Evaluation of Transmural Pressure Gradients in the Intraoperative Echocardiographic Diagnosis of Mitral Stenosis after Mitral Valve Repair

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Abstract

Objective: Acute mitral stenosis (MS) following mitral valve (MV) repair is a rare but severe complication. We hypothesize that intraoperative echocardiography can be utilized to diagnose iatrogenic MS immediately after MV repair.

Methods: The medical records of 552 consecutive patients undergoing MV repair at a single institution were reviewed. Post-cardiopulmonary bypass peak and mean transmural pressure gradients (TMPG), and pressure half time (PHT) were obtained from intraoperative transesophageal echocardiographic (TEE) examinations in each patient.

Results: Nine patients (9/552 = 1.6%) received a reoperation for primary MS, prior to hospital discharge. Interestingly, all of these patients already showed intraoperative post-CPB mean and peak TMPGs that were significantly higher compared to values for those who did not: 10.7±4.8 mmHg vs 2.9±1.6 mmHg; p<0.0001 and 22.9±7.9 mmHg vs 7.6±3.7 mmHg; p<0.0001, respectively. However, PHT varied considerably (87±37 ms; range: 20–439 ms) within the entire population, and only weakly predicted the requirement for reoperation (113±56 vs. 87±37 ms, p = 0.034). Receiver operating characteristic curves showed strong discriminating ability for mean gradients (AUC = 0.993) and peak gradients (area under the curve, AUC = 0.996), but poor performance for PHT (AUC = 0.640). A value of ≥7 mmHg for mean, and ≥17 mmHg for peak TMPG, best separated patients who required reoperation for MS from those who did not.

Conclusions: Intraoperative TEE diagnosis of a peak TMPG ≥17 mmHg or mean TMPG ≥7 mmHg immediately following CPB are suggestive of clinically relevant MS after MV repair.

Introduction

Mitral valve repair has become the procedure of choice for patients with significant MV dysfunction of most etiologies [1,2]. Repair of the MV is reportedly superior to replacement since it is associated with better preservation of valve tissue, subvalvular apparatus and left ventricular function, as well as improved long-term survival [3,4]. Furthermore, MV repair permits greater protection from endocarditis, thromboembolism and anticoagulation-related morbidity [5,6].

Recurrent mitral regurgitation (MR) is well recognized as the most common cause for failure of MV repair [7,8]. Another less common complication is the development of late mitral stenosis after MV repair especially for rheumatic disease [9] but also after MV repair for non-rheumatic MR [10]. Ibrahim et al. reported a 1% incidence of late MS, manifesting 3–9 years after MV repair for non-rheumatic MR [10]. Direct inspection of the MV repair in patients who underwent reoperation in this study revealed hindered, free leaflet motion associated with pannus formation on the anuloplasty ring[10]. In contrast to the development of late MS there is little information available on acute MS immediately following MV repair. In a case study, Maslow et al. reported the occurrence of a mitral stenosis immediately after mitral valve repair in a 37 year old female patient with myxomatous mitral valve disease [11]. In addition, an earlier study of Muratori et al. reported an incidence of a single case of intraoperatively diagnosed acute mitral stenosis out of a group of 142 patients also with myxomatous mitral valve disease who underwent mitral valve repair [12]. However, systematic reports of acute MS after MVP in larger cohorts of patients have not been published.

Echocardiography is commonly used to diagnose and quantify primary, native MS. Well established diagnostic criteria include amongst others planimetry, gradient measurements and estimation of pressure half-times [13]. However, alterations in MV orifice...
geometry following repair, or changes in chamber compliance after cardiopulmonary bypass (CPB) were shown to influence the intra- and postoperative echocardiographic evaluation of MS [14,15]. The calculation of mitral valve area by pressure half time measurements immediately after mitral valve repair was shown to underestimate the actual mitral valve area [15]. This led to the question which echocardiographic indices of MS severity still provide reliable information in the intraoperative setting, since specific echocardiographic criteria for the diagnosis of acute MS after MV repair have not been well established.

Intraoperative echocardiography is commonly used in the management of cardiac surgical patients [16,17]. In fact, intraoperative echocardiographic diagnosis of MS following MV repair would be desirable, since it would permit prompt surgical revision before the development of postoperative morbidity and mortality. Therefore, we retrospectively analyzed the medical records and intraoperative, transesophageal (TEE) Doppler echocardiographic examinations of patients undergoing MV repair for MR, to determine specific echocardiographic criteria for defining significant acute MS.

**Methods**

**Patient Population**

The study population consisted of all patients undergoing MV repair for MR at the Brigham and Women’s Hospital between 2001 and 2003 of whom a post-CPB, transmitral Doppler flow velocity profile was obtained and recorded for off-line analysis. 247 patients out of 552 were diagnosed with ischemic MR, 164 with myxomatous degenerative mitral valve disease, 27 with rheumatic heart disease and 17 patients were diagnosed with endocarditis leading to MR. All patients were consented for an intraoperative TEE during preoperative interview. Consent was given in written form. The approval for this retrospective study was obtained from the Institutional Review Board, Brigham and Women’s Hospital, to review the patients’ medical records and intraoperative TEE examination reports.

**Echocardiographic Data**

 Comprehensive intraoperative TEE examinations were performed using multiple plane probes (Siemens, Mountain View, CA; Philips Healthcare, Inc, Andover, MA). All TEE examinations were performed by cardiac anesthesiologists with extensive experience in perioperative echocardiography. Peak and mean TMPGs were determined using the simplified Bernoulli Equation from either pulse wave Doppler flow velocities (PWD) obtained at the tips of the mitral leaflets, or continuous wave Doppler to identify transmitral velocities when aliasing occurred despite optimal adjustment of the scale and baseline. TEE examinations were recorded on super VHS tape and analyzed of-line by a cardiac anesthesiologist (H.K.E.) and a cardiologist (R.B.) with extensive experience in perioperative echocardiography. Both examiners were blinded to the clinical outcome data. Analysis of the echocardiographic data included calculations of the peak and mean TMPG, and PHT from the post-CPB transmural Doppler flow velocity profiles. Values for mean and peak TMPG and PHT were obtained from the average of three separate measurements.

**Decision to return to CPB to re-do the mitral valve repair**

The decision to return to CPB to revise the original MV repair or replace the valve was made on an individual basis for each patient and included the following standard considerations: (a) the degree of hemodynamic instability (b) the patient’s co-morbidity (c) potential additional morbidity associated with a prolonged second period of CPB (d) the surgeons’ opinion as to their ability to produce a better result (e) echocardiographic findings, particularly from 2D echocardiography suggestive of MS (e.g. restricted leaflet mobility). Leaflet restriction was reported, but not objectively quantified, by the cardiac anesthesiologists who performed the intraoperative TEE examination. While echocardiographic measurements of TMPGs were available, cut-off values indicating significant acute iatrogenic MS following MV repair were not known at the time of this study.

**Review of Medical Records and Follow-Up**

Medical records were reviewed for patients’ demographics, type of surgical procedure and MV repair, and the incidence and indication for MV reoperation prior to hospital discharge.

**Statistical Analyses**

Demographic data were tabulated and descriptive statistics calculated. The echocardiographic data from the two independent analyses were averaged. Interobserver variability was assessed with Pearson correlation, and r and 95% confidence interval were calculated. Mean values for echocardiographic parameters were compared by unpaired t-test. Receiver operating characteristic (ROC) curves, area under the curve (AUC) and standard error (SE) were calculated with the use of the Graph Pad Prism 5 software. Values for best discrimination of cases requiring and not requiring reoperation were estimated by inspection. When exact P values were not specified, P<0.05 was considered significant.

**Results**

**Patient Population**

A total of 552 patients who underwent MV repair were included in the analysis. An additional 26 patients did not have interpretable Doppler recordings. Demographic data, type of surgical procedure and a description of the MV repair are displayed in Table 1. Nine (9/552 = 1.6%) patients with intraoperative TEE evidence of restricted MV leaflet motion underwent reoperation for MS prior to hospital discharge, including 4 patients who underwent surgical revision of the initial MV repair immediately following the post-CPB echocardiographic examination (Table 2). All of these patients were receiving inotropic and pressor support while attempting to wean from CPB following MV repair. None of these patients demonstrated significant concurrent MR.

**Interobserver Variability**

Interobserver variability was excellent for both measures of TMPG: Pearson’s r and 95% CI were 0.989 (0.987, 0.991) for peak gradient and 0.964 (0.958, 0.970) for mean gradient. PHT correlated less well between observers (r = 0.263 [0.183, 0.340]). All correlations were highly significant (P<0.0001).

**Transmirtal Pressure Gradients and Pressure Half-Time**

Mean and peak postoperative TMPGs for the entire population (mean ± SD) were 3.1±2.0 mmHg and 7.6±4.2 mmHg respectively. Patients with restricted MV leaflet motion by post-CPB intraoperative TEE who did not have persistent significant MR and required a MV reoperation for MS, had a mean TMPG of 10.7±4.8 mmHg vs. 2.9±1.6 mmHg without MS and had a peak TMPG of 22.9±7.9 mmHg vs. 7.6±3.7 mmHg without MS (P<0.0001 for each comparison) measured by intraoperative TEE. All of these patients were discharged from the hospital. PHT varied considerably (87±37 ms; range: 20–439 ms) and only weakly predicted a requirement for reoperation (113±56 vs.
Table 1. Patient Characteristics and Surgical Procedure (N = 552).

| Type of Repair | Surgical procedure          | N     | Primary Procedure | Reoperation |
|----------------|----------------------------|-------|-------------------|-------------|
| MV Repair      | MV Repair                  | 188 F/364 M | 203 10          |             |
| MV Repair + CABG | MV Repair + CABG       | 226 | 20              |             |
| MV Repair + other valve (AVR, TVR) | MV Repair + other valve (AVR, TVR) | 45 15 |                     |
| MV Repair + other valve (AVR, TVR) + CABG | MV Repair + other valve (AVR, TVR) + CABG | 33 0 |                     |

Type of Repair

- Isolated Annuloplasty: 453
- Annuloplasty + Leaflet Resection: 6
- Annuloplasty + Chordal Repair: 1
- Annuloplasty + Commisurotomy: 1
- Annuloplasty + Maze procedure: 1
- Annuloplasty + Pericardial Patch: 1
- Isolated Alfieri (“edge-to-edge”): 29
- Alfieri (“edge-to-edge”) + Leaflet Resection: 1
- Alfieri (“edge-to-edge”) + Commisurotomy: 1
- Alfieri (“edge-to-edge”) + Chordal Repair: 1
- Alfieri (“edge-to-edge”) + Ring Annuloplasty: 49
- Ring Annuloplasty + Leaflet Resection + Alfieri Stitch: 3
- Other: 5

Rings used for annuloplasty

- Carbomedics: 12
- Carpentier-Edwards: 341
- Cosgrove-Edwards: 7
- Duran: 1
- Medtronic: 1
- No ring: 37

Age 63.3 ± 14.1
Gender: M/F 188 F/364 M

Table 2. Characteristics of Patients with Mitral Stenosis after Mitral Valve Repair.

| Age | M/F | MR Etiology | Primary Procedure | P/M (mmHg) | Reoperation | Reoperation Type | LOS (d) | D/C y/n |
|-----|-----|-------------|-------------------|------------|-------------|-----------------|---------|--------|
| 67  | M   | Ischemic MR | CABG, AVR, Alfieri | 22/12      | Post CPB    | Alfieri Revision | 13      | y      |
| 54  | F   | Myxomatous  | ≠ 38 C-E-P        | 38/22      | Post CPB    | MVP Revision    | 7       | y      |
| 39  | M   | Myxomatous  | ≠ 30 CG           | 19/7       | 2 d         | # 36 CG         | 6       | y      |
| 69  | M   | Myxomatous  | ≠ 28 CG, CABG     | 17/7       | Post CPB    | MVR ≠ 29 Hancock | 10      | y      |
| 36  | F   | Myxomatous Endocarditis | ≠ 34 CG, Alfieri | 18/10 | 1 d | MVR ≠ 31 St Jude | 22 | y    |
| 76  | F   | Ischemic MR | ≠ 26 C-E-P        | 21/11      | Post CPB    | MVP ≠ 27 C-E-P  | 20      | y      |
| 52  | F   | Myxomatous  | ≠ 26 C-E-P, Alfieri | 31/12 | 8 d | # 28 CM Annulflex Ring | 15 | y    |
| 77  | F   | Myxomatous  | ≠ 28 MT Ring      | 17/7       | 6 d         | MVR ≠ 29 Hancock | 7       | y      |
| 54  | F   | Myxomatous  | ≠ 32 CG, Alfieri  | 19/7       | 12 h        | Alfieri Revision | 7       | y      |

M/F: Male/Female; MR: mitral regurgitation; P/M: peak and mean transmural mitral pressure gradients obtained by post-CBP; intraoperative transesophageal echocardiography; LOS: length of hospital stay; d/days; h:hours; D/C: discharge from hospital; y: yes; n: no; MVP: mitral valve repair; MVR: mitral valve replacement; CPB: cardiopulmonary bypass; AVR: aortic valve replacement; CABG: coronary artery bypass grafting; CG: Cosgrove-Edwards annuloplasty; C-E-P: Carpentier Edwards ring annuloplasty; MT: Medtronic; CM: Carbo Medics.

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Discussion

The development of MS following MV repair is most commonly associated with late degenerative changes and fibrous overgrowth, which restrict diastolic leaflet excursion over the time [10,18]. In contrast, acute MS following with mitral valve repair surgery can present intraoperatively, immediately after the termination of CPB. The exact incidence however remains unknown, as previous reports are either single case reports [11] or are based only on small numbers of patients [12] and studies in different centers might be highly influenced of patient heterogeneity. Here, we used intraoperative TEE to identify a peak or mean TMPG of at least 17 mmHg or 7 mmHg, respectively, as indicators of significant early MS in 9 out of 552 patients who subsequently required prompt surgical revision following an initial MV repair for primary MS. All of these patients survived to be discharged from the hospital. Thus, intraoperative TEE may be useful for accurately and efficiently identifying patients with acute MS following MV repair who may benefit from a prompt surgical revision before the development of significant postoperative morbidity and mortality.

Intraoperative ultrasound and TEE is a widely used, safe and practical technique [17,19–34]. TEE can be used for the intraoperative evaluation of the mitral valve [17,35], including evaluation for MS severity [36]. However, two-dimensional echocardiographic diagnosis of MS following post-MV repair may be difficult in some patients including those undergoing an Alfieri edge-to-edge repair in which the mid-portion of the anterior and posterior leaflet are intentionally sutured together to prevent MR [37]. Interestingly, although 3 of the 9 patients in our series who required reoperation for MS initially underwent edge-
Figure 1. Distribution of peak gradients, split by the requirement for reoperation for mitral stenosis (MS). (A) A peak gradient of $\geq 17$ mm Hg best separated cases requiring reoperation for MS from those that did not. (B) Receiver operator curves (ROC) for peak transmitral pressure gradients. The area under the curve (AUC [SE]) for peak transmitral pressure gradients ($0.996 \pm 0.003$) showed strong discriminating ability. doi:10.1371/journal.pone.0026559.g001
Figure 2. Distribution of mean gradients, split by the requirement for reoperation for mitral stenosis (MS). (A) A mean gradient of ≥7 mm Hg best separated cases requiring reoperation for MS from those that did not. (B) Receiver operator curves (ROC) for mean transmitral pressure gradients. The area under the curve (AUC [SE]) for mean transmitral pressure gradients (0.993 [0.003]) showed strong discriminating ability. doi:10.1371/journal.pone.0026559.g002
Figure 3. Distribution of pressure half times after mitral valve repair. (A) Distribution of pressure half times showed no significant difference in distribution between cases requiring reoperation for MS and those that did not. (B) Receiver operator curve (ROC) for pressure half time (PHT). The area under the curve (AUC [SE]) showed only weak discriminating ability (0.640 [0.092]).

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to-edge repairs, others have reported that this technique can still significantly decrease MR by reducing MV area while maintaining mean TMPG < 6 mmHg [37] and preserving MV reserve [38].

Classical Doppler echocardiographic measures for quantifying native MS may not be applicable immediately following MV repair due to acute changes in orifice geometry and chamber compliance [14]. Limitations in using Doppler echocardiography to assess MS severity have been described in patients undergoing mitral valvotomy. Although Hatle et al. demonstrated a reliable, inverse correlation between Doppler echocardiographic measurements of PHT and MV orifice area in patients with native MS [38], the same correlation between PHT and MV area could not be demonstrated in patients with MS immediately after mitral valvotomy [14]. Similarly, while Maslow et al. demonstrated good agreement and correlation between MV area with PHT and planimetry obtained with two-dimensional echocardiography in patients undergoing MV repair [39], others have shown that intraoperative TEE measurement of PHT following MV repair may be unreliable and can underestimate MV area [15]. In our study, PHT varied considerably and only weakly predicted a requirement for reoperation, suggesting that PHT may be dependent upon hemodynamic variables other than MV orifice area including net left atrial and ventricular compliance [14].

Estimating MV area using the PISA technique has been demonstrated in patients with native MS, and has been used to estimate mitral regurgitant orifice area following MV surgery [40]. However, PISA has not been consistently validated for assessing acute MS immediately after MV repair. Furthermore, the estimation of MV area using the PISA technique may be relatively time consuming, and therefore impractical to apply in the immediate post-CPB period while a hemodynamically unstable patient is being resuscitated.

Finally, 3D echocardiography is a rapidly evolving technique which is increasingly used intraoperatively during mitral valvuloplasty [41] and mitral valve repair [42]. In primary, native mitral stenosis, estimation of MVA with 3D echocardiography is considered to be the gold standard of diagnosis of mitral stenosis by some authors [43]. However, until now, no study is available which examined the reliability of 3D TEE MVA measurements in identifying acute MS in the intraoperative setting immediately after MVP.

Alternatively, as demonstrated in the present study, TMPGs obtained by Doppler echocardiography are reliable measures of MS severity, highly reproducible, easy to acquire and should therefore be considered an important component of the post-CPB intraoperative echocardiographic examination in patients undergoing MV surgery.

Echocardiographic calculation of TMPG as a measure of MS severity may be influenced by the presence of concurrent MR [44]. None of the patients in our study who required reoperation for significant MS demonstrated concurrent significant MR. Conventional echocardiographic measures of MS severity may also be influenced by changes in cardiac output. Mohan et al. used dobutamine stress echocardiography in 57 ambulatory patients with MS to show that alterations in transmural flow are associated with small and clinically insignificant changes in directly planimetric MV area, but more pronounced changes in MV as determined by PHT [45]. In addition, Firstenberg et al. also used stress echocardiography in 13 patients with MS to demonstrate that changes in cardiac output result in predictable changes in PHT [46]. Although increases in cardiac output may promote MV orifice stretching and reserve associated with decreases in PHT, increased flow rates may also be associated with higher TMPGs [46]. All patients with significant MS in our study who eventually underwent surgical revision were hemodynamically compromised and were receiving inotropic and pressor support, however intraoperative cardiac output was not routinely measured during the post-CPB echocardiographic examination. Therefore, we were unable to determine the specific influence of cardiac output on echocardiographic measures of MS severity.

Nonetheless, direct and indirect echocardiographic measures of MV area appear to remain valid under conditions of varying transmural flow [45,46]. Finally, Doppler echocardiographic measures of MS severity may also be influenced by changes in diastolic function including impaired LV relaxation and compliance. However, all of the patients in our study with a presumed diagnosis of acute MS post MV repair had echocardiographic evidence of restricted MV leaflet motion, and furthermore, it is uncommon for peak TMP to exceed 17 mmHg due to isolated, impaired LV compliance.

Intuitively, one might expect to see a higher prevalence of iatrogenic MS in patients undergoing MV repair for ischemic MR using a relatively restrictive annuloplasty compared to surgical approaches for repairing degenerative etiologies of MR. However, in our series, patients who underwent only annuloplasty ring placement for ischemic or functional MR seemed less susceptible to acute MS after MVP (2 out of 247 patients) perhaps due to extensive surgical experience in sizing rings. On the other hand, patients with myxomatous MV disease were more likely to require repairs that involved increased complexity associated with leaflet resection and reconstruction including edge-to-edge repairs. This might have been the reason for the increase in incidence of acute MS after MVP of myxomatous valves (6 out of 164 patients). Moreover, this might underline the benefit of intraoperative measurement of TMPGs especially during MVs of myxomatous mitral valves.

Some important limitations of the present studies should be noted. The present findings are somewhat confounded by the availability of Doppler data in an un-blinded fashion during surgery, such that the decision to revise the original MV repair may have been partly based on the echocardiographic findings. Thus, the lack of independence between the measure and the outcome has the potential to overestimate the strength of the relationships. Secondly, transmural flow measurements are flow dependent and the present study did not include the integration of flow measurements into the assessment of MS severity. Thirdly, despite the large number of patients that were included in the present study, only a relatively small number of patients were diagnosed with significant MS. Therefore, prospective studies utilizing flow dependent measures of MS severity following MV repair and including a greater number of patients with iatrogenic MS are warranted to validate these results.

In conclusion, elevated mean and peak TMPGs obtained in the post-CPB period are practical and reliable indicators of significant MS immediately following MV repair. However, these values should not necessarily be considered pathognomonic for isolated perioperative MV dysfunction. Nonetheless, identifying an increased TMPG following MV repair should alert the intraoperative echocardiographer to consider acute MS especially in the presence of concurrent hemodynamic instability, and may allow the cardiac surgeon to consider a prompt revision prior to the development of significant postoperative morbidity and mortality. Further study is warranted to prospectively evaluate the impact of both intraoperative TEE Doppler derived gradient pressures and 3D TEE indices of MV area on perioperative surgical decision making in patients undergoing valve MV repair [47,48].

**Author Contributions**

Conceived and designed the experiments: HKE RB SS JAF SKS. Performed the experiments: HKE RB SS JAF SKS. Analyzed the data: HKE RB SS AKR SKS. Wrote the paper: HKE AKR SKS.
References

1. Cohn LH (2002) Mitral valve repair for ischemic mitral regurgitation. Adv Cardiol 39: 153–156.

2. Bonow RO, Carabello BA, Chatterjee K, de Leon AC, Jr., Faxon DP, et al. (2008) 2008 Focused update incorporated into the ACC/AHA 2006 guidelines for the management of patients with valvular heart disease: a report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines (Writing Committee to Revise the 1998 Guidelines for the Management of Patients With Valvular Heart Disease). Endorsed by the Society of Cardiovascular Anesthesiologists, Society for Cardiovascular Angiography and Interventions, and Society of Thoracic Surgeons. Circulation 118: e323–661.

3. Kousn N, Bonomiddi I, Kontogianni D, Smith Piet, Nibyazanopoulos P (2005) Mitral valve repair versus replacement for isolated non-ischemic mitral regurgitation in patients with operative left ventricular dysfunction. A long-term follow-up echocardiography study. Eur J Echocardiogr 6: 435–442.

4. Zhao L, Kolen P, Berger MA, Zhang Z, Lewis C, et al. (2007) Comparison of recovery after mitral valve repair and replacement. J Thorac Cardiovasc Surg 135: 1257–1263.

5. Russo A, Grigioni F, Avierinos FJ, Freeman WK, Suri R, et al. (2000) Thromboembolic complications after surgical correction of mitral regurgitation incidence, predictors, and clinical implications. J Am Coll Cardiol 31: 1203–1211.

6. Muehrcke DD, Cosgrove DM, 3rd, Lytle BW, Taylor PC, Burgar AM, et al. (1997) Is there an advantage to repairing infected mitral valves? Ann Thorac Surg 63: 1718–1724.

7. Flameng W, Herijgers P, Bogaerts K (2003) Recurrence of Mitral Valve Stenosis due to fibrous tissue overgrowth after mitral valve repair. J Cardiovasc Ultrasound 39: 153–156.

8. Williams ML, Dohlman MA, Jollis JG, Horton JR, Shaw LK, et al. (1999) Mitral gradients and frequency of recurrence of mitral regurgitation after ring annuloplasty for ischemic mitral regurgitation. Ann Thorac Surg 68: 1197–1201.

9. Hermens JD, Joyce DH, Hirschfeld K, Chen C, Laub GW, et al. (1992) Factors affecting mitral valve reoperation in 317 survivors after mitral valve reconstruction. Ann Thorac Surg 54: 410–417; discussion 448.

10. Ibrahim MF, David TE (2002) Mitral stenosis after mitral valve repair for non-rheumatic mitral regurgitation. Ann Thorac Surg 73: 34–36.

11. Maslow A, Singh A, Mahmood F, Poppas A (2011) Intraoperative assessment of mitral valve area after mitral valve repair for regurgitant valves. J Cardiothorac Vasc Anesth 25: 486–490.

12. Muratori M, Berti M, Doria E, Antona C, Alamanni F, et al. (2001) Intraoperative transesophageal echocardiography as predictor of mitral valve repair. J Heart Valve Dis 10: 65–71.

13. Baumgartner H, Hung J, Bemmejo J, Chambers JB, Evangelista A, et al. (2009) Echocardiographic assessment of mitral valve stenosis: EAE/ASE recommendations for clinical practice. J Am Soc Echocardiogr 22: 1–23; quiz 101–102.

14. Thomas JD, Wilkins GT, Choong CY, Ahsanul VM, Palacios IF, et al. (1989) Inaccuracies of mitral valve pressure half-time immediately after percutaneous mitral valvotomy. Dependence on transmirtal gradient and left atrial and ventricular compliance. Circulation 90: 980–981.

15. Poh KK, Hong EC, Yang H, Lim YT, Yeo TC (2006) Transesophageal echocardiography as predictor of mitral valve repair. J Heart Valve Dis 15: 103–109.

16. Umana JP, Salehizadeh B, DeRose JJ, Jr., Nahan T, Lovtin A, et al. (1998) “Bow-tie” mitral valve repair: an adjunctive technique for ischemic mitral regurgitation. Ann Thorac Surg 66: 1640–1646.

17. Hatle L, Angelens B, Tromsdal A (1979) Noninvasive assessment of aortoventricular pressure half-time by Doppler ultrasound. Circulation 60: 1096–1104.

18. Maslow A, Gemignani A, Singh A, Mahmood F, Poppas A (2011) Intraoperative assessment of mitral valve area after mitral valve repair: comparison of different methods. J Cardiothorac Vasc Anesth 25: 221–228.

19. Ridkin RD, Harper K, Tijbe D (1995) Comparison of proximal isovelocity surface area method with pressure half-time and planimetry in evaluation of mitral stenosis. J Am Coll Cardiol 26: 458–465.

20. Zamanof J, Perez de Isla L, Suger J, Cordeiro P, Rodrigo JL, et al. (2004) Noninvasive assessment of mitral valve area during percutaneous balloon mitral valvuloplasty: role of real-time 3D echocardiography. Eur Heart J 25: 2006–2091.

21. Singh P, Manda J, Huang MC, Mehta A, Kesanolla SK, et al. (2009) Live/real-time three-dimensional transesophageal echocardiographic evaluation of mitral and aortic valve prosthetic paravalvular regurgitation. Echocardiography 26: 980–987.

22. Mannerts HF, Kamp O, Visser CA (2008) Should mitral valve area assessment in patients with mitral stenosis be based on anatomical or on functional evaluation? A plea for 3D echocardiography as the new clinical standard. Eur Heart J 29: 2073–2074.

23. Mohan JC, Maldharve S, Kumar A, Arora R, Patel AR, et al. (2004) Does chronic mitral regurgitation influence Doppler pressure half-time-derived calculation of the mitral valve area in patients with mitral stenosis? Am Heart J 148: 703–709.

24. Mohamed AC, Patel AR, Payse R, Gupta D, Kumar M, et al. (2002) Is the mitral valve area flow-dependent in mitral stenosis? A dobutamine stress echocardiographic study. J Am Coll Cardiol 40: 1809–1815.

25. Firstenberg MS, Prior DL, Greenberg NL, Wahl S, Pasquet A, et al. (2001) Effect of cardiac output on mitral valve area in patients with mitral stenosis: validation and pitfalls of the pressure half-time method. J Heart Valve Dis 10: 49–56.

26. Schlosshan D, Aggarwal G, Mathur G, Allan R, Cranney G (2011) Real-time 3D transesophageal echocardiography for the evaluation of rheumatic mitral stenosis. JACC Cardiovasc Imaging 4: 508–508.

27. Chu JW, Levine RA, Chua S, Poh KK, Morris E, et al. (2008) Assessing mitral valve area and orifice geometry in calcific mitral stenosis: a new solution by real-time three-dimensional echocardiography. J Am Soc Echocardiogr 21: 1006–1009.