Transthoracic real-time three-dimensional echocardiography offers additional value in the assessment of mitral valve morphology and area following mitral valve repair

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Aims The accurate postoperative assessment of mitral valve repair is important not only to document operative outcome, but also to confirm the functional morphology of the repaired valve. Methods and results We assessed 25 consecutive patients following mitral valve repair with transthoracic real-time 3-dimensional echocardiography (RT3DE) and 2-dimensional echocardiography (2DE). We compared the adequacy of the visualization of the mitral valve Carpentier segments, the site of the repair, and the accuracy of planimetry by RT3DE and 2DE in estimating the postoperative mitral valve area (MVA), compared to the Doppler-derived pressure half-time (PHT) value. Inter-observer variability and feasibility were also assessed for RT3DE. Adequate visualization of the mitral valve segments was more frequently obtained by 3DE imaging (163/170 by 3DE vs. 121/170 by 2DE, \( P < 0.001 \)). In particular, the mitral valve commissures were more clearly identified with 3DE. 3DE also was significantly better at correctly identifying the site of the repaired segment (26/30 by 3DE vs. 19/30 by 2DE, \( P = 0.05 \)). The difference in MVA (mean difference ± SD) determined by 3DE planimetry, when compared to PHT was \(-0.21 ± 0.46 \text{cm}^2\) and \(-0.44 ± 0.95 \text{cm}^2\) for 2DE (\( P = 0.014 \)). Planimetry by 3DE more closely correlated with the MVA calculated by PHT than 2DE planimetry (\( r = 0.89 \) for 3DE vs. \( r = 0.6 \) for 2DE). Imaging with RT3DE was both feasible, with a mean acquisition time of 15.82 ± 3.9 min, and reproducible, with good inter-observer variability for segment scoring with 3DE (\( k = 0.79 \)) and mean inter-observer difference in assessing MVA by 3DE planimetry of 0.18 ± 0.12 cm² (\( P = \text{NS} \)).

Conclusion This study suggests that RT3DE offers additional morphological postoperative data of repaired mitral valves, and increases the accuracy of MVA estimation by planimetry. It is both feasible in a busy echocardiography department and reproducible.

Introduction Accurate postoperative assessment of mitral valve repairs is essential to document operative success and also to confirm the functional morphology of the repaired valve. Advancing surgical repair techniques require detailed morphological information both preoperatively, to plan, and postoperatively, to audit, surgical outcome of mitral valve repair.¹ Conventional 2-dimensional echocardiography (2DE) can give some insight into the complex mitral valve anatomy preoperatively,²–⁴ but requires experience to integrate the 2D planes into a 3D structure. Imaging the mitral valve non-invasively is challenging because it has a complex 3D anatomy comprising valvular leaflets, commissures, annulus and subvalvar chordae and papillary muscles. In addition, area estimation by 2DE planimetry is highly dependent on examination technique.⁵

Three-dimensional echocardiography (3DE) has been shown to be superior to 2DE in assessing the mitral valve prior to repair⁶ and the use of real-time 3-dimensional echocardiography (RT3DE) is a useful additional tool in evaluating mitral valve disease.⁷,⁸ Assessing the mitral valve area (MVA) by 3DE enables the identification of the smallest orifice area

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by cropping down through the mitral valve apparatus to the level of the leaflet tips, and has been shown to be more accurate and reproducible than 2DE in the preoperative assessment of pathological valves.

In this study, we undertook a prospective comparison of transthoracic RT3DE and 2DE assessment of mitral valves following mitral valve repair at 3 months into the postoperative period. The two major attributes compared were: (a) the adequacy of the recognition of the mitral valve segments and the site of the repair compared to the operative gold-standard and (b) the accuracy of the estimation of the postoperative MVA measured by planimetry by each modality, compared to the Doppler-derived pressure halftime (PHT) value. The study was designed to confirm whether RT3DE offered additional morphological data in the postoperative assessment of repaired valves.

Methods

Study patients

We studied 25 consecutive patients (16 men and nine women, mean age 61 years) who had undergone mitral valve repair attending the surgical outpatient clinic for their three-month follow-up. No patients were excluded from the study. Twenty-two of the 25 patients were in sinus rhythm, two had atrial fibrillation and one had atrial flutter. All patients were in New York Heart Association (NYHA) functional class I. All patients had had a severe mitral regurgitation preoperatively due to either prolapse (16 patients) or flail (nine patients) of one or more mitral valve leaflet segments. All patients underwent surgical repair by a ‘French seam’ technique, whereby excess valvular tissue is plicated onto the ventricular side of the valve to form a ridge. In total, 30 mitral segments were repaired, with the majority being of segment P2 (21/30). Twenty-two mitral annuloplasty rings were inserted as part of the repair procedure. Researchers were blinded to the operative details, which were retrospectively analysed from the surgical notes after the patients had had their follow-up imaging.

Three-dimensional echocardiography

Patients were imaged in the left lateral position with breath held in mid-expiration, from parasternal and apical positions using an X3-1 matrix-array transducer attached to the iE33 echocardiography system (Phillips Medical Systems, Bothell, USA). Real-time, three-dimensional, full volume datasets generating a $60^\circ \times 60^\circ$ three-dimensional pyramid of voxels were acquired digitally over four cardiac cycles to assess valve morphology and from the apex over seven cardiac cycles for colour Doppler assessment, with the Nyquist limit set at 60 cm/s. To enhance the dataset quality gain, compress, and time-gain settings were optimized for each case. Multiple images were stored and the data then analysed off line using QLAB Ultrasound Quantification System software (Philips Medical Systems, Andover, USA) to inspect the mitral valve from left atrial and left ventricular perspectives using the any-plane crop function. This provided detailed en face, short axis views of the mitral valve and enabled the accurate identification of the level of the leaflet tips.

Mitral valve scoring

The visible mitral valve segments defined by the Carpentier classification were scored by a trained echocardiographer blinded to the details of the operation, using a modified scoring system devised by Salustri et al. Each of the six segments: lateral (A1), mid (A2), medial (A3) of the anterior leaflet and lateral (P1), mid (P2), medial (P3) of the posterior leaflet and two commissures: anterolateral and posteromedial (PMC) received a point, if they were clearly seen (Figure 1). The site of the repair, again defined by the Carpentier segment location, was also determined and later compared to the operative details.

Mitral valve area

The short axis en-face view with the smallest mitral area, cropped at the level of the mitral leaflet tips at maximal opening, was enlarged using the ‘zoom’ function for more accurate planimetric assessment of the MVA. The MVA was traced circumferentially three times and the mean area derived was recorded (Figure 2). A detailed description of the site and severity of residual regurgitation, mitral valve pathology, and leaflet mobility was also made.

Two-dimensional echocardiography

2DE and continuous-wave Doppler echocardiographic studies were performed using the Philips iE33 Echocardiography System attached to an X5-1 matrix array probe. Carpenter segment scoring from standard short axis and long axis views, identification of the site of repair, and description of residual regurgitation and leaflet mobility were again performed, by an echocardiographer blinded to the operative details and the result of the 3D dataset. Short axis views of the mitral valve were made from a parasternal transducer position and the smallest orifice area was identified by scanning from the left atrium in the direction of the left ventricular apex. The gain settings were adjusted until the lowest level was determined, at which the circumference was still visible and this was then traced by planimetry. A mean of three planimetry derived MVA measurements was recorded.

Doppler analysis

Continuous-wave Doppler of transmitral blood flow velocity was acquired from an apical transducer position and the MVA determined...
by the PHT method as previously described.14 A minimum of three beats in patients with sinus rhythm and five beats in patients with atrial arrhythmias were measured and the result averaged.

Feasibility
Average times for data optimization and acquisition, and subsequent off-line analysis of the 3DE dataset were recorded. The inter-observer variability was assessed for segmental score and mitral valve area calculation by planimetry by comparing the analysis of five 3DE datasets by two independent echocardiographers.

Statistical analysis
Frequency of visualization of the MV leaflet segments, commissures, and site of repair are expressed as percentages and a χ²-analysis is performed to assess significance. Mitral valve areas are expressed as mean (SEM) and paired Student’s t-test was used to analyse the data. Correlation and agreement between planimetry measured by 2DE and 3DE and PHT is expressed according to the method of Bland and Altman.15 Inter-observer variability of 3DE for segmental scoring is expressed by a Kappa value, and mean difference + SD for MVA. P, 0.05 is considered statistically significant. Statistical analyses were performed using PRISM 4 statistical and graph plotting software (GraphPad Software Inc.).

Results

3DE and 2DE mitral segment scoring
Adequate visualization of the mitral valve segments was more frequently obtained by 3DE imaging (163/170 by 3DE vs. 121/170 by 2DE, P < 0.001) (Table 1). In particular, the mitral valve commissures were more clearly identified with 3DE rather than 2DE, as were the adjacent peripheral valvular segments (Figure 3). 3DE also was significantly better at correctly identifying the site of the repaired segment (26/30 by 3DE vs. 19/30 by 2DE, P < 0.05).

Table 1 Comparison of 3DE and 2DE segment detection frequency
<table>
<thead>
<tr>
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<th>3D Echo</th>
<th>2D Echo</th>
<th>P-value (χ²)</th>
</tr>
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<tbody>
<tr>
<td>Segment recognition</td>
<td>163/170</td>
<td>121/170</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Commissure recognition</td>
<td>47/50</td>
<td>31/50</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Repaired segment identification</td>
<td>26/30</td>
<td>19/30</td>
<td>&lt; 0.05</td>
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Figure 2 Planimetry by 3DE of the repaired mitral valve viewed from the left ventricle, demonstrating the orifice area (A1).

Figure 3 Comparison of the ability of 3DE and 2DE to identify the Carpentier mitral valve segments.

3DE and 2DE vs. Doppler PHT method for MVA measurement
The difference in MVA (mean difference ± SD) determined by 3DE planimetry, when compared to PHT was −0.21 ± 0.46 cm² and −0.44 ± 0.95 cm² for 2DE (P = 0.014). Planimetry by 3DE more closely correlated with the MVA calculated by PHT than 2DE planimetry (r = 0.89, y = 1.01x + 0.18, SEE = 0.1 for 3DE vs. r = 0.6, y = 0/77x + 1.16, SEE = 0.21 for 2DE) (Figure 4).

Mitrail regurgitation and valve leaflet mobility
Residual regurgitation classified as trivial-mild on colour Doppler assessment, was identified in four patients following repair. RT3DE and 2DE graded the regurgitation similarly, but RT3DE was able to identify the site more accurately than 2DE (two eccentric regurgitant jets from repaired P2 coaptation edges, one regurgitant jet from the annular ring adjacent to the PMC commissure and a central regurgitant jet from A1 and P1). Both the techniques were equivalent at assessing leaflet mobility after repair, identifying the same three patients with restricted posterior mitral leaflet mobility after operation.

Feasibility
The acquisition time (mean ± SD) was 4.02 ± 1.68 min, and data analysis time was 15.82 ± 3.9 min. Inter-observer variability for segment scoring with 3DE showed good agreement, with a kappa value of 0.79. The mean inter-observer...
difference in assessing MVA by 3DE planimetry was $0.18 \pm 0.12$ compared to $0.35 \pm 0.15 \text{ cm}^2$ for 2DE.

**Discussion**

Transthoracic echocardiography plays an important role in the preoperative assessment of mitral valve pathology.\(^2\)–\(^4\) However, 2DE is limited in its ability to completely visualize the mitral valve, in particular, the commissures, and adjacent mitral segments are frequently not seen. These areas can be important sites of pathology. Comparisons between 2D transesophageal echocardiography (TEE) and 3DE have demonstrated that the latter has superior accuracy when assessing the morphology\(^6\)–\(^8\) and area\(^10\) of diseased mitral valves before operation. The accurate postoperative assessment of mitral valve repair is essential to document operative success and confirm the functional anatomy of the repaired valve. The accuracy, feasibility, and reproducibility of RT3DE compared to 2DE have not been studied previously in this patient group following mitral valve repair.

In this study, we have demonstrated additional value from imaging with transthoracic RT3DE over 2DE enabling a more complete morphological assessment of mitral valves following repair. Importantly, no patients were excluded from entry into this study, and the patients were unselected and therefore are representative of normal clinical practice. The adequate transthoracic assessment of mitral valve repairs with RT3DE, despite annuloplasty ring insertion and midline sternotomy is reassuring and indicates that in asymptomatic patients this imaging modality for postoperative mitral repair assessment may suffice, avoiding more invasive imaging with TEE.

We found that transthoracic RT3DE offered better segment resolution than 2DE in all, but the middle segments of both valve leaflets, where 2DE was equally good. In particular, RT 3DE was excellent in identifying the commissures. This is in agreement with previous reports of preoperative mitral valve assessment.\(^6\),\(^16\) However, RT3DE was better than 2DE in correctly identifying the site of repair, which was predominantly of segment P2. This suggests that visual resolution of the central segment P2 detail was still superior with RT3DE. Imaging the repair is important, as it can often be the site of residual pathology and regurgitation after repair.

The MVA measured by RT3DE planimetry had a stronger correlation to PHT-derived MVA than 2DE planimetry. PHT-derived MVA from Doppler echocardiography has gained clinical acceptance as a useful tool in assessing mitral valve area.\(^14\),\(^17\) The any-plane cropping function of apical, as well as parasternal datasets and improved morphological detail of the valve provided by RT3DE enable the smallest orifice area to be accurately identified at the leaflet tips. 2DE planimetry correlation with PHT is weaker, due to limitations in resolution, suboptimal images limited to the parasternal window only and inability to manipulate the 2D dataset-off line. Postoperative MVA assessment is important following mitral valve repair, as there is a risk of iatrogenic orifice obstruction.

RT3DE was equivalent to 2DE in the ability to assess leaflet mobility and gauge the severity of residual regurgitation. However, the ability to manipulate the 3D dataset and crop in any plane enabled a more accurate description of the anatomical site of residual regurgitation.

In agreement with previous studies,\(^7\) we found that acquiring the 3DE datasets from a parasternal transducer

![Figure 4](https://academic.oup.com/ehjci/article-abstract/9/5/625/2400017/628)
position produced the best mitral image quality and that cropping to view the mitral valve from the left ventricular side of the valve was adequate to visualize all segments of the mitral valve and identify the French seam repair. Cropping the left ventricular cavity from apex toward base also enabled the leaflet tips to be cut perpendicular to the crop plane and provided the smallest en face orifice for MVA calculation. The atrial view occasionally enabled a better view of the posterior leaflet, but overall did not provide a significant amount of additional data in the majority of patients studied.

Feasibility and reproducibility

Time to acquire the RT3DE datasets averaged around 4 min, with approximately 16 min required on average to analyse and process the 3D datasets. Approximately 20 min in total is required to analyse the functional morphology of a repaired mitral valve using RT3DE. The RT3DE data are also reproducible; inter-observer variability for segment visualization score has a \( k = 0.79 \). Therefore, RT3DE assessment of mitral valve repairs is both feasible in a busy clinical practice and reproducible.

Limitations

There are limitations in using transthoracic RT3DE to image mitral valve repairs. A poor acoustic window can prevent detailed visualization of the mitral valve, especially as the 3D matrix array probe has a larger footprint than the 2D probe. This was not a major problem in this study, with 88% of study patients having an adequate acoustic window. Transesophageal RT3DE was not available at the time this study was performed and rotational 3D TEE can suffer from reconstruction artifacts. However, it has recently been shown that 3D TEE is superior to 2D TEE in the preoperative assessment of diseased mitral valves, particularly, in defining A1 and commissural defects. Despite this, TEE remains an invasive test, not without complication and uncomfortable for the patient. Perhaps in selected cases, when a potential problem has been identified by transthoracic RT3DE or where there is a poor acoustic window transthoracically, transesophageal RT3DE may offer improved images of complex repairs in the future. However, in the vast majority, it would appear that follow-up imaging of mitral repairs by transthoracic RT3DE is more than adequate.

PHT-derived MVA has limitations and can be inaccurate especially, if there is coexistent aortic regurgitation30 or poor left ventricular compliance,31 as occurs with left ventricular hypertrophy. These features were absent in our small study cohort. In addition, inaccuracies in PHT-derived-MVA can occur in the immediate perioperative period due to altered loading conditions. This was not a problem in our study as all the patients were haemodynamically stable, NYHA class 1 and 3 months postoperation. Finally, atrial arrhythmias can degrade the validity of PHT-derived MVA measurements. Atrial arrhythmias occurred in only 3/25 patients and we compensated for this by taking a mean of five rather than three PHT-derived MVA readings. Despite these limitations, PHT-derived MVA is widely used clinically and was therefore selected as our preferred method of measurement.

Atrial arrhythmias, particularly atrial fibrillation, can lengthen the time to acquire a full volume 3D dataset, and this in turn can lead to motion artifacts due to respiratory movement. Again, this was relatively uncommon in our cohort, with only two patients suffering atrial fibrillation and one patient in atrial flutter at the time of echocardiography. The low incidence of atrial arrhythmia in our cohort may be attributable, in part, to the fact that our institution has a low threshold in offering mitral valve repair to patients with moderate-severe mitral valve disease who are asymptomatic or have mild symptoms. In centres that have a different approach, atrial arrhythmia may have a more profound limitation on imaging the repaired mitral valve. In our experience, over 90% of patients attending for follow-up after mitral valve repair are able to be successfully imaged with transthoracic RT3DE.

We analysed the mitral valve morphology only from en face short axis views and did not assess the mitral repair in the longitudinal plane. This has been shown to provide additional morphological data when assessing mitral valve disease with 3D rotational TEE.22 However, we found that with transthoracic RT3DE, adequate visualization was achieved in the en face view alone. Longitudinal views may have further improved the morphological assessment by RT3DE, but data processing would have taken longer and perhaps would have limited the technique’s clinical utility.

Conclusion

Imaging the mitral valve repair to assess valve morphology and area by transthoracic RT3DE at 3 months into the postoperative period has additional value than imaging with transthoracic 2DE alone. It is feasible and reproducible in the majority of patients. In particular, RT3DE enables the complete visualization of the repaired mitral valve, particularly at the commissures, where visualization is poor by 2D imaging. It can define the smallest mitral valve orifice more accurately than 2DE, by allowing optimal, en-face cropping through the leaflet tips. Therefore, the transthoracic RT3DE has an important clinical role, enabling accurate postoperative morphological assessment of repaired mitral valves. This non-invasive imaging technique could be used to audit mitral valve repair results and aide the development of new surgical repair strategies, which maintain the functional morphology of the valve.

Conflicts of Interest: none declared.

References

measurement of the stenotic mitral valve orifice area. Am J Cardiol 1979; 43:560–68.


