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Added Value of Interactive 3-D Stereo Vision Echocardiography in the Heart Valve Team: A Post Hoc Analysis for Optimal Decision Making in Patients With Mitral Valve Regurgitation

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Abstract

Objective: We assessed the added value of advanced echocardiography post hoc analysis for optimal decision-making in the Heart Valve Team (HVT) using an interactive, dynamic, live visualization system with true three-dimensional (3-D) stereo vision. **Methods:** HVT scrutinized the incremental value of 3 consecutive methods of presentation of full-volume echocardiographic data sets in terms of diagnosis and possibility of repair in 11 selected patients having mitral regurgitation (MR)(Table 1). The questionnaire investigated consecutively (a) standard two-dimensional (2-D) transesophageal echocardiography, (b) single-beat 3-D zoom of the surgical view of the mitral valve, and (c) advanced 3-D volumetric rendering technology (Personal Space Station, Vesalius 3D software, PS-Medtech, Netherlands). **Results:** In 4 of 11 reviews (36%), single-beat 3-D zoom had additional value over 2-D echocardiography in terms of mechanism/adjustments or adjustment of confirmation of diagnosis. Single-beat 3-D zoom had no additional value over 2-D echocardiography in terms of proposal/probability of repair. In 7 out of 11 (64%) reviews, true stereo 3-D visualization had additional value in terms of mechanism of pathology compared to 2-D and 3-D zoom and in 5 out of 11 (45%) reviews in confirmation of diagnosis. In 3 out of 11 (27%) reviews, true stereo 3-D visualization had additional value in terms of proposal of repair and in 4 of 11 (36%) in probability of repair over 2-D and 3-D zoom. **Conclusions:** Advanced easy-to-use true 3-D echocardiography limited differences in interpretation and strengthened the confidence in understanding the mechanisms and suitability for repair of mitral valve regurgitation, typically in more complex valve pathology.

Central Message

For use in diagnosis of complex mitral valve regurgitation in the heart valve team, advanced easy-to-use true 3D echocardiography presentation limited differences in interpretation and strengthened the confidence in understanding the mechanisms and reparability of mitral valve regurgitation.

Keywords

mitral valve, diagnosis, echocardiography, three dimensional

Introduction

Severe mitral valve pathology is recognized upon routine diagnostic workup, which basically consists of clinical presentation and echocardiographic findings.[1] Transthoracic echocardiography (TTE) and transesophageal echocardiography (TOE) have complementary roles in the diagnosis and evaluation of the severity of valve pathology.[2] Performing an initial TTE is

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usually recommended as a first line of investigation. TOE is recommended as the preferred diagnostic tool when TTE is not conclusive for determining severity and/or mechanism. In patients with complex valve disease, routine evaluation using two-dimensional (2-D) echocardiography may be unsatisfactory since the underlying pathology may not be adequately recognized, thus hampering appropriate decision-making. Three-dimensional (3-D) visualization has the potential to display the valve anatomy and its (dys)function more accurately, especially in surgical view, and is therefore helpful for cross talk in the Heart Valve Team (HVT) between cardiologists and cardiac surgeons. Emerging imaging modalities, such as stereo vision 3-D echocardiography, offer a novel way of readily visualizing the extent of valvular disease and the relationship of pathology to adjacent cardiac structures.[3] Displayed on a flat screen, "3-D" video footage and still frames have been incorporated in clinical decision-making in the past few years, especially in mitral valve repair. Although it does not have true stereo vision, this modality offers enhanced insight into valve pathology but omits specific augmented reality unveiling the true relation between anatomic structures.

The combination of echocardiographic features seen in true 3-D, like the mechanism of valve pathology, may help to decide if the valve is suitable for repair before surgical intervention.[4] With the advent of advanced off-line analysis systems for standard obtained 3-D data sets, important additional information can be made available for decision-making in HVT. Such HVTs consist of experts of cardiology and cardiac surgery and other specialists, and they are mandated by the European Society of Cardiology (ESC) guidelines on valvular heart disease.[1] Meetings on a regular basis are required in every heart valve center. Cardiac surgeons are used to viewing the mitral valve pathology in the operational field, the so-called surgical view; 3-D analysis facilitates the imaging of the valve as seen by them in the operation theater.

Working Hypothesis

Advanced analysis of 3-D TOE echo data sets can contribute to consensus in the HVT, to a more precise diagnosis and decision-making on valvular disease with the opportunity to improve outcomes. Rendering of anatomic details gives the individual panel members straightforward immediate information for experiencing a 3-D image without differences in interpretation of those images. It facilitates exact imagination of mitral valve pathology. Decision-making in the HVT meeting may be facilitated by incorporating in-depth advanced analysis of 3-D TOE/TTE of complex valvular disease and provides additional information about repairability of the mitral valve.

Methods

We retrospectively reviewed 11 selected patient cases with mitral valve pathology, which included organic and functional mitral valve regurgitation, requiring mitral valve repair (Table 1). Patients with images that were of insufficient quality to make any judgments on 3-D visualization were excluded from the study. This consisted of inappropriate technique of recording of full-volume data sets including artifacts caused, that is, by breathing, arrhythmia, not proper gain settings, poor quality of ECG, or wrong ECG gating. Patients were recruited from referrals of affiliated hospitals, from the outpatient clinic, and referring cardiologists. All patients underwent routine diagnostic workup (TTE, TOE/3-D TOE according to guidelines[1], and coronary angiography, if indicated) to assess underlying mechanism of the mitral valve disease, pathology of other

Table 1. Demographics of 11 Selected Patients with Mitral Valve Regurgitation.

Pt no.	Gender	Age	BMI kg/m^2	Rhythm	PAF	Chronic AF	CAG findings	DM	HA
1	Male	72	25.5	SR	Yes		No	No	No
2	Male	66	30.5	SR	No		CAD/MI	No	No
3	Male	70	26.9	SR	No		CAD/MI	No	No
4	Male	58	29.1	SR	No		No	No	No
5	Female	18	21.9	SR	No		ALCAPA/MI	No	No
6	Male	80	24.1	SR	No		No	No	No
7	Male	69	21.6	SR	Yes		No	No	No
9	Male	63	24.7	SR	Yes		No	No	No
10	Female	71		SR, pacemaker VAT	Yes		No	No	No
12	Male	64	21.1	AF	No	Yes	No	No	No
13	Female	73	31.7	AF	No	Yes	No	No	No
	Female: 3 (27%), male: 8 (73%)	**18-80, mean 64**		**SR 9 (82%), CAF 2 (18%)**	**6 (36%)**	**2 (18%)**	**3 (27%)**	**0**	**0**

AF, atrial fibrillation; ALCAPA, anomalous left coronary artery from the pulmonary artery; BMI, body mass index; CAD, coronary artery disease; CAF, chronic atrial fibrillation; CAG, coronary angiography; DM, diabetes mellitus; MI, myocardial infarction; HA, arterial hypertension; PAF, paroxysmal atrial fibrillation; SR, sinus rhythm.

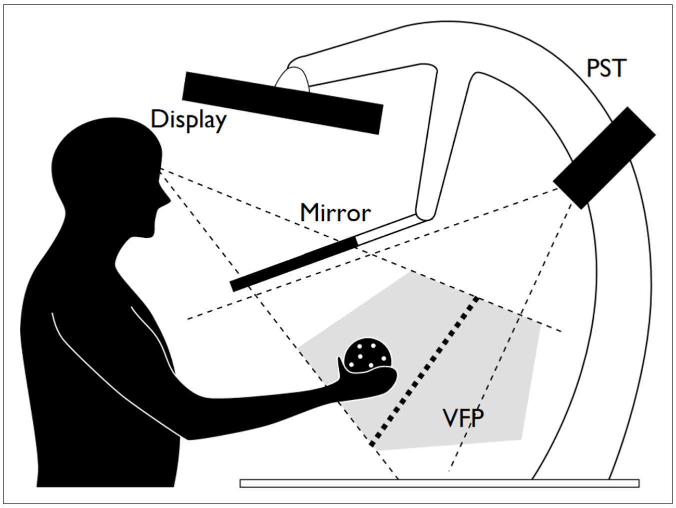

Fig. 1. Schematic representation of PS-Medtech C-Station.[5] The operator behind the mirror and the audience viewing a remote screen wear passive stereo glasses. The system that is equipped with the Vesalius3D software uses the Digital Imaging and Communications in Medicine (DICOM) files stored on the picture archiving and communication system (PACS). This data is transferred to Vesalius3D using a data library. The operator can select the DICOM images he/she wants to study by selecting this file from the library. After selection, the data are presented in Vesalius3D DICOM viewer for analysis. Analysis can be done using the three-dimensional (3-D) interaction devices provided with the Personal Space Station (PSS) or by using the traditional mouse and keyboard. PST, Personal Space Tracker (3-D interaction device); VFP, Virtual Focus Plane.

valves, and concomitant coronary artery disease (CAD). All TOE 3-D scans were performed with an iE33 Philips Ultrasound system (Philips, Best, the Netherlands) in UMC Utrecht or affiliated centers. Also, preoperative echocardiography was performed in the operating room under general anesthesia. To secure acquisition of full-volume data sets required for proper 3-D analysis in PS-Medtech system, the following TOE recording requirements and settings for mitral valve investigation were adopted: (a) Acquisition: 4 to 6 consecutive cardiac cycles; gain: set to slightly higher gain setting; frame rate 20–40/s. (b) Minimization of artifacts, such as stitching artifacts and dropouts, by demanding short breath hold or by stopping respirator in the operating room, and prevention of arrhythmia through avoiding iatrogenic causes of arrhythmia (e.g., the use of electric dissecting knife and patient motion when acquiring images).

Only cases with predominantly severe mitral valve insufficiency were included. Patients were considered to be suitable either for mitral valve plasty or repair or for the placement of a MitraClip (Abbott, USA). After standard workup, preliminary decisions were made in the usual way in the HVT. Subsequently, for this study, these patients were presented off-line in the separately appointed HVT panel. Using a 3-D workstation, 3-D reconstruction in preparation of the HVT meeting was made (Figs. 1 and 2; Personal Space Station [PSS], C-Station, and Vesalius3D software [PS-Medtech, Amsterdam, the Netherlands]).[5]

Full-volume echocardiographic data were used to acquire a 3-D reconstruction model. It takes less than 1 min to load the full-volume data set into the workstation when the station is

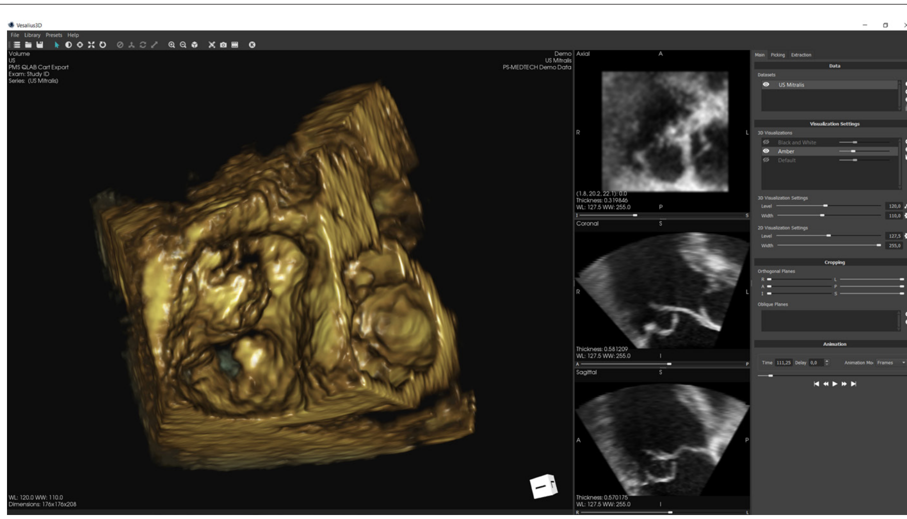

Fig. 2. Selection of screens seen by the operator to control setting for cropping of selected images. Mitral valve on the left with posterior leaflet prolapse. Loading of the data set takes less than 20 s. The construction of the stereo image is a stepwise process using the dices. After a short learning curve of a couple of cases (about 10), relevant crops are visualized while working live in the team setting. In addition, preanalysis measurements (dimensions) and specific cropped views can be prepared in advance of the meeting in less than 15 min. For further information, refer to the PS-Medtech website.[5]

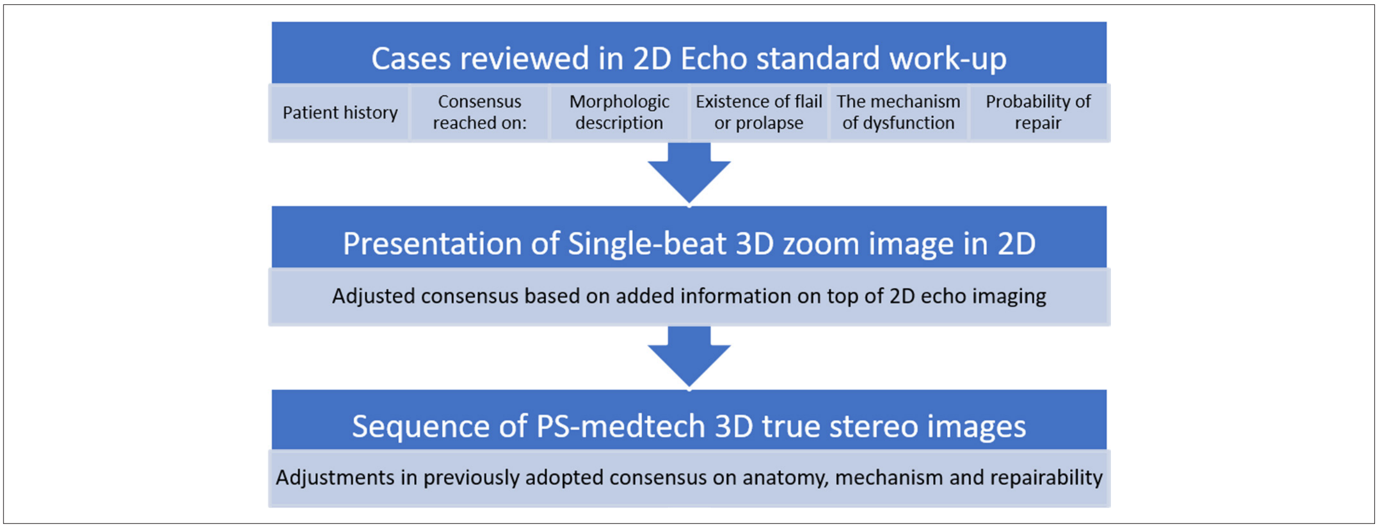

Fig. 3. The Heart Valve Team adjusted their consensus opinion when consecutively subjected to regular two-dimensional (2-D) echocardiography images, three-dimensional (3-D) single-beat zoom images in 2-D, and a standard sequence of 3-D true stereoscopic images using goggles (PS-Medtech).

connected to the institutional data bank. Production of the 3-D reconstruction takes about 30 s with predefined presets. The presentation of the specific views for the HVT takes altogether about 5 min. Any additional measurements (e.g., annulus circumference, height, as well as anteroposterior and commissural diameters to assess size and shape of the annulus) made in the 3-D environment required at least 15 min more for each patient and were made in advance. All 11 data sets of patient cases were analyzed prior to the exposure to the HVT panel by the study coordinator (IKP) for suitability, quality of the rendered 3D images, dropouts, and stitching artifacts.

The HVT Panel Questionnaire

The questionnaire was designed to record the description of the panel members in the consecutive test episodes (Fig. 3: 2-D echo, 3-D zoom, and PS stereo vision) on (a) morphologic description (e.g., estimation of annulus dilatation, localization of regurgitation in scallops A1-A3 and P1-P3, the existence of flail or prolapse, chordae rupture, and calcification, (b) the mechanism of dysfunction, and (c) probability of repair, completed with proposed surgical or interventional valvuloplasty technique with subjective scores sure, probable, and uncertain (see flow charts in supplemental material, total of 11 patients; forms numbered 1, 2, 3, 4, 5, 6, 7, 9, 10,12, and 13).[6]

The end points of the study were

- What are the percent (%) changes in opinions related to visualization of valve anatomy, mechanisms of regurgitation, diagnosis, and repair options when exposing HVT consecutively to 11 cases of MR using (a) classical workup with 2-D echocardiography, (b) single-beat 3-D zoom in 2-D, and (c) true 3-D stereo visualization? Does 3-D stereoscopic presentation have an additional value for presented MR cases? What is the time needed to prepare 3-D true stereoscopic analysis using PS-Medtech system? (Fig. 4)
- What is the ease of use?

The appointed HVT panel consisted of at least one cardiac surgeon (WS, GvA, and/or RM) and at least two cardiologists

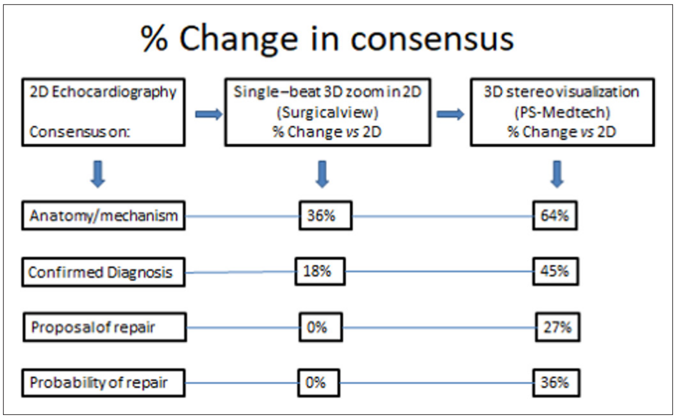

Fig. 4. Heart Valve Team reviewed post hoc 11 patients with mitral valve regurgitation using true stereoscopic visualization. Depicted are percent (%) changes in opinions related to visualization of valve anatomy, mechanisms of regurgitation, diagnosis, and repair options, when compared, in consecutive steps: single-beat 3-D zoom image in two-dimensional (2-D) with classical 2-D echocardiography and true three-dimensional (3-D) stereo visualization (PS-Medtech system) with 2-D echocardiography. Added value of 3-D visualization was mostly present in more complex mitral valve pathology (see further results and supplemental material for details).

(SC, AT, MJC, TvdS, and/or FM). The study coordinator (IKP) managed the stepwise process of review and operated the PSS stereo system. All panel members wore stereo goggles. Panel members were unaware of the diagnosis or the final operative strategy. First, the patient history was presented, followed by judgements/opinions using standard 2-D echocardiographic presentations. Second, adjusted consensus based on added information over 2-D echo imaging was discussed. Finally, in true stereo vision, the PSS system displayed the mitral valve pathology in the following steps: (a) surgical view including premeasured size of annulus septal–lateral dimension and commissure-to-commissure dimension including 3-D circumference of the annulus, (b) ventricular view, and (c) cropped cross section having the anterior leaflet on the left side, cutting away the image from A1-P1 toward A3-P3. Additional information on mechanism and severity of the valvular pathology was made available. The decision to treat, based on standard diagnosis, was compared to a hypothetical decision to treat, made on the basis of PSS analysis. The number of changes in opinions/judgements were recorded and depicted as percent change compared to classical 2-D workup (Fig. 3).

Statistical Analysis

In this descriptive study, the number of changes in opinions/judgements were recorded and depicted as percent change compared to classical 2-D workup (Fig. 4) without making further statistical comparison owing to limited number of observations.

Results

The available full-volume echocardiographic recordings were of sufficient quality to make judgments. In 4 of 11 reviews (36 %), single-beat 3-D zoom had additional value over 2-D echocardiography in terms of mechanism/confirmation of diagnosis. Single-beat 3-D zoom had no additional value over 2-D echocardiography in terms of proposal/probability of repair. In 7 out of 11 (64%) reviews, PS-Medtech true stereo 3-D visualization had additional value in terms of mechanism of pathology compared to 2-D and 3-D zoom, and in 5 out of 11 (45%) reviews, in terms of confirmation of diagnosis. When compared to 2-D and 3-D zoom, in 3 out of 11 (27%) reviews, true stereo 3-D visualization had additional value in terms of proposal of repair and in 4 of 11 (36%), in terms of probability of repair. The added information of true stereoscopic 3-D presentation consisted of more accurately identifying localization and extension of prolapsing or billowing segments. In selected case # 2 (see online supplemental video 1), anatomy of the deep indentation in segment P2-P3 was not revealed in 2-D by any team member. In another case (#9, see appendix form), we found in 2-D that prolapse of A1-A2-A3 was present with marked thickening of the leaflet, then in 3-D zoom mainly A2 was prolapsing, but in contrast in the true stereo 3-D with goggles it appeared that A3 was not prolapsing. In 2-D and true 3-D, a restricted posterior leaflet was observed. Although the team advised "possible repair," eventually this patient was operated in another university heart center where the valve was considered beyond repair because of extremely thickened anterior leaflet and retracted posterior leaflet.

Three-dimensional stereo visualization displayed anatomy and exact localization of prolapsing/billowing segments, deep indentation, restricted opening of the whole posterior mitral valve leaflet, tethering of anterior mitral valve leaflet, perforated valve leaflet, exact measurements, and shape of the annulus (see supplemental material for individual assets of PS-Medtech related to their patient history). The final diagnosis after changes made in the process of review can only be confirmed at the time of surgery. In all cases except for one (case #9), the intraoperative findings concurred with the changes made during the process of conversion from 2-D into true 3-D. In that specific exception, the valve proved to be beyond repair (too thickened anterior leaflet and the valve was replaced by a prosthesis). In one patient (case # 6), surgical confirmation was not possible because the patient died before the scheduled time of surgery.

Discussion

True stereoscopic presentation of advanced analyses of 3-D TOE echocardiographic data sets to a post hoc HVT panel did have a positive impact on the diagnosis and decision-making in complex mitral valvular disease in patients with good 3-D TOE data, with the opportunity to improve outcomes (not investigated in this study). The stereo images also provided additional information about repairability of the mitral valve, which was confirmed, with one exception, in surgical inspection.

Summarized, true 3-D stereo imaging advantages based on our experience are

1. Clear, unambiguous sight on valve pathology, limiting interpretation differences within the HVT
2. More confidence within HVT about mechanism and repair options
3. Time to prepare 3-D images by cardiologist was acceptable (5–15 min)
4. Ease of use by trained cardiologist
5. Appealing for HVT, residents, and students
6. Potentially improving treatment planning (indication for surgery and preoperative planning)

Display of anatomic details provided straightforward, unequivocal information for experiencing a 3-D image, without differences in interpretation of those images between panel members. In contrast, the correct interpretation of 2-D echocardiographic images cropped in different planes requires trained capability of the individual HVT members to translate images into a 3-D perception in their minds and there is no way to check whether these 3-D images are comparable or, better, identical. The recognition of common typical P2 prolapse without further pathology though not helped by using true stereo vision is typically clear in the 2-D and 3-D zoom image. In 36% of observations compared to 2-D, single-beat 3-D zoom had additional value over 2-D echocardiography in terms of mechanism/confirmation of diagnosis. However, since 3-D zoom is an image rendered in 3D but still seen in 2D, it fails to provide the accurate spatial relations between anatomic structures. In contrast, 3-D stereo vision gave more complete insight into the anatomy of the valve rendering the underlying pathology like chordae rupture and exact localization of prolapsing/billowing segments as well as deep indentation, which was missed (or not visualized at all) in the standard 2-D approach. This was typically true for more complex mitral valve disease leading to regurgitation. In still frames of rendered 3-D images, anatomic landmarks of the annulus were easier identified, which facilitated putting marker points for measurements. Measurements of the annulus in anteroposterior, mediolateral diameter were thought to be more accurate when measured from surgical view compared to 2-D echocardiographic images.[7,8] One could easily determine the exact shape of the annulus in 3-D environment (when removing volume rendering in the data set with a simple click), which unveils the change from typical saddle shape into a flattened, enlarged, and round annulus. The loss of the saddle shape of the annulus underlined the extent of the (structural) mitral valve disease. The 3-D workup of the patients to be discussed in the HVT could be restricted to cases where mitral valve pathology is thought to be complex at first glance, when viewed by the referring cardiologist, and where classical 2-D echocardiography did not immediately unveil the anatomy and mechanism of regurgitation. In the (academic) teaching environment, true 3-D stereo vision will help medical students, residents, and others not having in-depth familiarity with 2-D echocardiographic planes, to imagine the 3-D aspects of the regurgitant mitral valve.

New techniques utilizing computed tomography (CT) and magnetic resonance imaging (MRI),[9–13] though very promising, are still not widely accessible and are not part of the everyday practice. The PS-Medtech system turned out to be easily operated by a trained cardiologist or cardiac surgeon.[6] The presentations and simple measurements like A-P, M-L distance and leaflet length were prepared in about 5–7 min. PS-Medtech system lacks the possibility of exposing 3-D stereo vision with proper color Doppler. The most important aspect is recording of good-quality full-volume data sets, without having incorporated significant artifacts, as the system relies on all information encrypted in 3-D echocardiographic recordings. In our observations, however, occasionally presented artifacts did not always hamper making the right diagnosis and proposition of repair. The existence of a perforation suggested by a serious dropout in a leaflet could be excluded by the observation of absent regurgitant jet in 2-D echocardiography across the leaflet. The investigator (IKP) rejected some cases intended to be presented to the HVT because of the poor quality of the recordings containing too many artifacts.

Limitations

Although mimicking clinical practice, inconsistency and variability in the study may have been introduced by availability of limited number of panel members, which made estimation of intra- and/or interobserver impossible. The system does not provide 3-D color Doppler data. The limited number of observations prevented making of statistical comparisons.

Conclusions

For the HVT, advanced 3-D echocardiographic easy-to-use stereoscopic analysis had additional value over 2-D echocardiography in the majority of reviewed cases of mitral valve regurgitation, which was best demonstrated in more complex valve pathology. The technology limited differences in interpretation and strengthened the confidence in understanding the mechanisms and repairability of mitral valve regurgitation.

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Declaration of Conflicting Interests

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Supplemental Material

Supplemental material for this article is available online.

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