Role of 3D Echocardiography Derived Color-Coded Parametric Models of the Mitral Valve in Differential Diagnosis of Prolapse and Billowing

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Abstract

Differentiation between mitral valve (MV) prolapse (MVP) and billowing (MVB) on 2D echocardiography (2DE) is challenging. We hypothesized that color-coded models of maximal leaflet displacement from the annular plane into the atrium derived from 3D transesophageal echocardiography (3DTEE) would allow discrimination between these lesions.

3DTEE imaging of the MV was performed in 52 patients with (N=40) and without (N=12) degenerative MV disease. Definitive diagnosis of MVP versus MVB was made using inspection of dynamic 3D renderings and multiple 2D cut-planes extracted from 3D datasets. This was used as a reference standard to test an alternative approach, wherein the color-coded parametric models (MVQ, Philips) were inspected for integrity of the coaptation line and location of the maximally displaced portion of the leaflet. Diagnostic interpretations of these models by two independent readers were compared to the reference standard.

In all cases of MVP, the color-coded models depicted loss of integrity of the coaptation line and maximal leaflet displacement extending to the coaptation line. MVB was depicted by preserved leaflet apposition with maximal displacement away from the coaptation line. Interpretation of the 52 color-coded models by 2 novice readers took 4-8 minutes and resulted in good agreement with the reference technique (kappa 0.82 and 0.74).

3D color-coded models provide a static display of MV leaflet displacement allowing differentiation between MVP and MVB, without the need to inspect multiple planes. This provides information on lesion location and extent, which should be useful for planning MV repair.

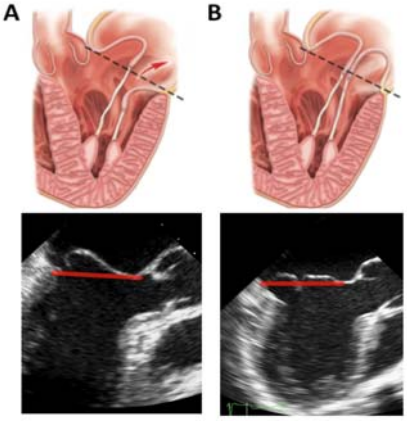
1. Introduction

MVP is the most common cause of mitral regurgitation (MR) [1]. Early surgery in the asymptomatic stage is recommended for MVP, if repair is deemed feasible, especially when the expected surgical success rate is >90% [2-3]. Successful MV repair is correlated to surgical expertise and the specific MV pathology, namely the extent and location of prolapsed and billowing scallops. Accordingly, differentiation between prolapse and billowing is important for the preoperative evaluation of degenerative mitral valve disease.

Although in the clinical setting, the terms 'billowing' and 'prolapse' are often used interchangeably, these entities are not identical, and differentiation between them on 2D echocardiography can be challenging. MVP is defined when the free edge of the leaflet remains above the plane of the annulus at end-systole, usually due to chordal or papillary muscle elongation or rupture, resulting in disruption of leaflet coaptation. MVB is defined when there is systolic protrusion of the body of the leaflet above the annulus plane with the free leaflet edge remaining at or below the annular plane during end-systole [4] (fig. 1). Using 2DE, MVP has been defined in the long axis view as end-systolic displacement of the body of the mitral valve leaflet ≥2 mm above the mitral annular plane. In this view, the most commonly visualized scallops are A2 and P2, making it difficult to diagnose prolapse of the remaining non-visualized scallops. Using transesophageal 2DE, identification of mitral leaflet scallops is easier [5-6], but mitral prolapse is still felt to be best identified in the long axis view.

3D TEE provides incremental benefit in the assessment of extent and location of degenerative mitral valve disease [7-8]. Specifically, the diagnosis of billowing versus prolapse can be performed by assessing multiple 2D cut-planes extracted from the 3D TEE datasets. The problem with this approach, however, is that it can be tedious and time-consuming. To circumvent this limitation, analysis software that generates color-coded parametric models of leaflet displacement from the annular plane into the atrium has been recently developed [7]. Since these models clearly depict the line of coaptation, we hypothesized that they could be useful for rapid differential diagnosis of MVP versus MVB. This study was designed to test this hypothesis and to generate a set of criteria that could be used as the basis for this objective diagnosis.

Figure 1. (A) Prolapse should be diagnosed when the free edge of the leaflet overrides the plane of the mitral annulus during systole (top), as illustrated with an example of anterior leaflet prolapse in this 2D TEE long-axis view (bottom). (B) Billowing should be diagnosed when there is systolic excursion of the leaflet body into the left atrium due to excess leaflet tissue, with the leaflet free edge remaining below the plane of the mitral annulus (top), as illustrated with a 2D TEE view (bottom).

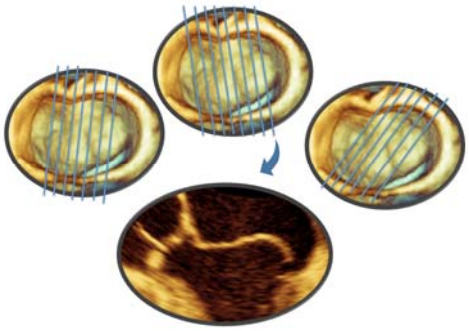


2. Methods

We retrospectively identified 40 patients with degenerative MV disease referred for a TEE evaluation and 12 patients with normal MVs (28 males; age 60±15 years). 2D and 3D TEE studies were performed using Phillips iE33 ultrasound system with an X7-2t matrix-array transducer. The 2D study was performed according to a standard clinical protocol, which comprises of a complete assessment of the MV. 3D zoomed datasets of the MV were acquired from the mid-esophageal long-axis view (120°) over 4 beats. 3D datasets were analyzed offline on an Xcelera workstation (Philips) by an expert reader. Mitral regurgitation was quantified from 2D TEE images using effective regurgitant orifice area and/or vena contracta criteria based on published guidelines [9].

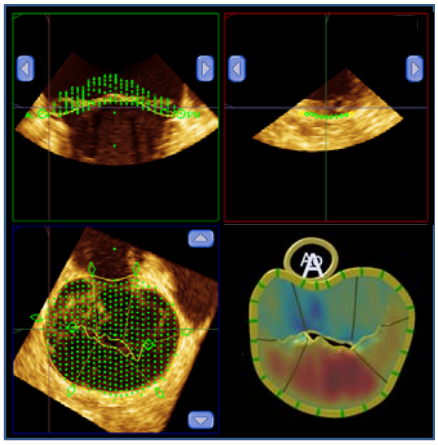
Visual inspection of dynamic 3D renderings of the MV and multiple 2D planes extracted from the 3D TEE datasets were used to diagnose leaflet segment prolapse and billowing. The results of this assessment were used as the reference standard for comparison with the volumetric modeling of the mitral valve. This analysis was conducted using 3D quantification software (QLAB, Phillips). After end-systolic frame was selected, multiple parallel 2D cut-planes were manually extracted from the 3D dataset along the coaptation line (fig. 2). Assessment of the leaflet edge position was accomplished by manually positioning the cut-planes across the area of apparent excess leaflet tissue. Prolapse was diagnosed when the tip of the leaflet was located in the left atrium (above the mitral annulus) at end-systole. In contrast, billowing was diagnosed if the tip of the leaflet was located at or below the annular plane at end-systole, and only the body of the leaflet protruded into the left atrium (fig. 2).

Figure 2. Extraction of multiple planes from the 3D TEE datasets across the coaptation line and excess leaflet tissue was used to determine leaflet free-edge position at end-systole for differential diagnosis of mitral valve prolapse versus billowing. The valve is thus "combed" in multiple directions (top, left to right) until a diagnostic cut-plane is identified (bottom), in which the leaflet free-edge position is clearly visualized.



Color-coded parametric models of the mitral valve were generated using MVQ software (Phillips), as previously described [7]. Briefly, 4 points were marked in 2 orthogonal planes (one plane being the mid-esophageal 120° view of the MV) in order to define the position of the MV in 3D space. These 4 points included the anterolateral and posteromedial hinge points of leaflet insertion and the anterior and posterior points. The annulus perimeter was manually outlined by defining annular points in serial planes rotated around the axis perpendicular to the mitral annular plane. Finally, the leaflets were traced in consecutive parallel long-axis planes spanning the annulus from commissure to commissure. Then the 3D model was constructed and displayed as a surface representing a topographic map of the mitral leaflets (fig. 3, bottom). The colors were coded to display the maximal leaflet displacement into the atrium from the annular plane at end-systole. The models were used to: 1) visualize the number, location, and extent of the prolapsed/billowing scallops, 2) define the spatial relationship between the prolapsed/billowing scallops relative to the coaptation line, and 3) assess the integrity of the coaptation line.

Figure 3. Construction of the color-coded parametric model of the mitral valve in a patient with posterior leaflet prolapse (see text for details).



Color-coded parametric models were reviewed by 2 echocardiographers with extensive experience with 3D imaging, who defined the diagnostic criteria for the following categories: normal MV, MVP, MVB, and combined MVB and MVP, using dynamic 3D rendering and the extracted 2D planes from the 3D TEE data set as the reference standard. MVP was diagnosed if a 2D cut plane across the excess leaflet tissue showed the mitral leaflet tip to be above the annulus at end-systole. MVB was diagnosed when a portion of the body of the leaflet protruded above the annular plane but with the leaflet tip remaining at or below the annulus at end-systole. Combined MVB and MVP were diagnosed if 3D renderings of the valve suggested both the presence of billowing segments and the above criteria for MVP were met.

Subsequently, the color-coded models were shown to 2 readers with intermediate experience in echocardiography and minimal experience interpreting 3D TEE images. Following a brief instructional session, which included review of two images in each category combined with an explanation on how to interpret these images based on the criteria defined by the experts, the readers independently reviewed the color-coded models of the 52 study patients and categorized them using the above definitions. Each interpretation was then compared to the above reference standard based on the visual inspection of multiple 2D planes extracted from the 3D datasets.

3. Results

Figure 4 shows an example of images obtained in a patient with a normal mitral valve, including the color-coded parametric model depicting intact coaptation line and no leaflet displacement above the annular plane (no red/orange coloring of the leaflets).

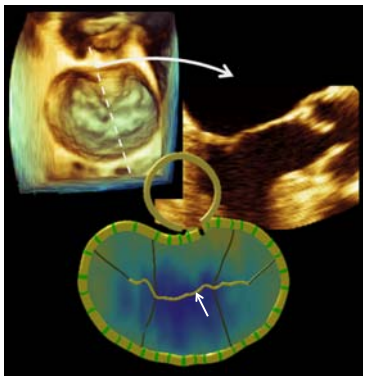


Figure 4. Example of images obtained in a patient with normal mitral valve: 3D rendered en-face view of the MV from the left atrial perspective (top left), a 2D cut-plane (see dotted white line and corresponding arrow that shows the plane from which the 2D display was obtained), which depicts leaflet coaptation and edge position with respect to the annular plane (top right), and the corresponding color-coded model (bottom) depicting intact coaptation line (white arrow) and no leaflet displacement above the annular plane, as reflected by absence of red/orange coloring of the leaflets.

Figures 5 and 6 show in the same format images obtained in two patients with MVP and MVB.

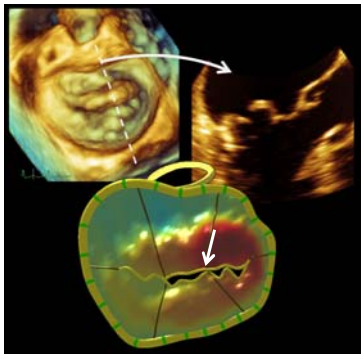


Figure 5. Example of complex MV prolapse, wherein the prolapsing leaflets appear on the 3D rendered en-face view of the MV as excess tissue protruding into the left atrium (top left). The 2D cut-panes through the excess tissue and coaptation line depict the leaflet edge positioned above the annular plane in the left atrium (top right). The end-systolic color-coded model depicts a defect in the coaptation line, and leaflet displacement into the left atrium (color-coded in red/orange), which extends to the leaflet edge (white arrow).

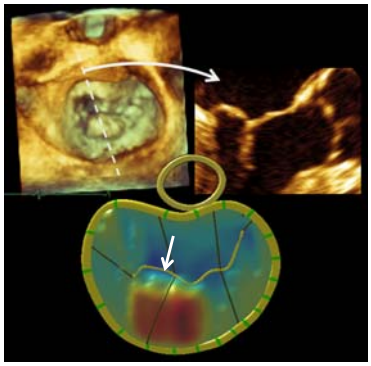


Figure 6. Example of multi-segmental MV billowing, wherein the billowing leaflets appear on the 3D rendered en-face view of the MV as excess tissue protruding into the left atrium (top left). The 2D cut-panes through the excess tissue and coaptation line depict the leaflet edges positioned at or below the annular plane (top right). The end-systolic color-coded model depicts an intact coaptation line (white arrow) with the body of the leaflet displaced into the left atrium (color-coded in red/orange), which does not extend all the way to the leaflet edge.

The reference standard technique based on visual inspection of the 3D renderings and multiple 2D planes extracted from the 3D TEE datasets identified 12 normal valves, 20 cases of MVB and 20 cases of MVP, of which 9 were identified as MVP alone and 11 as combined MVP and MVB (of different scallops).

The interpretation of the color-coded parametric models by one of the two novice readers took under 8 minutes for all 52 cases (average 9 sec/case) and resulted in excellent agreement with the reference technique (kappa 0.82). The second reader completed the interpretation in 4.5 minutes (average 5 sec/case) also showing good agreement with the reference technique (kappa 0.74).

4. Discussion

In this study we sought to define objective criteria for the diagnosis of MVB based on color-coded parametric displays of the mitral valve [10, 11]. Our secondary goal was to use these criteria to develop and test a fast, user-friendly less expertise-dependent algorithm for the differential diagnosis of degenerative MV disease, using color-coded parametric models of the mitral valve.

To achieve these goals, we used as a diagnostic reference standard the multiplanar reconstruction from 3D TEE datasets, which allows scallop visualization in multiple 2D cut-planes, making it possible to examine the leaflet free-edge of any scallop and to determine its position relative to the mitral annulus. While this approach is accurate, making it the ideal reference standard for the diagnosis of MVP and MVB, this methodology is tedious, time consuming and experience dependent and consequently impractical for routine clinical use. This method relies on repeatedly "combing" through the mitral valve leaflets in different directions and inspecting multiple 2D cut-planes in order to identify for each leaflet scallop the plane in which the position of the free edge is clearly visualized.

While the limitations of this methodology underscored the clinical need for a faster and more user-friendly approach, it allowed us to clearly define the differences between MV prolapse and billowing in the volumetric model. Specifically, end-systolic color-coded parametric models show that prolapsing scallops have the leaflet edge displaced towards the left atrium, adjacent to the disrupted coaptation line. In contrast, with mitral valve billowing, the coaptation line remains intact with only the body of the leaflet being displaced towards the left atrium. The displacement is frequently not contiguous with the coaptation line.

The definition for prolapse in the parametric model included: 1) leaflet free edge (tip) on the left atrial side of the mitral annulus, 2) prolapsing scallop extending to the coaptation line (leaflet edge) and 3) failure of leaflet tip apposition resulting in a defect in the coaptation line. In contrast, the definition of billowing included: 1) leaflet free edge at or below the mitral annular plane, 2) area of maximal billowing displacement, confined to the leaflet body, not including the leaflet edge or tip, which is located away from the coaptation line; 3) preservation of leaflet apposition with an intact coaptation line.

After establishing these definitions, it was possible for non-experts to distinguish between prolapse and billowing by assessing the integrity of the coaptation line and inspecting whether the area of excess tissue is adjacent to (prolapse) or away from (billowing) the coaptation line. The simplicity of this approach proved to be extremely valuable in terms of accuracy and time required to complete the analysis.

In summary, we described the 3D echocardiographic characteristics of mitral valve leaflet prolapse and billowing, as visualized on 3D color-coded parametric models. These provide easily interpretable information on the location and extent of the lesion. The diagnostic criteria described here constitute the basis for a fast and easy diagnostic algorithm, which should be useful in the planning of complex mitral valve repair.

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