. From an initial use for industrial work [1], 3D printing first made its debut in the field of clinical care in the 1990s with the manufacture of the first cranial bone model [2]. Its use has become widespread in various medical fields from bio-printing tissue organs [3] extending currently to patient-specific implants, prostheses, and replicated anatomical models for education and surgical planning [4,5]. Three-dimensional models of hearts with several congenital defects are currently available [2]. The diagnostic and educational values of such models as physical tools for training are currently on the rise.

Although the clinical use of 3DE has been around for more than two decades, models of cardiac structures generated from 3DE has not been thoroughly investigated. Echocardiographic 3D data sets of a mitral valve, obtained via the trans esophageal window, has shown to have enough spatial and temporal resolution for clinical use. However, till this day, this remains suboptimal for 3D printing. Hence, obtaining 3D prints from echocardiographic data has not been fully perfected and is still lagging other radiographic based images.

Many commercially available 3D rendering software are currently available. The rendered dynamic 3DE based images are an excellent adjunct to the conventional two-dimensional echocardiography for surgical repair. In addition to the rendered 3DE image, a 3D MVM (Fig.1) can be generated. 3D MVM can be used to perform several measurements that are crucial for understanding the structures of the MV and for planning surgical intervention.

On another note, projecting a 3D structure on a flat screen inevitably affects the viewer's depth perception. Unlike 3DE images, the 3D MVM provides excellent depth while conserving details when printed.

We hypothesize that printed 3D MVM (Fig. 3) could improve the understanding of the MV normal anatomy and pathology for cardiologists in training.

METHODS

This is a cross sectional questionnaire-based educational study that was administered to cardiology physicians in training, between June 2017 and March 2018, at the American University of Beirut-Medical Center (AUBMC). The study was approved by the Research Institutional Review Board of AUBMC. Cardiology fellows consented to participate in the study. Emphasis was placed on the fact that participation is voluntary and that they can withdraw from the study at any point in any time. Moreover, all data collected including videos, clinical models, and fellows' details (except for their year of training and subspecialty) were anonymous. Confidentiality was maintained throughout the study. Sixteen cardiology fellows at different levels of training (eleven adult cardiology trainees and five pediatric cardiology trainees) were recruited and have completed the study.

Imaging of the MV and the acquisition of 3D data sets were completed using a (t7-1) trans esophageal probe and (iE-33) echocardiography platform (Philips, Eindhoven Netherlands). Rendered 3D images of the mitral valve were generated using QLAB software v.8 (Philips, Eindhoven Netherlands) and were saved as anonymous video clips (Audio Video Interleave format, Microsoft, Washington, USA).

Native 3D data sets were imported into commercially available software (Image Arena, Tom Tec GmbH. Munich, Germany). Another plug in semi-automated specialized software (MVA package 2.1) was used to generate a geometrical model of the valve to include the annulus, leaflets and coaptation line. Pictures of each model, in three projections (profile, enface, and tilted) were saved in JPEG format (Joint Photographic Experts Group) and exported as stereolithographic files (STL).

Files of the 3D MVM were printed on a commercial Ultimaker 2+R 3D printer (Ultimaker B.V. Watermolenweg, Netherlands). The fidelity of the resulting models was highly conserved.

A total of six valves (One is normal and five are pathological) were used in the study. Pathological models included: two valves with single leaflet segment prolapse (Fig. 2:A1 and A2), two valves with at least two segments prolapse involving both leaflets and lack of leaflet coaptation (Fig.

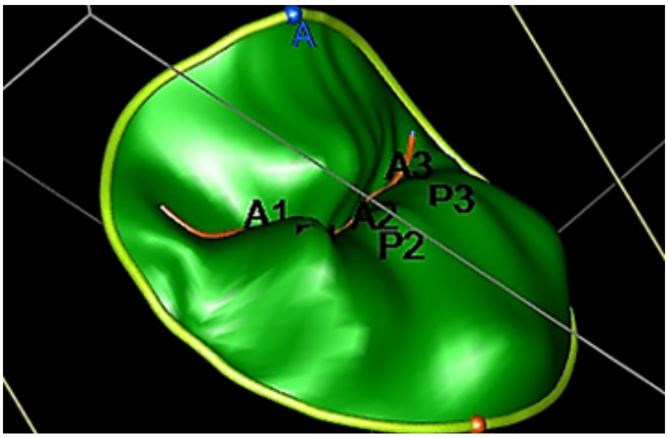

Fig. 1 A tilted picture of the 3D MVM showing the two leaflets are divided into a total of six scallops: A1, A2, A3 and P1, P2, P3 (A: anterior. P: posterior, 3D: three dimensional, MVM: mitral valve model).

Fig. 2 Showing a picture of the printed 3D MVM; (a1) and (a2): two valves with single leaflet segment prolapse; (b1) and (b2): two valves with at least two segments prolapse involving both leaflets, with lack of leaflet coaptation in one. (c): valve with a flail segment. (d): normal valve (3D: three dimensional, MVM: mitral valve model).

3: B1 and B2), and a fifth valve, marked as valve C, demonstrated a flail segment. Valve D was the normal valve (Fig. 2).

To test our hypothesis, a PowerPoint (Microsoft incorporation- Washington, USA) based questionnaire was prepared. The questionnaire was specifically designed for this project to elicit whether the 3D printed model improved participant's perception and knowledge about the MV or not.

Movie clips of 3DE of the 6 MVs were initially projected to the participants of the study, after which they were asked to name the pathological segment(s) of the MV leaflets, if any existed. Following that, pictures of the 3D MVMs of the same valves were sequentially projected on a flat screen. Participants were asked if that had added to their understanding of the valve regarding the following categories: (1) anatomy in general, (2) area and prolapse of the leaflets, and (3) shape of the annulus: whether it resembles a circle or an ellipse and the difference in the elevation between the antero-posterior and medio-lateral planes. Finally, the corresponding printed 3D MVMs were handed over to the participants for tangible assessment. The same questionnaire was administered once again following their assessment of the printed 3D MVM.

STATISTICAL ANALYSIS

Data were entered and analyzed using the Statistical Package for Social Sciences program (SPSS Inc, Chicago, IL). For each case, the number and percentage of fellows giving the correct answer and whether the printed 3D MVM improved their understanding of MV anatomy and pathology was calculated and presented as a mean and standard deviation. Each fellow was asked to assign a response to each of the four questions describing how a certain image modality improved their understanding of MV anatomy and pathology. The available answers were: 'extremely', 'very', 'moderately', 'slightly', and 'not at all'. For the presentation of the perception data, we have created three groups of responses. A negative perception as indicated by "not at all" and "slightly" answers, a neutral perception as indicated by "moderately" answer, and a positive perception as indicated by "very" and "extremely". Percentages of negative, neutral and positive responses were calculated for each category in all 6 cases.

In order to assess the overall responses and compare outcomes between adult and pediatric fellows on one hand, and between the 7 junior (first-year trainees) and the 9 senior fellows (second and third year trainees) on the other; the number and percentages of positive answers were compared and the difference in mean scores was calculated using the Mann-Whitney test where p-value <0.05 was used to indicate statistical significance.

COMPLIANCE WITH ETHICAL STANDARDS

This study was approved by the Institutional Review Board (IRB) and the Ethics Committee at the American University of Beirut Medical Center and AUB Faculty of Medicine. Consent was obtained from all fellows (pediatric and adult cardiology) prior to enrollment. Enrollment was optional and participation was solely up to the fellow's choice.

RESULTS

1-Video Clips:

Based on the video clips of the valves, fourteen participants (87.5%) identified the normal case correctly. Twelve (75%) and seven (44%) of them named the correct prolapsing segment in the two models with one pathological segment. However, six (37.5%), four (25%) and only one (6.3%) participant correctly identified all the pathological segments in the last three complex cases (with more than one prolapsing segment present).

2- Pictures of the 3D MVM:

Following the projection of the pictures of the 3D MVM, (44.8%), (41.7%), (40.6%) and (51.6%) of the group agreed that the pictures of 3D MVM improved their understanding of the general appearance of the valve, its area, prolapsing segments, and shape of the annulus respectively. Among the junior fellows, (38.1%) indicated that the picture of the 3D MVM improved their general understanding of the valve's anatomy, (45.2%) stated that it improved their perception of the valve's area, (46.3%) agreed that it positively changed their understanding of the leaflet prolapse, and (40.5%) agreed that their understanding of the shape of the annulus was improved. This is in comparison to the senior fellows of whom (42.6%), (44.4%), (55.6%) and (42.6%) agreed that the picture of 3D MVM improved their understanding of the valve in general, its' area, prolapsing leaflets, and the shape of the annulus respectively (Table 1).

3- Inspection of Printed 3D MVM:

Inspection of 3D MVM has improved the fellows' understanding of the mitral valve in all 4 categories according to the percentages of the positive responses obtained: 1- general appearance of the valve (76%); 2- area of the valve (74.7%); 3- prolapsing segments (78.9%) and 4- shape of the annulus (68.8%). When comparing fellows according to their level of training; senior fellows were more likely to agree that the printed 3D MVM was helpful in improving their understanding of the MV in all categories when compared to their junior counterparts. (77.8%) of senior fellows agreed that the printed 3D MVM improved their understanding of the general appearance of the valve vs. (73.8%) for junior fellows ((p =0.05). The results were the same regarding their understanding of the shape of the annulus: (75.9%) vs. (59.5%) (p =0.01) and that of the prolapsing segments: (81.5%) vs (75.6%) (p=0.03). However, there was no statistical difference between junior and senior fellows regarding whether the printed 3D MVM improved their understanding of the valve's area: (75.6%) vs. (74.1%) (p=0.05)

4- Picture vs. Print of 3D MVM:

When comparing the pictures of the 3D MVM to its corresponding print, the whole group perceived that the printed 3D MVM had significantly improved their understanding of the mitral valve over the pictures in all four categories: (76%) vs. (46%) (p<0.0001) for the general appearance, (74.7%) vs. (44.8%) (p<0.0001) for the area, (78.9%) vs. (51.6%) for prolapsing segments (p<0.0001),

All Trainees (n=16)		**Picture of 3D Model**	**Print of 3D Model**	**p-value**
	Response n= 96	n (%)	n (%)	
General appearance	Negative	23 (24.0)	8 (8.3)	
	Neutral	34 (35.4)	15 (15.6)	
	Positive	39 (40.6)	73 (76.0)	<0.0001
Area of valve	Negative	24 (25.0)	9 (9.5)	
	Neutral	29 (30.2)	15 (15.8)	
	Positive	43 (44.8)	71 (74.7)	<0.0001
Prolapsing segments	Negative	24 (25.3)	5 (5.3)	
	Neutral	22 (23.2)	15 (15.8)	
	Positive	49 (51.6)	75 (78.9)	<0.0001
Shape of annulus	Negative	22 (22.9)	9 (9.4)	
	Neutral	34 (35.4)	21 (21.9)	
	Positive	40 (41.7)	66 (68.8)	<0.0001
Pediatric trainees (n=5)				
	Response (n=30)	n (%)	n (%)	
General impression	Negative	2 (6.7)	0 (0.0)	
	Neutral	8 (26.7)	7 (23.3)	
	Positive	20 (66.7)	23 (76.7)	= 0.10
Area of valve	Negative	2 (6.7)	0 (0.0)	
	Neutral	7 (23.3)	6 (20.7)	
	Positive	21 (70.0)	24 (79.3)	= 0.06
Prolapsing segments	Negative	3 (10.3)	1 (3.4)	
	Neutral	6 (20.7)	5 (17.2)	
	Positive	20 (69.0)	24 (79.3)	= 0.03
Shape of annulus	Negative	2 (6.7)	0 (0.0)	
	Neutral	8 (26.7)	8 (26.7)	
	Positive	20 (66.7)	22 (73.3)	= 0.10
Adult Trainees (n=11)				
	Response (n=66)	n (%)	n (%)	
General impression	Negative	21 (31.8)	8 (12.1)	
	Neutral	26 (39.4)	8 (12.1)	
	Positive	19 (28.8)	50 (75.8)	<0.0001
Area of valve	Negative	22 (33.3)	9 (13.6)	
	Neutral	22 (33.3)	9 (13.6)	
	Positive	22 (33.3)	48 (72.8)	<0.0001
Prolapsing segments	Negative	21 (31.8)	4 (6.1)	
	Neutral	16 (24.4)	10 (15.2)	
	Positive	29 (43.8)	52 (78.7)	<0.0001
Shape of annulus	Negative	20 (30.3)	9 (13.6)	
	Neutral	26 (39.4)	13 (19.7)	
	Positive	20 (30.3)	44 (66.7)	<0.0001

Table 1. The change in fellows' perception of mitral valve anatomy after examination of 3D printed model as compared to the picture of 3D model. P-value is calculated for the positive response

and (69%) vs. (42%) (p<0.0001) for the shape of the annulus (Table 2).

These results were the same regardless of the year of training. Junior fellows agreed that the printed 3D MVM improved their understanding of the MV in all four categories when compared to the picture: (73.8%) vs. (38.1%) (p<0.0001) for general appearance, (75.6%) vs. (45.2%) for the valve's area (p<0.001), (75.6%) vs. (46.3%) (p<0.001) for prolapsing segments, and (59.5%) vs. (40.5%) (p= 0.02) for the shape of the MV. Senior fellows followed the same trend: (77.8%) vs. (42.6%) (p<0.0001) for the general appearance, (74.1%) vs. (44.4%) (p<0.0001) for the area, (81.5%) vs. (55.6%) (p<0.0001) for prolapsing segments, and (75.9%) vs. (42.6%) (p<0.0001) for the shape of the annulus.

DISCUSSION

The complexity of the MV has been challenging to image ever since the initial stages of echocardiography. A landmark in the imaging of the MV was the clinical use of Trans Esophageal Echocardiograms (TEE) [6]. Two dimensional (2D) TEE and its application on the MV imaging [7,8] has expanded the scope of repair surgery [9]. Despite all advancements, the understanding of the MV pathology requires the assimilation of 2D images with direct intraoperative valve findings. Ahmed et al. reported that this approach could be challenging for less experienced echo cardiographers; especially in cases of complex MV prolapse involving multiple MV segments [10].

Training a cardiologist on echocardiography is a tedious and lengthy process. The biggest challenge for a trainee is to mentally reconstruct a 3D image from multiple slices of 2D planes for a given structure. To achieve such a purpose, the advantage of 3D TEE over 2D TEE is obvious, especially for a complex structure like the MV. Furthermore, La Canna et al. eluded to an additional diagnostic value of 3D TEE in that it provides more accurate mapping of the MV prolapse and further details of its anatomy [11].

Currently, 3D images rendered from 3DE are projected on 2D monitors. The mere fact of projecting a 3D structure on a flat screen is a significant shortcoming, despite the use of different hues and shadows to improve depth perception.

Recently, 3D printing has gained momentum in the medical field. Anatomical structures from different systems of the body are printed with a very high degree of accuracy [4,5]. Moreover, the price of printing has decreased significantly, and most centers nowadays can print their own 3D images.

While printing cardiac structures from CT and MRI scans are done routinely nowadays, printing from echocardiographic data has not been perfected yet. This is mainly due to the relatively low special resolution of 3DE images. Mahmood et al. [12] and others have printed 3D MVMs generated from echocardiographic data. The resulting prints closely mimicked the original echocardiographic pictures. This imaging modality, however, still requires refinement to better describe leaflet coaptation, valve chordae, papillary muscles and left ventricular geometry [13]. On the other hand, printing 3D MVM from echocardiographic data is practical and might be cost effective for the following reasons: 1- the same 3D software used to generate the 3D model is used to export the printable 3D file; hence there is no need to acquire a specialized rendering software as it is the case with CT scan and MRI. 2- Printing time is short (around 10 minutes) and the material used is minimal. 3- valves could be printed on a regular commercial 3D printer without any need for an industrial level printer.

In the field of surgery, the improvement in MV surgical outcomes coinciding with the use of 3D based images was highlighted by Beraud and his group [14]. Hien et al. had shown in a multicenter study that the use of 3DE of the MV improves the understanding of prolapse segments [15]. The fact that this was true for beginners and experienced echo cardiographers alike was of interest. Taking it one step further, Hadeed and his group proposed in a brief communication the use of printed 3D models of complex congenital lesions as a roadmap for surgical repair [16]. Recently, Premyodhin et al. published their experience in the use of a specially constructed MV molds that simulated natural tissue in the preoperative simulation of robotic mitral valve repair [17].

From an educational point of view, Biglino et al. showed in a recent publication the benefit of using 3D models of the heart as an educational tool for the training of both adult and pediatric cardiac nurses [18]. Costello et al. found that pediatric residents' understanding of lesions, like ventricular septal defect, could be further enhanced by the printed model as compared to educational seminars in anatomy and echocardiography. They proposed that 3D printed heart models can be effectively incorporated into a simulation-based congenital heart disease and critical care training curriculum for pediatric resident physicians (19).

One of the advantages of the physical inspection of the 3D model over a 2D projection of its image could be explained by the loss of the depth perception that is intrinsic to projecting a 3D structure onto a 2D screen.

In this study, we sought to prove that a 3D MVM, printed based on echocardiographic data, can enhance the understanding of the normal and abnormal anatomy of MV even at a high level of training. Our data clearly shows that 3D MVM, when physically examined by the cardiology fellows, did significantly improve their understanding even after seeing a 3D image of the same model. This observation was not only valid for the prolapsing segments but also for the area and shape of the valve and the complex anatomy of the annulus. This was the case irrespective of the level of training of the cardiology fellows.

In the future, further advancement in the spatial and temporal resolution of echo generated 3D images along with the advancement in 3D printing will permit the printing of actual structures of normal as well as congenitally deformed hearts from echocardiographic data in high fidelity and accuracy. Eventually, combining valves and sub valvular apparatus printed from echocardiographic data with heart models printed from CT or MRI scans will further improve our understanding of congenital heart disease as well as surgical planning.

CONCLUSION

Printed 3D MVMs based on echocardiographic data have a positive impact on the understanding of the MV anatomy and pathology for adult and pediatric cardiology trainees. It might further enhance the diagnostic power of 3DE especially in complex cases of MV disease.

Study Limitations:

Although the number of study participants was small, the results were coherent for the superiority of the 3D printed model.

Fundamental limitations of ultrasound, such as reverberation, shadowing, dropouts, and movement artifacts, can limit identification of landmarks on echocardiographic image. Optimal image acquisition with good image quality is an important aspect to 3-dimensional echocardiography, which in turn will the affect the image quality of the 3D MVM.

This study could thus serve as a starting point for larger studies to assess the effectiveness of 3D model's integration in the medical education.

References

1. Sun Z, Squelch A. 3D printed models of complex anatomy in cardiovascular disease. Heart Res Open J. 2015; 2(3): 103-108. doi: 10.17140/HROJ2-118

2. Kim MS, Hansgen AR, Wink O, Quaife RA, Carroll JD. Rapid prototyping: a new tool in understanding and treating structural heart disease. Circulation. 2008 May 6;117(18):2388-94. doi: 10.1161/CIRCULATIONAHA.107.740977

3. Daemen JHT, Heuts S, Olsthoorn JR, Maessen JG, Sardari Nia P. Mitral valve modelling and three-dimensional printing for planning and simulation of mitral valve repair. Eur J Cardiothorac Surg. 2019 Mar 1;55(3):543-551. doi: 10.1093/ejcts/ezy306

4. Frame M, Leach W. DIY 3D printing of custom orthopaedic implants: a proof of concept study. Surg Technol Int. 2014 Mar;24:314-7

5. Gerstle TL, Ibrahim AMS, Kim PS, Lee BT, Lin SJ. A plastic surgery application in evolution: three-dimensional printing. Plast Reconstr Surg. 2014 Feb;133(2):446-451. doi: 10.1097/01.prs.0000436844.92623.d3

6. Souquet J, Hanrath P, Zitelli L, Kremer P, Langenstein BA, Schlüter M. Transesophageal phased array for imaging the heart. IEEE Trans Biomed Eng. 1982 Oct;29(10):707-12. doi: 10.1109/TBME.1982.324864

7. Lambert AS, Miller JP, Merrick SH, et al. Improved evaluation of the location and mechanism of mitral valve regurgitation with a systematic transesophageal echocardiography examination. Anesth Analg. 1999 Jun;88(6):1205-12. doi: 10.1097/00000539-199906000-00004

8. Shanewise JS, Cheung AT, Aronson S, et al. ASE/SCA guidelines for performing a comprehensive intraoperative multiplane transesophageal echocardiography examination: recommendations of the American Society of Echocardiography Council for Intraoperative Echocardiography and the Society of Cardiovascular Anesthesiologists Task Force for Certification in Perioperative Transesophageal Echocardiography. J Am Soc Echocardiogr. 1999 Oct;12(10):884-900. doi: 10.1016/s0894-7317(99)70199-9

9. Sidebotham DA, Allen SJ, Gerber IL, Fayers T. Intraoperative transesophageal echocardiography for surgical repair of mitral regurgitation. J Am Soc Echocardiogr. 2014 Apr;27(4):345-66. doi: 10.1016/j.echo.2014.01.005. Epub 2014 Feb 15

10. Ahmed S, Nanda NC, Miller AP, et al. Usefulness of transesophageal three-dimensional echocardiography in the identification of individual segment/scallop prolapse of the mitral valve. Echocardiography. 2003 Feb;20(2):203-9. doi: 10.1046/j.1540-8175.2003.03010.x

11. La Canna G, Arendar I, Maisano F, et al. Real-time three-dimensional transesophageal echocardiography for assessment of mitral valve functional anatomy in patients with prolapse-related regurgitation. Am J Cardiol. 2011 May 1;107(9):1365-74. doi: 10.1016/j.amjcard.2010.12.048

12. Mahmood F, Owais K, Taylor C, et al. Three-dimensional printing of mitral valve using echocardiographic data. JACC Cardiovasc Imaging. 2015 Feb;8(2):227-9. doi: 10.1016/j.jcmg.2014.06.020

13. Witschey WR, Pouch AM, McGarvey JR, et al. Three-dimensional ultrasound-derived physical mitral valve modeling. Ann Thorac Surg. 2014 Aug;98(2):691-4. doi: 10.1016/j.athoracsur.2014.04.094

14. Beraud AS, Schnittger I, Miller DC, Liang DH. Multiplanar reconstruction of three-dimensional transthoracic echocardiography improves the presurgical assessment of mitral prolapse. J Am Soc Echocardiogr. 2009 Aug;22(8):907-13. doi: 10.1016/j.echo.2009.05.007

15. Hien MD, Großgasteiger M, Rauch H, Weymann A, Bekered-

jian R, Rosendal C. Experts and beginners benefit from three-dimensional echocardiography: a multicenter study on the assessment of mitral valve prolapse. J Am Soc Echocardiogr. 2013 Aug;26(8):828-34. doi: 10.1016/j.echo.2013.04.015

16. Hadeed K, Dulac Y, Acar P. Three-dimensional printing of a complex CHD to plan surgical repair. Cardiol Young. 2016 Oct;26(7):1432-4. doi: 10.1017/S1047951116000755

17. Premyodhin N, Mandair D, Ferng AS, et al. 3D printed mitral valve models: affordable simulation for robotic mitral valve repair. Interact Cardiovasc Thorac Surg. 2018 Jan 1;26(1):71-76. doi: 10.1093/icvts/ivx243

18. Biglino G, Capelli C, Koniordou D,et al. Use of 3D models of congenital heart disease as an education tool for cardiac nurses. Congenit Heart Dis. 2017 Jan;12(1):113-118. doi: 10.1111/chd.12414

19. Costello JP, Olivieri LJ, Su L, et al, Kim PC, Jonas RA, Nath DS. Incorporating three-dimensional printing into a simulation-based congenital heart disease and critical care training curriculum for resident physicians. Congenit Heart Dis. 2015 Mar-Apr;10(2):185-90. doi: 10.1111/chd.12238.