

Three-dimensional Echocardiography in Characterization of Degenerative Mitral Valve Disease

Eco tridimensional en la evaluación de la enfermedad degenerativa de la válvula mitral

MARTÍN A. MUNÍN[†], JORGE THIERER^{MTSAC}, MARÍA S. GOERNER, IGNACIO M. RAGGIO, JOSÉ GODIA, JULIO ORTEGA, GUSTAVO SÁNCHEZ, FERNANDO SPERNANZONI, VÍCTOR TORRES, JAVIER GUETTA^{MTSAC}

ABSTRACT

Background: Degenerative mitral valve regurgitation is a highly prevalent disease representing the most common cause of mitral valve surgery, whose outcome is closely associated with the type of procedure. Three-dimensional (3D) transesophageal echocardiography allows assessing the complexity and extension of the degenerative process, thus optimizing the therapeutic strategy.

Objectives: The aim of this study was to assess the characteristics and dimensions of the mitral valve apparatus with 3D-transesophageal echocardiography to identify patients with different complexity and extension of the disease, and to compare these results with a population without heart disease.

Methods: Twenty-five patients with severe degenerative mitral valve regurgitation and 26 patients without cardiovascular disease were prospectively included and studied with 2D-and 3D transesophageal echocardiography. A three-dimensional valve model was built with the best 3D sequence to obtain leaflet and annulus measurements (normalized by body surface area). The population with mitral regurgitation was divided into two groups: group A consisting of 17 patients with prolapse in only one segment was compared with Group B including 8 patients with more than one prolapsed segment. Then, mitral annulus morphology and dimensions of patients with mitral regurgitation were compared with the population without heart disease. Data are presented as median and interquartile range. The Wilcoxon test was used to compare groups. A two-tailed p value <0.05 was considered statistically significant.

Results: Seventy-six percent of patients with mitral regurgitation were men, with average age 60.6 (53-73.2) years. Group B patients presented left ventricular end-diastolic diameter and mitral annulus with significantly enlarged area, circumference and intercommissural diameter. Anterior valve area and prolapse volume were significantly larger in group B.

No differences in mitral valve annulus morphology were observed when patients with mitral regurgitation were compared with the group without heart disease.

Conclusions: In patients with severe degenerative mitral regurgitation, 3D-transesophageal echocardiography allows identifying marked differences between populations with different extension of valvular involvement. The data thus obtained might have added value when deciding the therapeutic conduct.

Key words: Echocardiography, Transesophageal - Echocardiography, Three-dimensional - Mitral Valve - Mitral Valve Insufficiency - Mitral Valve Prolapse

RESUMEN

Introducción: La insuficiencia mitral de causa degenerativa es una enfermedad de alta prevalencia que, de hecho, constituye la causa más común de necesidad de cirugía sobre la válvula mitral y su resultado está en íntima relación con el tipo de procedimiento que se realice. El ecocardiograma transesofágico tridimensional (3D) permite determinar la complejidad y la extensión del proceso degenerativo y, de este modo, optimizar la estrategia terapéutica.

Objetivos: Evaluar las características y las dimensiones del aparato valvular mitral en la insuficiencia mitral degenerativa grave con el propósito de reconocer pacientes con diferente complejidad y extensión de la enfermedad mediante ecocardiograma transesofágico 3D y, asimismo, compararlas con una población sin cardiopatía.

Material y métodos: Se incluyeron prospectivamente 25 pacientes con insuficiencia mitral grave degenerativa y 26 pacientes sin enfermedad cardiovascular, a los que se estudió con ecocardiograma transesofágico en 2D y 3D. Con la mejor secuencia 3D se construyó un modelo tridimensional valvular del que se obtuvieron mediciones de las valvas y el anillo (indexadas por la superficie corporal). La población con insuficiencia mitral se dividió en dos grupos: grupo A, compuesto por 17 pacientes con prolapso de un solo segmento y grupo B, conformado por 8 pacientes con más de un segmento con prolapso. Ambas poblaciones se compararon entre sí. Posteriormente se compararon la morfología y las dimensiones del anillo mitral de los pacientes con insuficiencia mitral versus la población sin cardiopatía. Los datos se presentan como mediana con rango intercuartil. En la comparación de los grupos se empleó la prueba de Wilcoxon. Se consideró significativa una $p < 0,05$ a dos colas.

REV ARGENT CARDIOL 2016;84:317-322. <http://dx.doi.org/10.7775/rac.v84.i4.6162>

SEE RELATED ARTICLE: REV ARGENT CARDIOL 2016;84:298-299. <http://dx.doi.org/10.7775/rac.v84.i4.8933>

Received: 02/23/2016 – Accepted: 04/20/2016

Address for reprints: Dr. Martín A. Munín - Francia 2048 - (1602) Florida, Vicente López, Pcia. de Buenos Aires, Argentina - e-mail: mmunin@hotmail.com

Centro de Educación Médica e Investigaciones Clínicas (CEMIC)

^{MTSAC} Full Member of the Argentine Society of Cardiology

[†] To apply as Full Member of the Argentine Society of Cardiology

Resultados: El 76% de los pacientes con insuficiencia mitral eran hombres. La edad promedio fue de 60,6 (53-73,2) años. Los pacientes del grupo B presentaron diámetro diastólico del ventrículo izquierdo y anillo mitral con área, circunferencia y diámetro intercomisural significativamente más grandes. El área de la valva anterior y el volumen del prolapso fueron significativamente mayores en el grupo B.

Cuando se compararon todos los pacientes con insuficiencia mitral con los pacientes sin cardiopatía, no se observaron diferencias en la morfología del anillo valvular mitral.

Conclusiones: En pacientes con insuficiencia mitral grave degenerativa, el ecocardiograma transesofágico 3D permite poner en evidencia diferencias notables entre poblaciones con desigual extensión del compromiso valvular. Los datos así obtenidos podrían tener valor agregado a la hora de decidir la conducta terapéutica.

Palabras clave: Ecocardiografía transesofágica - Ecocardiografía tridimensional - Válvula mitral - Insuficiencia de la válvula mitral - Prolapso de la válvula mitral

Abbreviations

2D	Two-dimensional
3D	Three-dimensional
BSA	Body surface area
FED	Fibroelastic deficiency
LV	Left ventricular

LVDD	Left ventricular diastolic diameter
LVSD	Left ventricular systolic diameter
MR	Mitral regurgitation
TEE	Transesophageal echocardiography

INTRODUCTION

Degenerative mitral valve regurgitation (MR) is a highly prevalent disease, and is the most common cause for the need for mitral valve surgery. (1-3) Mitral valve surgery outcomes are intimately related with the type of procedure. Patients undergoing plastic valve repair have lower surgical mortality and higher postoperative ejection fraction than those with elective valve replacement. (3-5) However, valve repair surgery is a less performed procedure in our setting. (6) Training of surgeons in mitral valve repair techniques, as well as full knowledge of valvular heart disease in presurgical situations are necessary requirements to accomplish a higher number of repair procedures with better outcomes.

Degenerative mitral valve disease includes two categories: fibroelastic deficiency (FED) and Barlow's disease. (7, 8) The correct diagnosis of these entities, as well as the extension of the pathological process on the valve is extremely important in the strategy of these patients' management. Patients with a more complex valve disease should be operated-on in centers with more experience in mitral valve repair techniques. (9, 10)

The correct evaluation of the complexity and extension of the mitral valve degenerative process is difficult when two-dimensional (2D) echocardiography is the study tool. Conversely, three-dimensional transesophageal echocardiography (3D-TEE) allows better definition of valve disease due to its ability to show in one view the real configuration of the whole mitral apparatus in motion. (11) In addition, this technology, through the construction of a mitral valve model at end-systole, allows the real and reproducible quantification of each of the components of the mitral valve apparatus. (12, 13) Model-derived measurements may be useful to separate populations of patients with MR having different valve impairment,

optimizing the treatment strategy.

The aims of the present study were to evaluate the mitral valve anatomical characteristics and dimensions of patients with severe degenerative MR, to identify patients with different complexity and extension of valve disease using 3D-TEE, and to compare the mitral annulus morphology of patients with MR vs. a population without heart disease.

METHODS

Between June 2008 and December 2013, 25 patients with severe degenerative MR referred to our laboratory for transesophageal echocardiography (TEE) were prospectively included in the study. In the same period, 26 patients without cardiovascular disease (sinus rhythm, left ventricular diastolic diameter (LVDD) <56 mm, ejection fraction ≥55%, without abnormal segment motion, without valvular stenosis or >grade I/IV regurgitation, and pulmonary systolic pressure <40 mmHg), undergoing TEE for febrile syndrome of probable emboligenic origin, were prospectively included in the study as controls.

All patients underwent transthoracic Doppler echocardiography and TEE, according to standard technique. In all cases, 3D-TEE sequences of the mitral valve apparatus were acquired, two in 3D zoom imaging mode (live) and two in full volume mode. 3D image acquisition required approximately two additional minutes of study. The echocardiographic study was performed with Philips iE33 equipment and X7-2t transesophageal probe (Philips Medical Systems, Andover, MA). Images were digitally stored and transferred to a workstation set up with mitral valve quantification software (Q-Lab 9.0 Philips Medical Systems). Using the best acquired 3D zoom sequence, a three-dimensional model of the mitral valve at end-systole was built, enabling the corresponding leaflet and annulus measurements. End-systole was defined as the last frame with the aortic valve open. To build the model, automatic volume cross-sections were performed with the mitral valve in three orthogonal planes (Figure 1A). Then, four reference points were assigned in the annulus (anterolateral, posteromedial, anterior and posterior) and next, in 10 successive rotational planes another 20 sites

were marked to complete 24 points defining the three-dimensional annulus configuration. Subsequently, the mitral valve volume was sectioned in multiple parallel planes from the anterolateral to the posteromedial commissure every 2.5 millimeters. Points were assigned to the leaflets in each of these planes (Figure 1B). The 3D valve model was thus built, representing with a color code a topographic map of the mitral leaflets and annulus. This map codifies in red the leaflet tissue situated above the annular plane (prolapse), and in blue the leaflet tissue lying below it (Figure 2). Then, the program automatically generates the dimensions, geometry, and annular and leaflet area measurements. In each patient mitral annulus measurements were: intercommissural diameter, anteroposterior diameter, height (distance in millimeters between the highest insertion point and the lowest insertion point of the annulus), 3D circumference, 3D area, and height to intercommissural diameter ratio (saddle-shaped annular measurement). Leaflet measurements were: anterior leaflet length and area, prolapse height (distance between the annular plane and the leaflet section above the annulus lying highest in the left atrium) and prolapse volume (volume enclosed between the annular plane and the mitral leaflets towards the atrium). Measurements were subsequently normalized by body surface area (BSA).

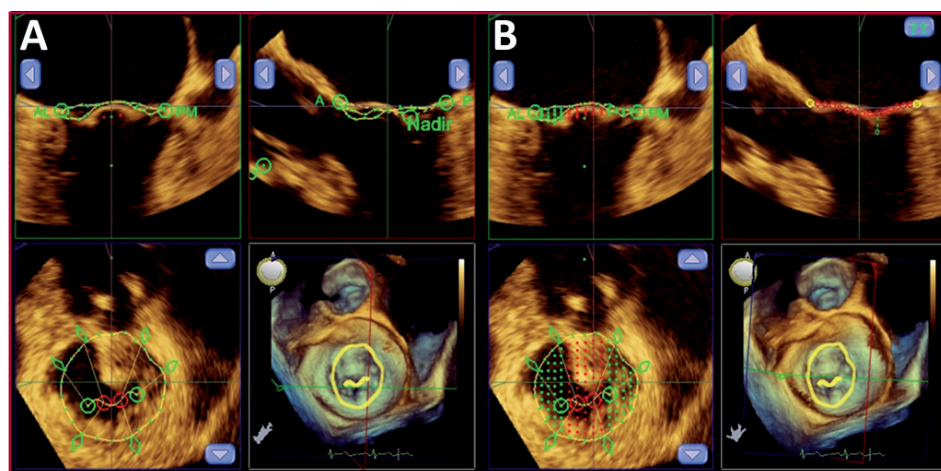
Ethical considerations

The study was approved by the institutional Ethics Committee, and all patients signed an informed consent before participating in the study.

RESULTS

Average age of patients with MR was 60.6 years (53-73.2) and 76% were men. Estimated BSA was 1.91 (1.75-2.06) m², LVDD was 31.4 (29.7-33.8) mm/m², LV systolic diameter (LVSD) 19.6 (16.7-20.7) mm/m², shortening fraction 39.4% (36.2-44), LV ejection fraction (LVEF) 66 (60-70)%, and left atrial diameter 24.6 (21.7-29.2) mm/m². Table 1 shows the results comparing groups A and B. It can be seen that group A patients (with only one segment with prolapse) had higher incidence of ruptured tendinous cord (94.11% vs. 25%, $p=0.001$). Group B patients (more than one segment with prolapse) presented with significantly larger LVDD. Results from 3D mitral valve reconstruction show that group B patients exhibited mitral annulus with significantly larger area, circumference and intercommissural diameter. The annular geom-

Fig. 1. A: Assignment of points to the mitral annulus. The initial four points are assigned in two orthogonal planes of valve volume at end-systole: anterolateral and posteromedial (upper left); anterior and posterior (upper right). **B:** Valve volume sectioned in multiple parallel planes from the lateral region to the medial region (bottom left). Points are assigned to leaflets in each section plane (bottom right).



The population with MR consisted in two groups: Group A, consisting of 17 patients with only one segment prolapse (identified with only one segment in red in the 3D reconstruction model) was compared Group B, involving 8 patients with prolapse in more than one segment.

Later, the “mitral annulus morphology” of all patients with MR was compared with the population without heart disease. The following characteristics were studied: 1) annular height to intercommissural diameter ratio (saddle-shaped annular measurement); 2) intercommissural to anteroposterior diameter ratio (annular circularity index); and 3) annular circumference to LVDD ratio, to evaluate annular size relative to left ventricular (LV) size.

The DuBois equation was used to calculate BSA.

Statistical analysis

Data are presented as median with interquartile range. The Wilcoxon test was used to compare groups. A two-tailed p value <0.05 was considered significant. STATA version 10.0 software package was used for statistical analyses.

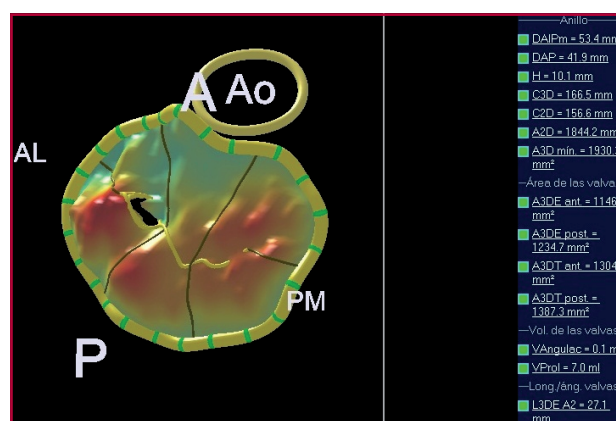


Fig. 2. Three-dimensional reconstruction model of the mitral valve at end-systole. Segments with prolapse are represented in red (see color image in the web). A: Anterior. AL: Anterolateral. Ao: Aortic valve P: Posterior. PM: Posteromedial.

Table 1. Comparison between groups A and B

	Group A (n=17)	Group B (n=8)	p
Age, years	61.9 (57-73.2)	52.2 (34.2-69.8)	0.1157
Men, %	82	62	0.344
BSA, m ²	1.92 (1.79-2.06)	1.83 (1.69-2.1)	0.6834
LVDD/m ² BSA, mm	30.77 (29.45-31.44)	33.43 (31.9-36.21)	0.0360
LVSD/m ² BSA, mm	19.43 (16.42-20.68)	19.92 (19.28-20.54)	0.3220
SF, %	38.8 (33.4-44)	41 (37.15-44.25)	0.4842
LVEF, %	68 (61-72)	61.5 (59.5-64.2)	0.1153
LA diameter/m ² BSA, mm	24.6 (21.7-28.3)	24 (21.7-31.5)	0.8157
Ruptured tendinous cord	(16/17) 94.11%	(2/8) 25%	0.001
Mitral annulus area/m ² BSA, mm ²	750.7 (681.2-795.5)	1030.9 (891.7-1049.7)	0.0036
Annulus circumference/m ² BSA, mm	72.6 (69.1-75.1)	89.2 (77.2-92.1)	0.0144
Annulus circumference /LVDD	2.36 (2.25-2.44)	2.59 (2.43-2.74)	0.0911
IC annulus diameter/m ² BSA, mm	22.2 (21-23.2)	26.9 (25.2-30.3)	0.0017
AP annulus diameter/m ² BSA, mm	20.7 (19.7-22.1)	22.4 (20.6-27.4)	0.0709
IC/AP diameter/m ² BSA, mm	1.06 (1.01-1.09)	1.23 (1-1.32)	0.1453
Annulus height/m ² BSA, mm	4.7 (4.4-5.7)	5.1 (3.1-5.8)	0.8613
Annulus height/IC diameter	0.22 (0.2-0.26)	0.19 (0.11-0.21)	0.0415
Anterior leaflet area/m ² BSA, mm ²	550 (468.1-603.4)	764.4 (641.8-895.6)	0.0014
Anterior leaflet length/m ² BSA, mm	16.6 (14.5-18.8)	19.1 (16.7-21.8)	0.0623
Prolapse height/m ² BSA, mm	4.6 (3.8-5.8)	4.6 (4.2-7.1)	0.2944
Prolapse volume/m ² BSA, ml	0.84 (0.51-1.4)	2.27 (1.82-3.82)	0.0007

BSA: Body surface area. LVDD: Left ventricular diastolic diameter. LVSD: Left ventricular systolic diameter. SF: Shortening fraction. LVEF: Left ventricular ejection fraction. LA: Left atrial. IC: Intercommissural. AP: Antero-posterior.

Table 2. Mitral valve annulus morphology of all patients with mitral regurgitation vs. patients without heart disease

	Group A (n=17)	Group B (n=8)	p
Age, years	64.5 (39.1-69.7)	60.6 (52.9-73.2)	0.6647
BSA, m ²	1.845 (1.7-2.03)	1.91 (1.75-2.06)	0.3225
LVEF, %	63.7 (60-67)	66 (60-70)	0.5581
Annulus height/m ² BSA, mm	4.4 (3.6-5.4)	4.8 (3.9-5.7)	0.3001
Aortic and mitral angle, degrees	120.7 (115-126)	122 (120-133)	0.1871
Annulus height/IC diameter	0.24 (0.21-0.27)	0.21 (0.19-0.24)	0.0765
IC diameter/Annulus AP diameter/m ² BSA, mm	1.121 (1.037 - 1.161)	1.07 (1.01 - 1.13)	0.1270
Annulus circumference/LVDD	2.36 (2.18 - 2.5)	2.38 (2.32 - 2.64)	0.2137

BSA: Body surface area. LVEF: Left ventricular ejection fraction. IC: Intercommissural. AP: Anteroposterior. LVDD: Left ventricular diastolic diameter

etry of group B patients evidenced flatter annuli, with less saddle-shape structure. Also, in group B patients, the anterior leaflet area was significantly larger, and although valve prolapse height was similar in both groups, prolapse volume was significantly higher in group B.

A comparative analysis of mitral valve annulus morphology was performed between patients with MR vs. patients without heart disease. Table 2 shows that although annular diameters, circumference and area

were significantly larger in patients with MR, no significant differences were found in annular morphology between groups.

DISCUSSION

This study shows that in our population of patients with severe degenerative MR, 3D-TEE, through its quantification tool, was useful to identify populations with different complexity and extension of the pathological process. In the 3D mitral valve reconstruction

model, patients with more than one prolapsed segment have mitral annulus with significantly larger area, circumference and intercommissural diameter, and less saddle shape configuration. The frequency of ruptured tendinous cord is much lower, while the anterior valve area and prolapse volume are significantly larger than in patients with only one segment involved in prolapse.

The many advantages provided by 3D-TEE make it an extremely useful tool for the management of elective surgery in patients with severe degenerative MR: 1) the working mitral valve apparatus can be seen from its atrial and ventricular perspectives in only one view, achieving better identification of the site and extension of the pathological process; 2) It is less operator-dependent; and 3) It allows examining the valve in the same orientation the surgeon will have during surgery, improving the interpretation and communication among physicians in charge of the patient's care. (14) Moreover, this technology, through a 3D reconstruction model of the mitral valve apparatus, shows in different color shades the degree and distribution of prolapsed segments, at the same time providing dimensions, areas, angles and volumes of the leaflets and annulus. Therefore, the information obtained with 3D-TEE allows better discrimination of more severely ill patients than 2D TEE, optimizing the strategy of MR management in order to perform interventions of more complex patients in centers with more experience in mitral valve repair. (12, 15)

Plastic surgery of anterior mitral leaflet prolapse is more difficult, with lower success rate and higher need of reoperation during follow-up. (16) In this scenario, the contribution of TEE is also important, due to its ability to better define the disease and reclassify the pathology. Patients with anterior prolapse due to FED will have better valve repair success rate than those with prolapse as a result of Barlow's disease. In our study two patients in group A had anterior leaflet prolapse, and leaflet flail with ruptured tendinous cord. In these cases, prolapse was assumed as secondary to FED, and this diagnosis was confirmed in the operating room with successful repair.

Similarly to our experience, other authors have shown that presurgical morphological quantification of mitral valve disease with 3D-TEE is useful to define the degree of valvular involvement. (12, 17, 18) The original study of Chandra et al. on 57 patients with severe degenerative MR showed that patients with Barlow's disease had larger annuli and leaflets and prolapse with greater height and volume than FED patients. (12) However, the most interesting observation of this study was finding a cut-off point of 1.15 ml for prolapse volume, which allowed differentiating without superposition all patients with Barlow's disease vs. FED.

Several studies have shown that mitral valve measurements obtained with 3D-TEE are very precise and reproducible. (12, 13) Also, the study of Biaggi et al. revealed that 3D-TEE mitral valve anatomy measure-

ments are more accurate compared with surgical findings. (18) Moreover, Tsang et al. reported that these parametric maps are very useful for less experienced echocardiographers to improve diagnostic accuracy in the identification of mitral valve disease. (19)

Mitral annulus dimensions, perimeter and area of patients with MR were significantly higher than in the population of patients without heart disease. However, no significant differences were found in the comparative analysis of annular "morphology". These data are probably related with the fact that our population of patients with MR had predominance of FED cases (only one segment with prolapse), where degenerative involvement is lower and annular morphology is less implicated.

Limitations

Although 3D-TEE quantitative data showed that patients with more than one segment prolapse had more complex degenerative disease, these findings could not be confirmed with surgery, since some of the patients were not followed-up at our center and not all patients underwent surgery.

Our population of patients with MR was not well balanced since there was predominance of patients with prolapse of only one segment. Nonetheless, significant differences could be found between groups.

The acquisition of 3D images as well as building the valvular reconstruction model requires certain training and extra study time.

CONCLUSIONS

3D-TEE is a valuable tool for the pre-surgical study of degenerative MR. The technique provides images with faithful anatomical representation of the functioning mitral apparatus, and its quantification tool helps defining the complexity of the pathological process. The data obtained may be useful in decision-making on the management strategy of these patients.

Conflicts of interest

None declared. (See authors' conflicts of interest forms in the website/Supplementary material).

REFERENCES

1. Nkomo VT, Gardin JM, Skelton TN, Gottdiener JS, Scott CG, Enriquez-Sarano M. Burden of valvular heart diseases: a population based study. *Lancet* 2006;368:1005-11. <http://doi.org/dhzdrf>
2. Iung B, Baron G, Tornos P, Gohlke-Bärwolf C, Butchart EG, Vahanian A. Valvular heart disease in the community: A European experience. *Curr Probl Cardiol* 2007;32:609-61. <http://doi.org/chtr59>
3. Gammie J, Sheng S, Griffith B, Peterson E, Rankin J, O'Brien S, et al. Trends in mitral valve surgery in the United States: results from the Society of Thoracic Surgeons Adult Cardiac Surgery Database. *Ann Thorac Surg* 2009;87:1431-7. <http://doi.org/bffsbq>
4. Enriquez-Sarano M, Schaff H, Orszulak T, Tajik A, Bailey K, Frye R. Valve repair improves the outcome of surgery for mitral regurgitation. A multivariate analysis. *Circulation* 1995;91:1022-8. <http://doi.org/sgp>

5. David T, Burns R, Bacchus C, Druck M. Mitral valve replacement for mitral regurgitation with and without preservation of chordae tendineae. *J Thorac Cardiovasc Surg* 1984;88:718-25.
6. Lowenstein Haber D, Guardiani F, Pieroni P, Pfister L, Carrizo L, Villegas E, et al. Real Facts in Cardiovascular Surgery in Argentina. Th XVI CONAREC Registry. *Rev Argent Cardiol* 2010;78:228-37.
7. Barlow J, Pocock W. Billowing, floppy, prolapsed or flail mitral valves? *Am J Cardiol* 1985;55:501-2. <http://doi.org/b8w4hx>
8. Anyanwu A, Adams D. Etiologic classification of degenerative mitral valve disease: Barlow's disease and fibroelastic deficiency. *Semin Thorac Cardiovasc Surg* 2007;19:90-6. <http://doi.org/b5pzx5>
9. Nishimura R, Otto C, Bonow R, Carabello B, Erwin J, Guyton R, et al. 2014 AHA/ACC Guideline 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. *J Am Coll Cardiol* 2014;63:e57-e185. <http://doi.org/f2r55h>
10. Adams D, Rosenhek R, Falk V. Degenerative mitral valve regurgitation: best practice revolution. *Eur Heart J* 2010;31:1958-66. <http://doi.org/cmd5pf>
11. Sugeng L, Shernan S, Weinert L, Shook D, Raman J, Jeevanandam V, et al. Real-time three-dimensional transesophageal echocardiography in valve disease: comparison with surgical findings and evaluation of prosthetic valves. *J Am Soc Echocardiogr* 2008;21:1347-54. <http://doi.org/bcz6h6>
12. Chandra S, Salgo I, Sugeng L, Weinert L, Tsang W, Takeuchi M, et al. Characterization of degenerative mitral valve disease using morphologic analysis of real-time three-dimensional echocardiographic images. Objective insight into complexity and planning of mitral valve repair. *Circ Cardiovasc Imaging* 2011;4:24-32. <http://doi.org/c9qfsh>
13. Munín M, Thierer J, Raggio I, Goerner M, Lombardero M, Godia J, et al. Three-Dimensional Echocardiographic Analysis of Mitral Valve Characteristics. *Rev Argent Cardiol* 2014;82:297-302. <http://doi.org/bhjjw>
14. Tsang W, Lang R. Three-dimensional echocardiography is essential for intraoperative assessment of mitral regurgitation. *Circulation* 2013;128:643-52. <http://doi.org/bhjjx>
15. 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. *J Am Soc Echocardiogr* 2012;25:3-46. <http://doi.org/dt5z3f>
16. Suri R, Hartzell P, Schaff D, Dearani J, Sundt III T, Daly R, et al. Survival advantage and improved durability of mitral repair for leaflet prolapse subsets in the current era. *Ann Thorac Surg* 2006;82:819-27. <http://doi.org/cb75v7>
17. Maffessanti F, Marsan NA, Tamborini G, Sugeng L, Caiani EG, Gripari P, et al. Quantitative analysis of mitral valve apparatus in mitral valve prolapse before and after annuloplasty: a three-dimensional intraoperative transesophageal study. *J Am Soc Echocardiogr* 2011;24:405-13. <http://doi.org/d329cv>
18. Biaggi P, Jedrzkiewicz S, Gruner C, Meineri M, Karski J, Vegas A, et al. Quantification of mitral valve anatomy by three-dimensional transesophageal echocardiography in mitral valve prolapse predicts surgical anatomy and the complexity of mitral valve repair. *J Am Soc Echocardiogr* 2012;25:758-65. <http://doi.org/sgq>
19. Tsang W, Weinert L, Sugeng L, Chandra S, Ahmad H, Spencer K, et al. The value of three-dimensional echocardiography derived mitral valve parametric maps and the role of experience in the diagnosis of pathology. *J Am Soc Echocardiogr* 2011;24:860-7. <http://doi.org/fp5svw>