Clinical applications

The road to mitral valve repair with live 3D transesophageal echocardiography (TEE)

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Chronic severe mitral regurgitation due to mitral valve prolapse is well established as a significant cause of cardiovascular morbidity and mortality [1-3]. Surgical intervention is often necessary in these patients to preserve life expectancy. Mitral valve repair is now well established as surgical techniques have advanced and repair is applicable in practically all patients with mitral valve prolapse due to degenerative mitral valve disease [2]. Valve repair offers a distinct event-free survival advantage compared with replacement using a bioprosthetic or mechanical valve [3, 4].

Despite consensus regarding the outcome and benefits of mitral valve repair, and support from practice guidelines [5], it is interesting to note that a significant number of patients with degenerative mitral-valve disease continue to undergo planned mitral valve replacement all over the world. The reasons for this are multifactorial, but one principal issue is a poor match between the complexity of the degenerative mitral process and the expertise and experience of the operating surgeon [6]. Moreover, assessment by echocardiographers of the etiology of prolapse disease as well as the location of the lesion depends on the skill and experience of the readers.

Transesophageal echocardiography is the imaging modality of choice for the mitral valve, and recent advances in live 3D imaging technology are facilitating definitive assessment of patients with chronic mitral regurgitation. This article describes the clinical utility of 3D cardiac imaging using the Philips X7-2t TEE transducer and the iE33 3D echocardiographic imaging system.

Assessment of mitral regurgitation by 2D echocardiography

2D transthoracic echocardiography is the most common imaging modality used to assess patients with suspected mitral regurgitation. Frequently these patients present to the clinic with symptoms of dyspnea, fatigue or other symptoms of left heart failure. The classic finding on physical examination is a systolic murmur radiating to the left axilla. 2D echo color Doppler techniques show the presence of a regurgitant jet within the left atrium. Figure 1 shows a 2D echocardiogram of the mitral valve.

Patients with mild or moderate mitral regurgitation that does not affect left ventricular function often do not require surgical intervention. In these patients, the goal of medical management is to improve or maintain the functional status of the patient. In severe mitral regurgitation, however, the surgical option of mitral valve repair may be indicated.

Figure 1. 2D echocardiogram obtained from a TEE in the mid-esophageal position. The left atrium is at the top and left ventricle below. The anterior and posterior mitral leaflets are shown. Note that the anatomic nature of the valve is not imaged as the surgeon sees it.
function, or physical symptoms such as decreased exercise tolerance, are simply followed over time to determine whether valvular or ventricular function is worsening. When deterioration ensues, the indicated therapy remains cardiac surgery. Importantly, standard 2D echocardiograms sometimes do not provide images with sufficient detail to delineate the exact mechanism of regurgitation, and specifically the type of disease creating the prolapse, such as fibroelastic deficiency or Barlow’s disease.

The test of choice for assessment, especially intraoperatively, to plan and assess mitral valve repair is transesophageal echocardiography (TEE). However, until recently, standard TEE provided only live 2D images.

**2D versus 3D echocardiographic transducers**

Ultrasound has been in use for cardiac imaging for over fifty years. Echocardiography combines portability, safety, low cost and widespread availability. The most significant advances that have occurred over the years include:

- development of two-dimensional real-time imaging to replace (spatial) one-dimensional M-mode imaging
- development of spectral Doppler techniques to evaluate valve flow and chamber filling
- development of color Doppler for spatial mapping of blood flow movement
- the placement of an ultrasound imaging sensor on a transesophageal gastroscope.

The ultrasound transducer gives echocardiography a unique position among cardiac imaging techniques. The transducer converts electrical energy into mechanical oscillations and vice versa.

In order to understand what sets 3D systems apart from conventional scanning systems, it is necessary to consider some acoustic principles. Current 2D systems transmit and receive acoustic beams in a flat 2D scanning plane. This is accomplished by sweeping an acoustic scan line within this 2D plane (Figure 2).

True three-dimensional ultrasound steering has been the subject of much academic and industrial research that began in the 1980s. The key difference between 2D and 3D imaging is that the latter involves beam sweeping in three dimensions (Figure 3). This poses several technical challenges:

- creating a transducer array with up to 3000 electrically active elements
- processing 3D data at rates exceeding 50 - 100 Mbytes/s
- presenting 3D data on a 2D screen
- quantifying data for physiologic measurements and for 3D intervention [7, 8].

The X7-2t transducer has been developed to overcome the problems of three-dimensional acquisition and processing. In this transducer the conventional PZT transduction material has been replaced by PureWave crystals. These crystals are far more homogeneous than the conventional material, down to the atomic level, enabling them to transfer energy with greater efficiency and precision, and with a greatly enhanced bandwidth. The result is better acoustic penetration and higher spatial resolution.

Transmission of a 3D image generated using thousands of elements via a conventional cable would require a cable containing thousands of wires, making it prohibitively thick. The first transducers for three-dimensional echocardiography were used with chest wall imaging. The problem of transmitting the acquired data was solved by integrating the beamforming circuitry in the handle of the transducer, rather than in the system itself. This allowed a relatively thin ergonomic cable to be used for this clinical application, as much of the processing already took place in the handle. However, while the handle of a chest wall transducer could hold these electronics, they would not fit into the tip of a TEE probe. Another revolutionary leap was needed to miniaturize the circuitry even more.
In 2007, innovations in miniaturizing beamforming electronics made it possible to create a 3D TEE imaging transducer [7]. Figure 4 shows the tip of a TEE transducer containing several thousand elements and electronics with a processing capacity that, ten years ago, would have been equivalent to 50 laptops. Moreover, reduced power consumption keeps the heat dissipation low enough to make 3D TEE imaging safe for esophageal use.

**Mitral valve anatomy**

In addition to defining a segmental approach to mitral valve anatomy, Carpentier and coworkers also proposed a pathophysiologic triad that is a useful adjunct to clearly differentiating the particulars of mitral regurgitation [9]. The triad consists of the etiology (such as Barlow’s disease or fibroelastic deficiency), the lesions (in the case of degenerative diseases primarily chordal rupture, chordal elongation, leaflet distension, annular and/or leaflet and/or papillary muscle calcification, and annular dilatation), and the dysfunction (which is defined based on the systolic position of the margin of the leaflets in relation to the annular plane).

The main two etiologies of degenerative mitral valve disease are Barlow’s disease and fibroelastic deficiency [10, 11]. Barlow’s disease results in myxoid degeneration of the mitral valve, creating excess tissue in multiple valve segments, chordal thickening and elongation and, less commonly, rupture usually associated with significant annular dilatation and sometimes calcification. Fibroelastic deficiency, on the other hand, results from a presumed deficiency of connective tissue [12], and leads to thinning of chordae and single, or sometimes multiple, chordal rupture. The prolapsing segment may be distended, but the remaining segments of the valve are classically entirely normal (Figure 5).

Distinguishing Barlow’s disease (Figure 6) from fibroelastic deficiency, as well as clearly defining the lesions and type of leaflet dysfunction, is of utmost importance for the imager, as it will guide appropriate informed...
transesophageal echocardiography (TEE) is, however, currently the most valuable modality for imaging of the mitral valve, and is generally regarded as a standard of care for the surgical assessment of mitral valve disease [14].

When using two-dimensional (2D) TEE to diagnose mitral valve pathology, or judge the success of mitral valve repair, the operator needs to obtain multiple two-dimensional multi-planar tomographic views with and without color Doppler to fully characterize the mitral valve. The systematic examination consists of four standard mid-esophageal views (four chamber, bi-commissural, two-chamber and long axis views) and the transgastric basal short axis view.

**Examination of the mitral valve using real time 3D TEE**

The recent development of a three-dimensional fully-sampled matrix-array TEE (Live 3D MTEE) transducer now allows real-time acquisition and on-line display of 3D images of the mitral valve and ventricle [15]. To obtain the surgical view of the mitral valve (i.e., the view the surgeon has when positioned on the patient’s right side when examining the mitral valve through the opened left atrium), the valve is best imaged in the 3D zoom mode. This mode displays a small magnified pyramidal volume of the mitral valve which may vary from a 20° × 20° up to 90° × 90° depending on the density setting, resulting in high-quality volume rendered images of mitral valve MV apparatus including the anterior and posterior leaflets, as well as annulus, commissures and subvalvular structures. Prior gated 3D TEE acquisition methods display the mitral valve from both atrial and ventricular perspectives that are unique to 3D imaging. What distinguishes 3D MTEE from rotational 3D acquisition is the consistency of superb quality of the mitral valve, devoid of rotational artifacts. It is anticipated that with the ability of real-time acquisition, on-line adjustments of rendering and cropping capabilities, this modality will be used routinely in the peri-operative planning of MV surgery.

**Pre-operative assessment of mitral regurgitation**

An accurate segmental analysis is the optimal approach to performing a thorough echocardiographic assessment of the mitral valve affected by a disease process. It enables the various anatomical components of the mitral valve to be assessed individually in a systematic manner, which will allow identification of all lesions and resulting dysfunctions, as well as help determine the etiology in most circumstances. Transesophageal echocardiography (TEE) is, however, currently the most valuable modality for imaging of the mitral valve, and is generally regarded as a standard of care for the surgical assessment of mitral valve disease [14].

**Post-repair assessment**

Immediately following mitral valve repair, there are several important aspects of the final valve anatomy which must be addressed by the imager. Of course, the most critical aspect of post-operative valve analysis is to confirm the absence of significant residual mitral regurgitation. The depth of coaptation should be documented and be at least 5 mm in a 2D long axis view to ensure adequacy of coaptation.

It is important to perform a segmental assessment to rule out residual regurgitation along any aspect of the coaptation surface, including the commissures. If a residual leak is identified, the lesions responsible (such as a leaflet clef or perforation) and the residual dysfunction (such as leaflet restriction or prolapse) should be sought and reported in a segmental fashion. Common causes of a residual leak include uncorrected segmental prolapse or restriction, a residual restricted leaflet indentation, an incorrectly sized or positioned ring that distorts the zone of coaptation, leaflet perforation of the leaflet from an annuloplasty suture or a defect way.

Myocardial motion occurs in three dimensions, thus 2D scanning does not capture the entire motion.

Live 3D MTEE allows real-time acquisition and display of 3D images of the mitral valve.
in a leaflet closure line. Any significant degree of mitral valve regurgitation (other than trivial to mild regurgitation) should usually prompt a return to cardiopulmonary bypass and subsequent valve re-exploration to correct residual or new defects. This strategy is imperative to avoid a heightened risk of re-operation in the patient early during follow-up, as there is a correlation between residual mitral regurgitation and early re-operation.

Systolic anterior motion (SAM) of the anterior mitral leaflet is a phenomenon almost unique to mitral valve repair, resulting from a mismatch of annular septo-lateral dimension and the residual combined leaflet height. Typically, the margin of the anterior leaflet is displaced into the outflow tract, causing both a significant outflow tract gradient as well as varying degrees of mitral insufficiency. The best echocardiographic view to interrogate this is the mid-esophageal long axis view. In some circumstances volume loading and increasing the ventricular after-load repositions the anterior leaflet minimizing the outflow tract gradient and valve regurgitation. If such maneuvers are not successful, valve re-exploration with placement of a larger ring, leaflet height shortening, or even valve replacement, is required.

**Live 3D TEE from the cardiac surgeon’s perspective**

Surgical techniques have progressed significantly, so that even some of the most complex cases of mitral prolapse are now treated with repair rather than replacement. It has now become imperative that cardiologists additionally become familiar with the classification of the etiology and lesions that underlie the degenerative disease process that results in the mitral valve prolapse. As these techniques have evolved, however, cardiac imaging of the mitral valve has remained unchanged in mainstream practice since the advent of multiplane TEE. Now, live 3D TEE represents a significant step forward in the management of patients with mitral valve disease.

The lesions and etiology of degenerative mitral valve disease have specific implications in terms of the “complexity” of techniques required to achieve a successful valve repair. A better understanding of the etiology and lesions will guide optimal referral and management of patients with severe mitral regurgitation.

While the overall mitral valve repair rate continues to increase in the United States, the rate of progress is too slow for many patients, as current estimates suggest that replacement rates still approach 50% in patients with degenerative disease. Most simple prolapses due to fibroelastic deficiency can be repaired by experienced cardiac surgeons, while most complex valves can be repaired in the hands of mitral valve subspecialists, so by matching the valve to the surgeon, most valves should be successfully repaired [6, 13].

Echocardiographers should become more familiar with the causes of degenerative mitral regurgitation, and specifically the lesions that lead to the valve dysfunction. New 3D echocardiographic techniques are making this easier. The lesions identified on echocardiography guide the surgical approaches and techniques needed to effect a repair. For example, if the echocardiographer notes a tall posterior leaflet (> 2 cm) then such a patient should only be referred to a surgeon comfortable with the techniques used to address excessive leaflet height (such as the sliding leaflet plasty [16, 17]).

The use of real-time 3D echocardiography is facilitating both lesion identification and localization, as it becomes integrated into everyday practice, and this is providing better information for the cardiologist, anesthesiologist and surgeon to guide optimal referral and surgical practice. This provides significant information both for referral and for surgical planning. These 3D echocardiographic visualization and quantification techniques provide more information about valve morphology than was ever available before, while making it easier for the cardiologist, anesthesiologist and surgeon to provide optimal care for their patients.