Taking Command of Three-Dimensional Stitching Artifacts: From an Annoyance to an Easy Tool for Navigating Three-Dimensional Transesophageal Echocardiography

Samuel D. Maidman, MD, Daniel Bamira, MD, Richard Ro, MD, Alan F. Vainrib, MD, and Muhamed Saric, MD, PhD, *New York, New York*

Despite many recent advances in three-dimensional (3D) transesophageal echocardiography (TEE) imagining, the process of orienting 3D TEE images is nonintuitive and uses assumptions based on idealized anatomy. Correlating two-dimensional TEE cross-sectional images to 3D reconstructions remains an additional challenge. In this article, we suggest the repurposing of the stitching artifact generated in 2-beat electrocardiogram-gated 3D TEE as a means of exactly orienting 3D images within a patient's unique anatomy. We demonstrate the application of this strategy to assess a normal mitral valve to localize scallops of mitral valve prolapse and to visualize typical left atrial appendage two-dimensional cuts in a 3D space. By taking command of stitching artifacts, cardiac imagers can successfully navigate the complex structures of the heart for optimal, individualized echocardiographic views. (J Am Soc Echocardiogr 2022;■:■-■.)

Keywords: 3D TEE, Stitching, Artifact, Image processing

Over the past 50 years, transesophageal echocardiography (TEE) has undergone tremendous advances. What initially started in 1971 as a rudimentary technique for measuring flow in the aortic arch has quickly developed into a dependable strategy for performing a comprehensive evaluation of the anatomy and hemodynamics of the heart as well as guidance of complex transcatheter procedures for repair of heart defects.[1-4] Much of this development can be attributed to advances in technology. The modern TEE probe and system are capable of not only providing complete two-dimensional (2D) cross-sectional and Doppler imaging but also of producing real-time three-dimensional (3D) images.[5]

While 3D imaging provides lifelike representation of cardiac structure, 3 major limitations remain: (1) the process of attitudinally orienting 3D TEE images is often nonintuitive, (2) correlating to 2D cross-sectional images remains challenging, and (3) multibeat acquisitions are often required to improve spatial resolution with a potential downside of a stitching artifact.

The current terminology of 3D TEE imaging is essentially based on the celestial coordinate system where in addition to the x axis, the y axis (the 2D sector width) is often referred to as the azimuth and the z axis (3D sector width) as the elevation.[6] Even with experience, it is often difficult to exactly determine where in a 3D TEE rendering the exact location of the corresponding 2D cross-sectional planes that were used to generate the 3D image is.

Sophisticated high-end software packages are now being added to 3D TEE ultrasound systems that provide 2D to 3D correlations (such as the MultiVue from Philips Healthcare, Amsterdam, The Netherlands).[7] These often expensive additions are useful, but they may still not provide exact 2D cross-sectional angles, and they are often not available on legacy ultrasound machines (which are still frequently utilized, even in well-equipped, tertiary medical center laboratories). Here we provide an alternative to such high-end systems. While the stitching artifact of a multibeat acquisition is often an annoyance, we present a creative use of the stitching artifacts as a deep insight into image processing and suggest taking advantage of the artifact as a tool akin to a sextant for determining the exact location of 2D cross-sectional cuts in a 3D image for an individual patient. We illustrate the utility of stitching artifacts in visualization of the mitral valve (MV) and left atrial appendage (LAA) when using 2-beat acquisitions in the focused wide-sector (zoom) mode.

BACKGROUND

In 1999, national organizations started publishing guidelines containing instructions for specific, anatomically directed cross-sectional transesophageal views to standardize the multiplane 2D TEE examination.[8] To assess the MV, the original guidelines presented 6 different 2D views: (1) midepigastric (ME) 4 chamber, (2) ME mitral commissure, (3) ME 2 chamber, (4) ME long axis, (5) transgastric basal short axis, and (6) transgastric 2 chamber.[8] Ever since, guidelines have been updated with 2D TEE views of additional structures, including the LAA at 4 multiplane angles: 0°, 45°, 90°, and 135°. By visualizing structure in multiple discrete 2D views, cardiac imagers then must attempt to generate a mental schema of true 3D structure. However, it is widely recognized that variation exists in the anatomic

From the Leon H. Charney Division of Cardiology, Department of Medicine, NYU Grossman School of Medicine, New York, New York.

Conflicts of Interest: None.

Roberto M. Lang, MD, FASE, served as guest editor for this report.

Reprint requests: Muhamed Saric, MD, Adult Echocardiography Laboratory, 550 First Avenue, New York, NY 10016 (E-mail: *Muhamed.Saric@nyulangone.org*).

Received Sept 15, 2022. Accepted for publication Sept 19, 2022.

0894-7317/$36.00

https://doi.org/10.1016/j.echo.2022.09.013

Abbreviations
2D = Two-dimensional
3D = Three-dimensional
ECG = Electrocardiogram
LAA = Left atrial appendage
ME = Midepigastric
MV = Mitral valve
TEE = Transesophageal echocardiography

morphology of the heart and positioning of the heart in the chest, as well as its relationship to the esophagus, making this task fraught with assumption and error.[1,2,5,8]

The early 2000s saw the ushering in of the 3D era of TEE with the development of fully sampled matrix-array transducers.[5] Many of the challenges associated with anatomic positioning are overcome given the volumetric nature of a 3D image. In contrast to 2D TEE, where views are based on their specific multiplane angle, 3D TEE images are described by their orthogonal ultrasound plane (sagittal, coronal, transverse) as well as viewing perspective.[5] Using this technology, structures like the MV or LAA are reconstructed to allow for a full evaluation of their truly 3D morphology. Difficulty remains, however, in correlating these 3D views with those from standard 2D imaging. Where exactly in the 3D TEE view of a structure is a particular 2D TEE cut, and what exactly is the 2D view showing?

High-quality 3D TEE is also based on striking the perfect balance between temporal and spatial resolution. The use of an electrocardiogram- (ECG-) gated 3D TEE mode, as opposed to single-beat real-time imaging, maximizes resolution in both domains, which is especially crucial in wide-angle acquisitions of structures like the MV or LAA.[2] In this mode, multiple narrow volumes of information are acquired over several heartbeats and then stitched (or spliced) together to construct a larger volumetric data set.[5] Inherent in this modality is the potential risk of artifacts that are created by irregular heart rhythms or unintentional patient motion (i.e., during respiration). Thus, mild conscious sedation enhances one's ability to observe and capture these artifacts. Deemed "stitching artifacts," they make the image seem divided by strong demarcations and appear at the interface of subvolumes that are incorrectly juxtaposed.[2] Stitching artifacts are most prominent when sector slices are acquired in a sweeping motion perpendicular to the reference image being viewed.[5] This pitfall is well described in the literature, and society guidelines present different strategies for mitigating the risk for stitching artifacts, including minimizing the number of pyramidal volumes needed to generate the image of interest and avoiding imaging planes where artifacts are visible.[2,5] Nevertheless, stitching artifacts are considered a "necessary evil" in the current era of 3D TEE, and cardiac imagers have become accustomed to working around the artifacts to achieve high-resolution reconstructions.

INNOVATION

From our practice using modern TEE probes that are capable of both 2D and 3D imaging, we have discovered that the location of stitching artifacts can not only be predicted but can also be controlled using multiplane angle rotation. Protocols for 3D TEE examination specify multiplane rotation angles only when using 2D views as part of the process for acquiring optimal 3D reconstructions. Once in the 3D mode, the previously set 2D multiplane angle is generally considered irrelevant and therefore neglected. However, we observed that during 2-beat ECG-gated 3D TEE

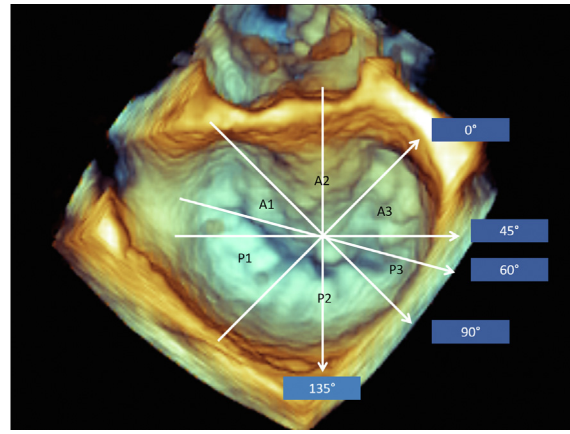

Figure 1 Three-dimensional TEE zoom imaging in the so-called surgeon's view of the MV with the idealized multiplane angles of rotation superimposed. The MV leaflets are labeled per the Carpentier *et al.* classification system.[8]

modes stitching artifacts always occur parallel to the angle of the probe's most recent 2D multiplane rotation.

This finding has 2 key applications: (1) cardiac imagers can intentionally change the multiplane angle of rotation during ECG-gated 3D echocardiography to move stitching artifacts away from structures of interest; and (2) stitching artifacts can be used as a tool for determining the exact anatomic orientation of cardiac structures, thereby allowing for the capture of optimal 2D and 3D TEE images.

Mitral Valve Imaging

Normal MV. The idealized MV is subdivided into 6 leaflet scallops per Carpentier *et al.*'s classification, 3 anterior and 3 posterior.[8] The 6 different 2D views presented in the original TEE guidelines to fully characterize the MV assume that the 2D multiplane angle is the only changing variable, when, in reality, the cut plane is also determined by the TEE probe's depth and rotation as well as the patient's intrinsic anatomy—both in general and in the relationship between the esophagus and the cardiac structure being imaged.[8] Nevertheless, schematics of an *idealized* MV in the so-called surgeon's view superimpose a Cartesian coordinate system where the perfect horizontal axis is at exactly 45°, cutting through exactly P_3-$A_3A_2A_1$-P_1 (Figure 1).[1] This axis serves as the basis for the suggested TEE multiplane angles of rotation specified in the guidelines.[1]

A 2-beat 3D acquisition of the MV in the so-called surgeon's view with the multiplane 2D imaging angles set to 0° demonstrates a clearly visible stitching artifact (Figure 2A). Note the angle of the stitching artifact as it transects the MV; it is at 0°, the same angle that the multiplane is set to on the probe. Rotating the set multiplane angle 45° results in a correlating rotation of the stitching artifact within the 3D image (Figure 2B). This relationship between the set multiplane angle and location of the stitching artifact is preserved when rotating to 70° (Figure 2C) and then 135° (Figure 2D). The 4 still views shown in Figure 2 are exhibited in the composite Video 1.

These findings provide deep insight into the image processing underlying multibeat ECG-gated 3D echocardiography: pyramidal subvolumes are always captured and then stitched together at the angle parallel to the multiplane rotation of the probe. They also demonstrate the real location of a specific cutting plane within a particular patient.

HIGHLIGHTS

- 3D TEE stitching artifacts occur parallel to the probe's 2D multiplane rotation angle.
- Cardiac imagers can move stitching artifacts to assess structures of interest.
- Stitching artifact manipulation can help with image orientation and optimization.

Knowledge of the real location of specific cutting planes then assists in determining the true structures being visualized as well as the vantage point of cuts when in a 2D mode. Vantage points are always perpendicular to cutting planes. While sophisticated, high-end software packages allow for a similar display of the relationship between cut location and vantage point, the software still depends on the assumption that the anatomy being visualized matches the schematics of the *idealized* MV (Figure 1). By taking advantage of the stitching artifact, cardiac imagers can identify a "true north" within each patient and then optimize accordingly.

Mitral Valve Prolapse. Understanding the interplay between probe multiplane angle rotation and stitching artifact location has an inherent utility when attempting to evaluate MV pathology. One example is in a patient with moderate mitral regurgitation and prolapse of P2. When the multiplane angle is set to 0°, the resulting stitching artifact nearly perfectly transects the P2 MV leaflet scallop (Figure 3A). When rotating to 65°, the P2 scallop remains partially obstructed by the stitching artifact (Figure 3B). To improve 3D TEE reconstructions to better reveal the finding of P2 prolapse, probe settings must be adjusted to a rotation differing from the standard angles. Furthermore, knowing the 3D location of 65° in relation to the rest of the MV allows for optimal visualization during 2D imaging. As opposed to toggling the multiplane rotation based on the guidelines-recommended transducer angle for the 2D midesophageal long-axis view of 120° to 140° and then making slight adjustments, based on the stitching artifact found during 3D TEE, directly rotating to 130° will immediately bring P2 into view (Figure 3C).[1]

Left Atrial Appendage Imaging

The use of stitching artifact as a tool for image optimization extends beyond the MV as the same principle applies for all 2-beat ECG-gated 3D TEE studies. Visualizing the LAA by 2D TEE is often challenging given the diversity in LAA shape, number of lobes, and lobe positioning.[2] Careful evaluation of the LAA and its associated landing zone is crucial for percutaneous occlusion device placement, and guidelines recommend 4 common angles in 2D TEE for a complete assessment of the LAA: 0°, 45°, 90°, and 135°.[2,9] Figure 4A demonstrates a 3D en face zoom view of the LAA. In this image, the multiplane is rotated to 45°, and a stitching artifact is visible that transects the LAA in addition to the nearby left upper pulmonary vein. By rotating the multiplane to 135° as shown in Figure 4B, the stitching artifact moves and now transects the pulmonary artery. Figure 4A also demonstrates a 2D TEE view at 45° that confirms the proximity of the LAA to the left upper pulmonary vein. A 2D view captured at a rotation of 135° displays the LAA as adjacent to the pulmonary artery (Figure 4B). Taking command of the location of the stitching artifact allows for better characterization of cardiac

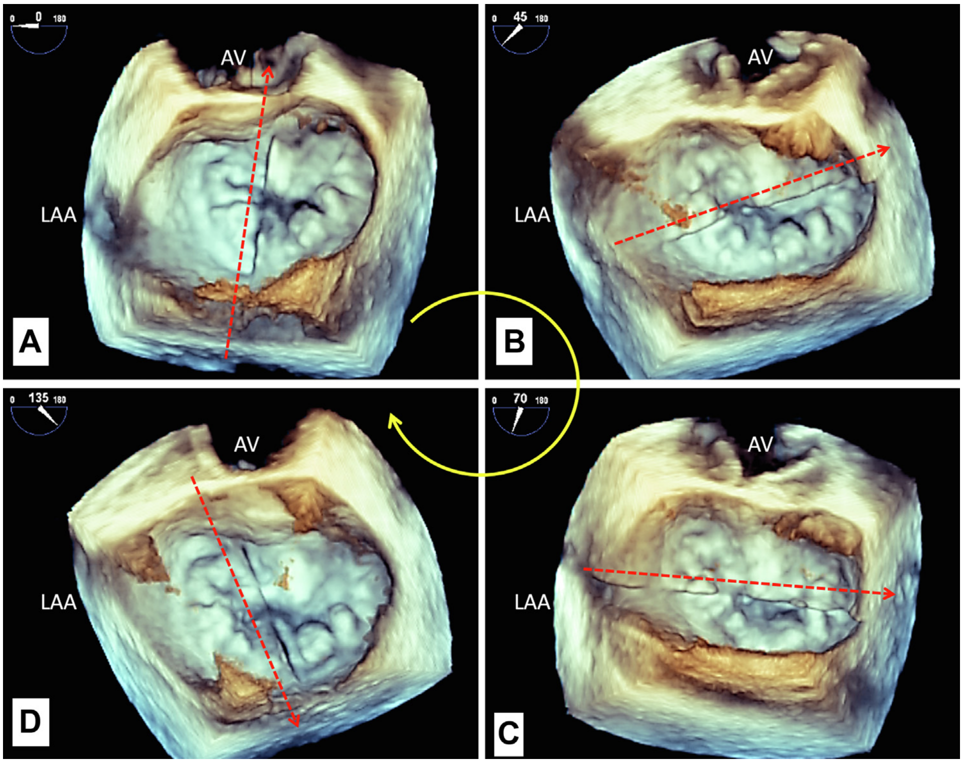

Figure 2 Two-beat 3D TEE zoom images in the so-called surgeon's view of a normal MV. Each 3D TEE panel shows a stitching artifact matching the probe's 2D TEE angle of rotation. **(A)** 0°; **(B)** 45°; **(C)** 70°; and **(D)** 135°. This figure corresponds to Video 1. *AV*, Aortic valve.

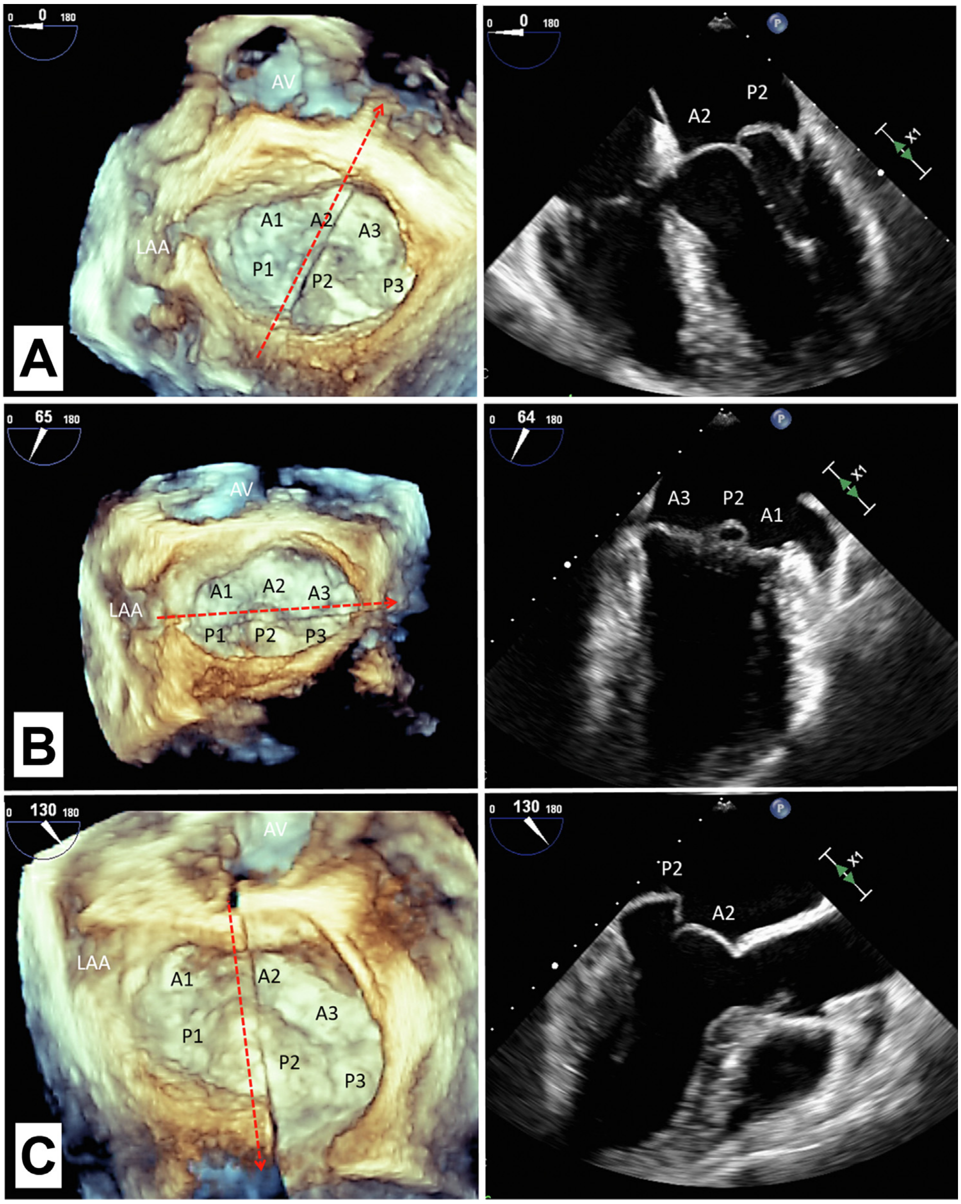

Figure 3 Two-beat 3D TEE zoom images in the so-called surgeon's view of a MV with prolapse of P2 scallop of the posterior leaflet. Each 3D TEE panel shows a stitching artifact corresponding to the probe's 2D TEE angle of rotation as well as the respective 2D TEE image as viewed from that angle. **(A)** 0°; **(B)** 65°; and **(C)** 130°. The MV leaflets are labeled per the Carpentier *et al.* classification system.[8] *AV*, Aortic valve.

structures like the LAA that are more variable in terms of anatomic positioning and morphology.

AREAS OF FUTURE STUDY

We purposefully used basic concepts in 3D TEE to describe the stitching artifact. However, the strategy can be applied for complex structural procedures, including optimizing 2D visualization of the grasp angle for mitral clip procedure, improving the guidance of LAA occlusion device deployment, and improving 2D imaging guidance in tricuspid edge-to-edge repair. Conceptually, the strategy is not limited to TEE, and the same phenomenon also occurs with 3D transthoracic echocardiography. These are some of the applications of this strategy that we plan to highlight in future publications.

CONCLUSION

Previously considered an annoying pitfall of ECG-gated 3D echocardiography, we hereby suggest an inherent utility of stitching artifacts. The primary objective of the stitching artifact strategy is to provide a very simple, cost-free method for easy correlation between 2D and 3D cuts in real time, as opposed to often costly postprocessing commercial software. While experienced echocardiographers are very familiar with identifying routine anatomy (i.e., the mitral scallops) in 2D and 3D imaging using current technologies, and we envision our

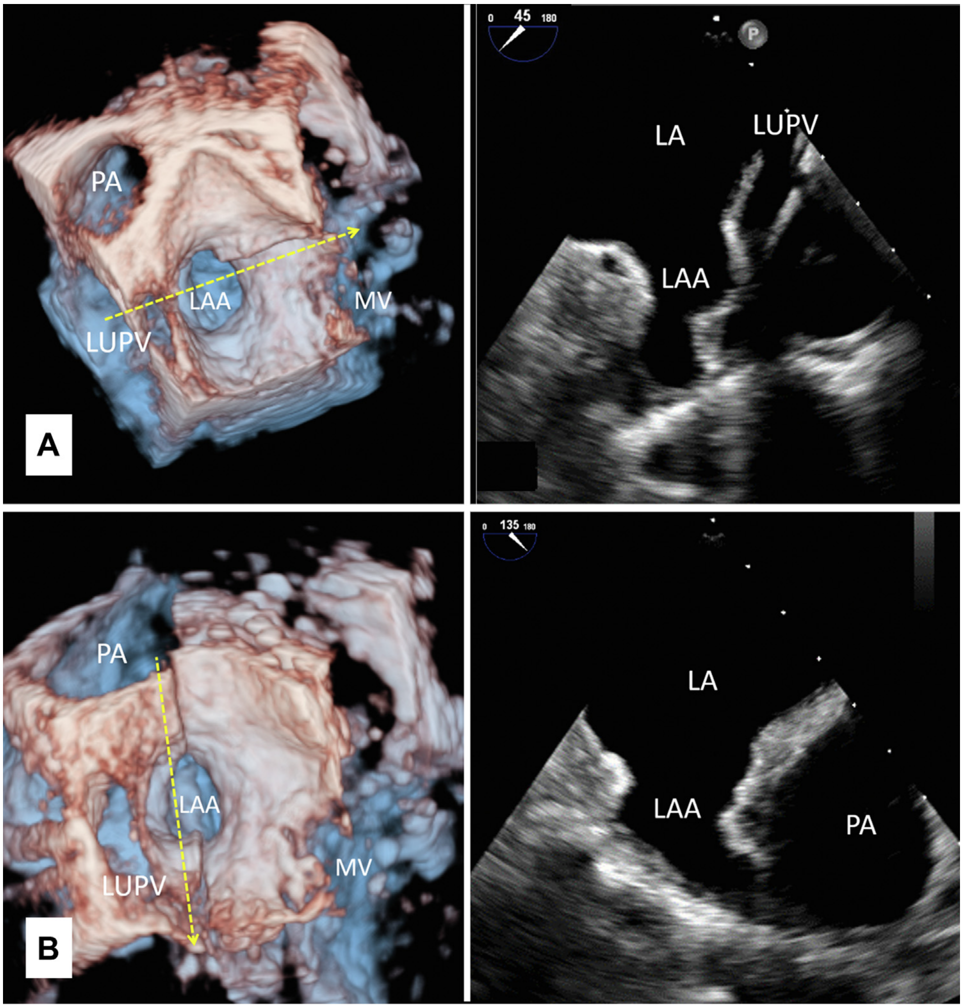

Figure 4 Two-beat 3D TEE zoom images of the LAA. Each 3D TEE panel shows a stitching artifact corresponding to the probe's set angle of rotation as well as the respective 2D TEE image as viewed from that angle. **(A)** 45°; **(B)** 135°. *LA*, Left atrium; *LUPV*, left upper pulmonary vein; *PA*, pulmonary artery.

observation to be of primary utility to trainees and/or less experienced TEE users, the strategy can serve as a tool on the proverbial tool belt, ready to be wielded when visualizing atypical structures or on legacy ultrasound machines. By taking command of their underlying mechanism of creation, cardiac imagers can control stitching artifacts' locations and use them as reference points for image optimization. Applications of this strategy include its use for intraprocedural guidance pictures during complex structural interventions. Stitching artifacts should be appreciated as a valuable instrument for navigating the various structures of the heart during 3D echocardiography.

SUPPLEMENTARY DATA

Supplementary data related to this article can be found at https://doi.org/10.1016/j.echo.2022.09.013.

REFERENCES

1. Hahn RT, Abraham T, Adams MS, Bruce CJ, Glas KE, Lang RM, et al. Guidelines for performing a comprehensive transesophageal echocardiographic examination: recommendations from the American Society of Echocardiography and the Society of Cardiovascular Anesthesiologists. J Am Soc Echocardiogr 2013;26:921-64.
2. Hahn RT, Saric M, Faletra FF, Garg R, Gillam LD, Horton K, et al. Recommended standards for the performance of transesophageal echocardiographic screening for structural heart intervention: from the American Society of Echocardiography. J Am Soc Echocardiogr 2022;35:1-76.
3. Side CD, Gosling RG. Non-surgical assessment of cardiac function. Nature 1971;232:335-6.
4. Corrigan FE 3rd, Gleason PT, Condado JF, Lisko JC, Chen JH, Kamioka N, et al. Imaging for predicting, detecting, and managing complications after transcatheter aortic valve replacement. JACC Cardiovasc Imaging 2019;12:904-20.
5. Lang RM, Badano LP, Tsang W, Adams DH, Agricola E, Buck T, et al. EAE/ASE recommendations for image acquisition and display using three-dimensional echocardiography. Eur Heart J Cardiovasc Imaging 2012;13:1-46.
6. Saric M, Perk G, Purgess JR, Kronzon I. Imaging atrial septal defects by real-time three-dimensional transesophageal echocardiography: step-by-step approach. J Am Soc Echocardiogr 2010;23:1128-35.
7. Tang GHL, Lerakis S, Kini A, Khan JM, Kovacic JC. 4-Dimensional transesophageal echocardiographic guidance during TAVR with BASILICA. JACC Cardiovasc Imaging 2020;13:1601-14.

8. Shanewise JS, Cheung AT, Aronson S, Stewart WJ, Weiss RL, Mark JB, 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;12:884-900.
9. Vainrib AF, Harb SC, Jaber W, Benenstein RJ, Aizer A, Chinitz LA, et al. Left atrial appendage occlusion/exclusion: procedural image guidance with transesophageal echocardiography. J Am Soc Echocardiogr 2018;31:454-74.