

# Anatomy of the mitral valve: understanding the mitral valve complex in mitral regurgitation

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Imaging the mitral valve requires an understanding of the normal anatomy and how this complex structure is altered by disease states. Mitral regurgitation is increasingly prevalent. Despite the fall in rheumatic disease, it is the second most common valvular lesion seen in adults in Europe. In this review, the morphology of the normal and abnormal valve is reconsidered in relation to the key structures, with a view to aiding the reader in understanding how this might relate to echocardiographic identification of abnormalities.

## Keywords

Mitral regurgitation • Anatomy

## Introduction

Imaging the mitral valve (MV) requires an understanding of the normal anatomy and how this complex structure is altered by disease states. The MV is composed of several structures working in synchrony to open during diastole and close in systole effectively within the high-pressure systemic environment. Morphological changes of the valve can affect mechanical integrity resulting in abnormal leaflet closure and regurgitation of blood back into the left atrium causing loss of ventricular pressure and forward flow.

Mitral regurgitation is increasingly prevalent. Despite the fall in rheumatic disease, it is the second most common valvular lesion seen in adults in Europe.<sup>1</sup> Surgical repair should be performed whenever possible when the likelihood of successful repair is high. Since retaining the native valve has significant advantages, including the preservation of left ventricular function and long-term survival.<sup>2</sup> In this review, the morphology of the normal and abnormal valve is reconsidered in relation to the key structures with a view to aiding the reader in understanding how this might relate to echocardiographic identification of abnormalities.

## Normal mitral valve anatomy

### Leaflets

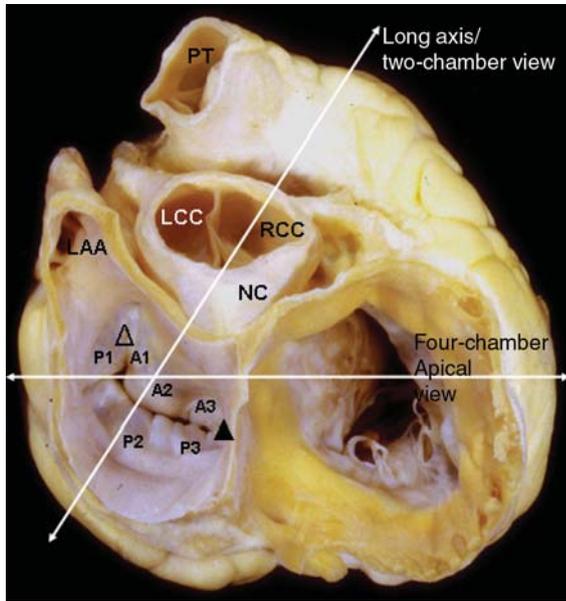
The MV comprises two leaflets, annular attachment at the atrioventricular junction, tendinous chords and the papillary muscles (PMs). The two leaflets of the MV are noticeably different in

structure and are referred to as the anterior and posterior leaflets by clinicians. Although neither description is anatomically correct, the terms aortic and mural leaflets are preferred.<sup>3</sup> The mural (posterior) leaflet is narrow and extends two-thirds around the left atrioventricular junction within the inlet portion of the ventricle. In adults, the mural leaflet has indentations (sometimes called 'clefs') that generally form three scallops (segments) along the elongated free edge. These indentations do not usually extend all the way through the leaflet to the annulus; if this is seen, then this is usually associated with pathological valve regurgitation. Carpentier's nomenclature<sup>4</sup> describes the most lateral segment as P1, which lies adjacent to the anterolateral commissure, P2 is central and can significantly vary in size, and most medial is P3 segment, which lies adjacent to the posteromedial commissure (*Figure 1*).

The semicircular aortic (anterior) leaflet of the MV is much broader than the mural leaflet, comprises one third of the annular circumference and has a clear and rough zone (*Figure 2*). The distinguishing feature of this leaflet is the fibrous continuity with the left and non-coronary cusps of the aortic valve and with the interleaflet triangle between the aortic cusps that abuts onto the membranous septum.<sup>5</sup> The aortic leaflet is also divided arbitrarily into three regions labelled A1, A2 and A3 corresponding to the adjacent regions of the mural leaflet (*Figure 1*).

From the attachment point of each leaflet at the annulus to the free edge, the leaflet is described as having basal, clear and rough zones (*Figure 2*). The basal zone is described as the area where the leaflet connects to the atrioventricular junction. The thin central portion of the leaflet is the clear zone. The thick rough zone at the free edge of the leaflet is the main area of chordal

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**Figure 1** Specimen picture showing the base of the heart with the location of two- and four-chamber echocardiographic views superimposed (double-headed arrows). (1) Base of the adult heart specimen showing the mitral valve with double-headed arrows superimposed demonstrating the two- and four-chamber echocardiographic approach.  $\Delta$ , anterolateral commissure;  $\blacktriangle$ , posteromedial commissure; A1–A3, divisions of the aortic mitral leaflet; P1–P3, divisions of the mural leaflet of the mitral valve; LAA, left atrial appendage; PT, pulmonary trunk; NC, non-coronary cusp of the aorta; LCC, left coronary cusp of the aorta; RCC, right coronary cusp of the aorta.

attachment and the region of coaptation (i.e. where the leaflets meet) and apposition (overlap of the leaflet free edge).

## Annulus

The term annulus is used to describe the junctional zone which separates the left atrium and left ventricle, this also gives attachment to the mitral valve. It is not a rigid fibrous ring but pliable, changing shape during the cardiac cycle. Instead, it incorporates several structures along its hinge point (see Histology section). The annulus, which demarcates the leaflet hinge line, is of oval shape, the commissural diameter being larger than the anteroposterior diameter (i.e. through A2 and P2). The aortic valve is in fibrous continuity with the aortic mitral leaflet (anterior) and the right and left fibrous trigones.<sup>6</sup> This region of the annulus is thus fibrous and less prone to dilatation. Beyond this point, the remaining two-thirds of the annulus are mainly muscular. In significant mitral regurgitation, this region is often seen to dilate, as well as being more prone to calcification.

## Chordae tendinae

In the normal valve, the leaflets have fan-shaped chords running from the papillary muscles and inserting into the leaflets. Depending on where they attach, there are three types of chordae

tendinae. Primary chords attach to the free edge of the rough zone of both leaflets. Secondary chords attach to the ventricular surface in the region of the rough zone (i.e. body of the leaflet). The tertiary chords are found in the mural (posterior) leaflet only which has a basal zone. These chords attach directly to the ventricular wall (Figure 3).<sup>7</sup> The posteromedial PM gives chords to the medial half of both leaflets (i.e. posteromedial commissure, P3, A3 and half of P2 and A2). Similarly, the anterolateral PM chords attach to the lateral half of the MV leaflets (i.e. anterolateral commissure, A1, P1 and half of P2 and A2). Among the secondary chords of the aortic (anterior) leaflet, there are two that are the largest and thickest. Termed strut cords, these arise from the tip of each papillary muscle and are thought to be the strongest.

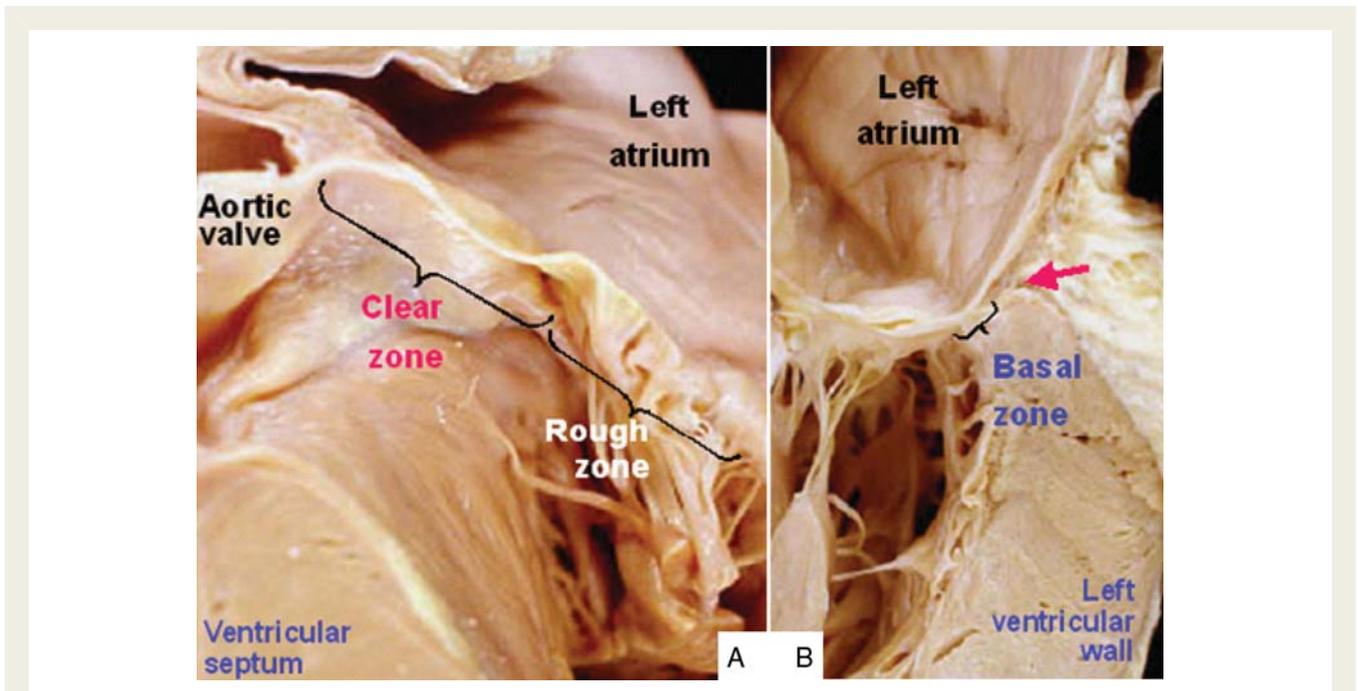
## Papillary muscles

The PM bundles are generally described in anterolateral and posteromedial positions and are positioned along the mid to apical segments of the left ventricle. The former is usually seen to attach at the border of the anterolateral (lateral) and inferolateral (posterior) walls, and the latter over the inferior wall of the left ventricle and in the majority of adults the PM can have up to three heads.<sup>8</sup> However, we have observed that this distribution can vary significantly, particularly, in patients with myxomatous-type leaflets (degenerative MV disease). In some cases, one or both PMs are undefinable and replaced with multiple small muscle bundles attaching to the ventricular wall (Figure 4).

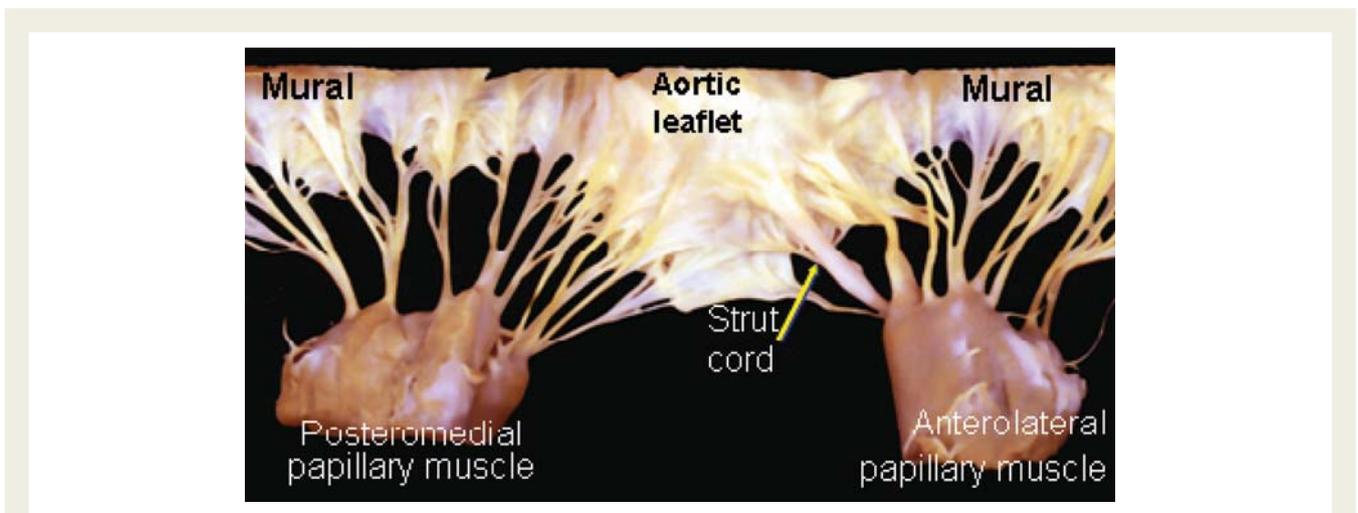
## Histology of normal mitral valve leaflets

The adult mitral leaflet contains distinct atrialis, spongiosa, fibrosa and ventricularis histological layers.<sup>9</sup> Each layer comprises extracellular components including interstitial fibroblasts and connective tissue fibres. Three types of collagen are present in the leaflet, primarily type I collagen at 74%, with type III collagen consisting of 24% and type V collagen at 2%.<sup>10</sup> The fibrous tissues, along with elastic fibres, are integrated together within a ground substance and are covered by a layer of endothelial cells. The endothelial layer of cells is continuous with the luminal surface of the atrium and the ventricle.

The atrialis is the uppermost layer adjacent to the left atrium. It is composed of mainly aligned elastic and collagen fibres covered with overlying endothelium. Beneath the atrialis is the spongiosa layer which largely consists of an extracellular matrix, or ground substance, of proteoglycans and glycosaminoglycans, along with elastic fibres. This layer is the major component of the free edge. The glycosaminoglycans and proteoglycans are hydrophilic and attract water molecules.<sup>11</sup> This characteristic causes the ground substance to expand and swell at the free edge, providing a natural physical protective buffer to the leaflet along the point of apposition to offset the effect of leaflet closure at the free edge. Beneath the spongiosa is the fibrosa layer. It is the major load-bearing layer, comprising the central structural collagenous core of the leaflet. The collagen fibres are compact and aligned providing strength and stiffness to the leaflet and are surrounded by glycosaminoglycans and proteoglycans. The fibrosa layer is situated nearest to the ventricular surface of the leaflet that faces the greatest pressure during valve closure. This layer extends from the



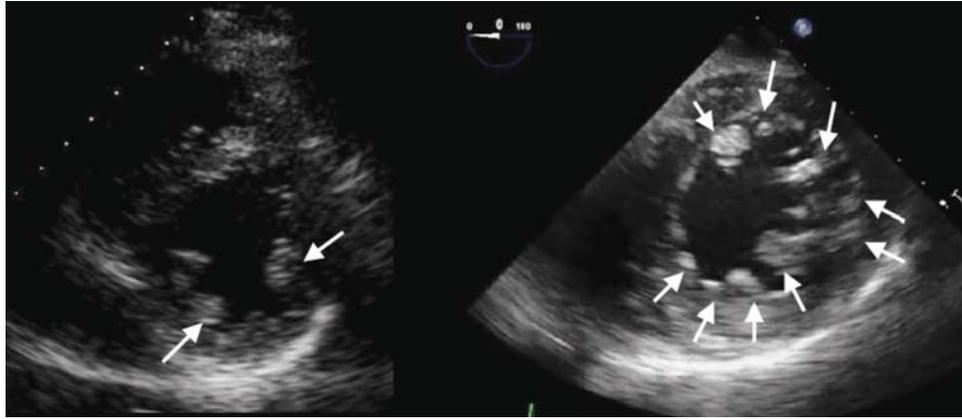
**Figure 2** (A) The aortic leaflet of the mitral valve is in fibrous continuity with the leaflets of the aortic valve, this comprises the clear zone of the leaflet. The undersurface of the rough zone in this mitral leaflet has many cordal attachments. (B) The mural leaflet of the mitral valve has a basal zone (bracket) which inserts into the annulus at the left atrioventricular junction (arrow).



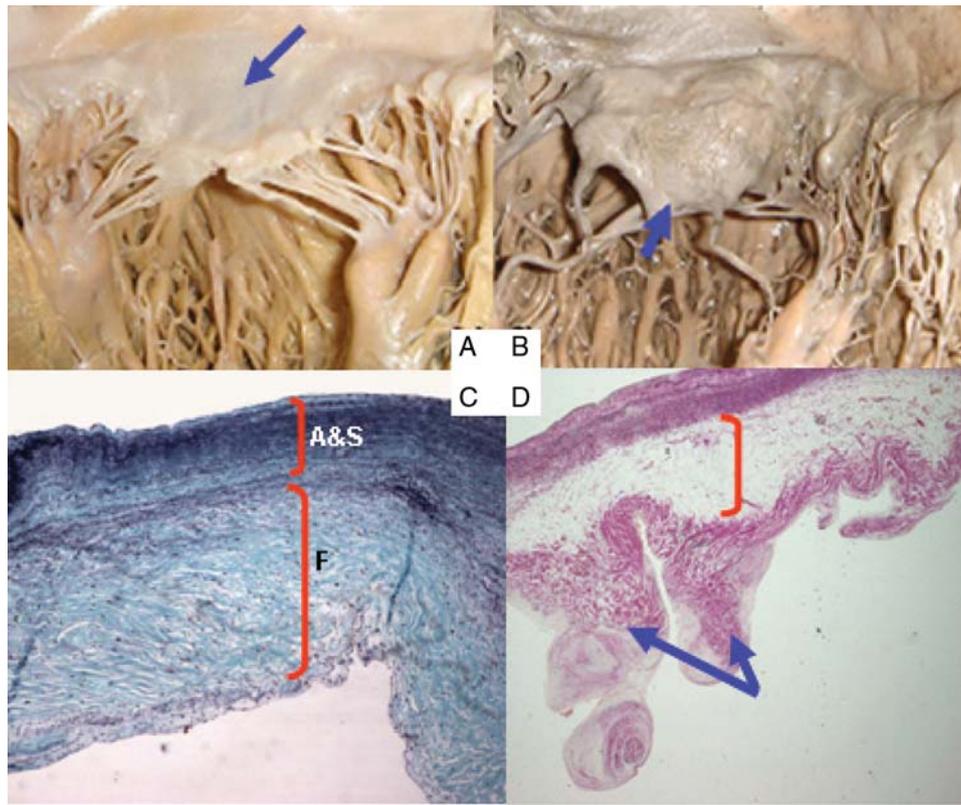
**Figure 3** View of the ventricular surface of an adult mitral valve. The chords extend not only from the free edge of the leaflet to the papillary muscles but also from the ventricular surface. This difference in chordal attachment, such as the stabilizing strut chords connecting the ventricular surface to the papillary muscles, demonstrates that the thickness and morphology of the leaflet varies from the annular attachment to the free edge.

annulus into two-thirds of the leaflet; it is absent at the free edge. The final layer of the mitral leaflet is the ventricularis, which is covered by a continuous sheet of endothelial cells that overlie elastic fibres and collagen fibres. The thickness of each layer varies from the attachment site at the annulus to the free edge. At the proximal region of the leaflet, near the annulus, the fibrosa is the thickest layer but it becomes thinner towards

the free edge of the leaflet and is totally absent at the edge. The spongiosa and atrialis layers increase in thickness distally becoming the main component of the leaflet at the free edge. Myocardial cells from the atrium do extend a short distance into the base of the mitral leaflet supporting the leaflet. However, there is no myocardial continuity between the atrial and ventricular walls in the normal leaflet. At the atrioventricular



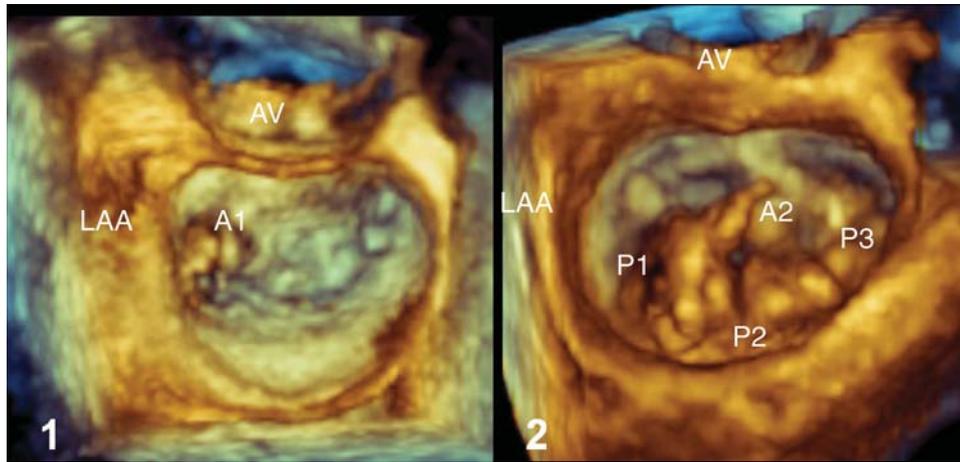
**Figure 4** Papillary muscle head orientation and distribution. Transthoracic 2D images: left image shows the normal arrangement of the two papillary muscles (most inferior is the posteromedial). The right image shows multiple small heads scattered around the ventricular wall, neither papillary muscle can be clearly defined. This patient has a prolapse of several segments of both leaflets.



**Figure 5** (A) Normal adult mitral valve at 22 years old. The clear zone of the aortic leaflet (arrow) is thin only at the free edge does the normal leaflet become thickened. (B) Floppy mitral valve demonstrating the thickening of the leaflets along with the elongation of the tendinous chords (32 years old). (C) Histological section of a normal mitral valve. With increasing age, more elastic fibres are present (purple staining fibres) alongside collagen fibres (blue). F, fibrosa; A&S, atrialis and spongiosa. Massons trichrome stain,  $\times 2.5$  (37 years old). (D) This histological section of a floppy mitral valve shows the near absence of fibres in the central fibrosa of the leaflet (bracket). Non-disrupted collagen fibres are present within the attached chords (arrows). Elastic van Geison stain,  $\times 2.5$  (27 years old).

junction, fibrofatty tissues interpose around the circumference. A complete cord-like fibrous ring as implied by the term ‘annulus’ seldom exists.<sup>12</sup> At this fibrous–myocardial junction where the

leaflet inserts, there are a number of smooth muscle cells associated with veins and arterioles. These vessels are confined to the base of the leaflet.



**Figure 6** Three-dimensional transesophageal images, surgical view (live 3D zoom mode). Image 1 (fibroelastic deficiency) shows a single segment prolapse, A1 which is flail due to chordal rupture. The remainder of the anterior (aortic) and posterior (mural) leaflets are relatively normal in appearance. Image 2 shows Barlow's valve, with multiple segment involvement (prolapsing segments are labelled). Deep clefts or indentations can also be appreciated. LAA, left atrial appendage; AV, aortic valve.

## The abnormal mitral valve

Complete closure (coaptation) and correct apposition (symmetrical overlap, usually a minimum of 4–5mm) of both leaflets is essential in preventing regurgitation. Since there are a number of ways in which valve failure may occur, it is useful to first establish the underlying aetiology, as this aids in initiating the process of understanding the mechanisms involved in valve failure. However, the two are not necessarily synonymous; it is nonetheless a useful starting point. Carpentier's functional classification describes leaflet motion in relation to the mitral annular plane. Type 1 describes normal leaflet motion. Mitral regurgitation is due to either perforation of the leaflet, such as trauma or endocarditis, or annular dilatation, usually the result of left ventricular disease. Type 2 describes excessive leaflet motion above the annular plane into the left atrium and is a result of leaflet prolapse usually the result of degenerative disease. Finally type 3 describes leaflet restriction and is categorized into two types; type 3a, where the restriction is throughout the cardiac cycle, i.e. in systole and diastole (usually the result of rheumatic valve disease) and type 3b, where the leaflet restriction is seen in systole alone (usually the result of regional wall motion abnormalities seen in ischaemic mitral regurgitation). The commonest mitral regurgitation aetiologies are degenerative (~60%), rheumatic (post-inflammatory, 12%) and functional (25%). The latter includes 'ischaemic' mitral regurgitation. Other less common causes include congenital abnormalities and endocarditis. With all these aetiologies mitral annular (or orifice), dilatation is observed to varying degrees.

## Degenerative mitral valve disease

The term 'degenerative' covers a range of abnormalities and includes Marfan's and Ehler's Danlos syndrome. Changes to the valve include thickening and stretching (due to disruption of the structural collagen core) of the leaflet tissue<sup>13</sup> (Figure 5). The abnormal leaflets can become twice as extensible.<sup>14,15</sup> A spectrum from a single



**Figure 7** Three-dimensional transesophageal images, surgical view (live 3D zoom mode). The white arrow points to a deep cleft within the P2 segment, which extends from the free edge to the annulus. This coincided with the region of severe mitral regurgitation.

segment of one leaflet through to all segments of both leaflets may be involved. The former has been coined 'fibroelastic deficiency' by Carpentier, whereas the latter describes Barlow's disease with myxomatous-type leaflets (Figure 6). In fibroelastic deficiency, often the prolapsing segment is relatively normal in appearance; the prolapse being the result of focal chordal elongation with or without rupture. At the other end of the spectrum, the widespread involvement of the majority of the segments is seen. This process affects the subvalvular structures with chordal thinning



**Figure 8** (A) Specimen demonstrating rheumatic mitral valve. The leaflets fuse from the zones of leaflet apposition (arrows). LAA, left atrial appendage. (B) Three-dimensional transesophageal images, surgical view (live 3D zoom mode). The leaflets are thickened and the commissures are fused. LAA, left atrial appendage. (C) showing a rheumatic mitral valve. Congenital stenosis of the valve is due to the fusion of the papillary muscles. Ao, aorta.

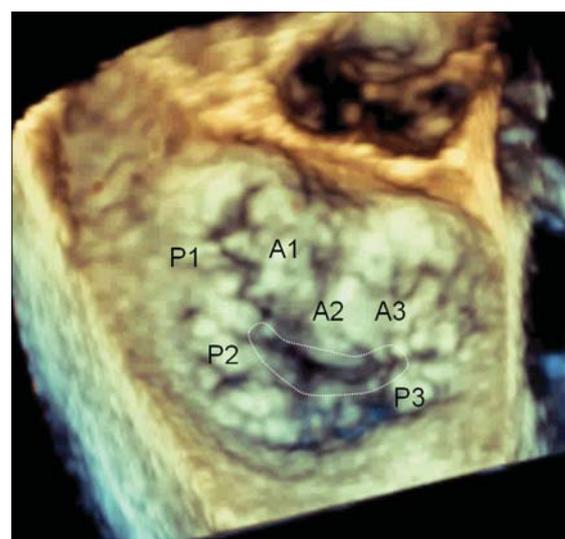
and elongation. This results in the effected leaflet segments ballooning into the left atrium.<sup>16–18</sup> Echocardiographically, they are described as ‘prolapsing’ back into the atrium. The mural leaflet is the most frequent area to develop thickening.<sup>19,20</sup> Mechanical stresses on the degenerative chords have the propensity to rupture.<sup>21,22</sup> If this involves the primary chords (to the leaflet rough zone), then there may be total eversion of the leaflet free edge into the left atrium. This is described as a ‘flail’ segment and its recognition is helpful as it is inevitably associated with severe regurgitation. The same disease process can result in focal regions of thickening with retraction and restriction, although this is far less common.

Primary defects of the leaflet have been observed in our practice. These include unusually deep clefts within the valve, which may be within a segment and extend from the free edge to the annulus (Figure 7). This is usually the primary site of regurgitation. This can occur without obvious prolapse of the segment, although it is usually seen adjacent to the prolapse. This type of relevant anatomy is increasingly being observed with the routine use of three-dimensional echocardiography, with its ability to image the MV in real time in the beating heart. It has been postulated that such defects could represent congenital lesions and are the underlying abnormality that cause such valves to regurgitate. Further PM abnormalities have also been noted in some patients and may represent the same congenital process (see earlier).

The regurgitant jet may cause mechanical attrition resulting in the secondary feature of fibroelastic thickening. Fibrin and platelet-rich thrombi aggregates are seen at the leaflet free edge and contribute to leaflet thickening.<sup>23,24</sup> These aggregates can be attributed to abnormal jet flows of blood and asymmetrical regurgitation of flow between the leaflets.<sup>25</sup>

### Rheumatic mitral regurgitation

Rheumatic valve disease is an acquired abnormality and usually involves some degree of valve stenosis with or without mitral regurgitation. Typically, the leaflets become fused at the commissures (Figure 8). The leaflets thicken and become rigid, whereas



**Figure 9** Three-dimensional transesophageal images, surgical view (live 3D zoom mode). This shows ischaemic mitral regurgitation. The patient suffered an inferoposterior infarction with resultant tethering of the posteromedial papillary muscle. The image depicts the failure of coaptation (dotted region) of leaflets in the P2 and P3 regions. These segments are restricted to closure in systole.

the chords can be shortened and attach to fibrotic PMs. These changes represent post-inflammatory changes which usually progress over time. Additionally, calcification within the leaflets, annulus, and subvalvular apparatus may occur. Fusion of the leaflets results in an eccentrically located funnel-shaped orifice. The mechanism of regurgitation is leaflet restriction with reduced motion described both in systole and in diastole. This is distinguished from functional mitral regurgitation where the primary abnormality

is the left ventricle, and unless severe, the restriction of leaflet motion is seen in systole alone.

## Functional mitral regurgitation

In this form of mitral regurgitation, the MV leaflets and subvalvular apparatus are morphologically normal. There is instead an abnormality of the left ventricular wall (with or without cavity dilatation) with a resultant change in left ventricular geometry. The wall motion dysfunction can be focal or global; the location and extent of which are reflected in the degree of PM malposition. This places tension on the chordal apparatus and is reflected in the restriction of leaflet motion in systole. An inferoposterior myocardial infarction with a thinned akinetic inferoposterior basal ventricular wall typically causes posterior leaflet restriction in the region of P3 and P2. There may be complete failure of coaptation in this region (leaflet tips fail to meet) or apposition (leaflets coapt but there is loss of the usual rough zone overlap of 4–5 mm, which is reduced) (Figure 9).

## Conclusion

The complex interactions of the normal MV are reliant on each component playing a complete role for the efficient working of the valve. Mitral regurgitation can be primary due to leaflet abnormalities, such as degenerative or rheumatic, and secondary due to dysfunction of the left ventricle with an otherwise structurally normal MV (such as dilated or ischaemic cardiomyopathy). An understanding of the normal anatomy of the MV complex and how this changes in disease states are important when assessing the mechanism of valve failure. This in turn will aid the assessment of the likelihood of a successful surgical MV repair and its potential durability.

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