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The mitral valve:
New insights into the clinical anatomy

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ABSTRACT
The thorough knowledge of anatomical details regarding the mitral valve is of utmost importance for diagnostic interrogation and surgery. Considering the mitral valve into the larger context of "the mitral valvar complex" *adds new and important details from the anatomic and physiologic points of view. This review article presents the more recent data and ideas regarding this vast topic and underlines some practical clinical applications. Eventually, the mitral valve does not represent solely a passive flap at the atrioventricular junction, but a finely-tuned and active set of elements acting in a coordinated manner. Age and the various disease processes change or alter this disposition and ask for a more elaborate medical thinking and skilled surgical maneuvers.*

Keywords: anatomy, mitral valve, echocardiography, valvar plasty

Mitral valve closure prevents systolic backflow of blood from the left ventricle into the atrium; this depends on the coordinated action of interrelated anatomical elements: the left atrium, the mitral valve leaflets, *"the annulus"*, the chordae, the papillary muscles, and the left ventricular wall. Alterations in the structure and function of any of these elements lead to mitral valvar incompetence. Accumulating data suggest the fact that mitral valve closure does not represent a passive process; instead, the model of an active valve emerges (1).

The broader concept of *"mitral valvar complex"* allows a better characterization of both normal and abnormal valvar function (Table 1). Beside the mitral valve proper, new elements of diagnostic and therapeutic relevance are included.

<table>
<tr><td colspan="2">Valvar leaflets (and commissures)</td><td rowspan="4">Mitral valve</td><td rowspan="8">Mitral valvar complex</td></tr>
<tr><td colspan="2">"Annulus"*</td></tr>
<tr><td>Chordae tendineae</td><td rowspan="2">Subvalvar apparatus</td></tr>
<tr><td>Papillary muscles</td></tr>
<tr><td colspan="3">Left atrial myocardium</td></tr>
<tr><td colspan="3">Left ventricular myocardium</td></tr>
<tr><td colspan="3">Left atrial and left ventricular endocardium</td></tr>
<tr><td colspan="3">Aorto-mitral curtain ("mitral-aortic continuity")</td></tr>
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TABLE 1. The mitral valvar complex
* see text or a further characterization of "the annulus"

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The thorough knowledge of anatomical details and of their functional characteristics, together with the implementation and use of a correct nomenclature, are of utmost importance for the diagnostic interrogation and therapeutic approach in mitral valve disease.

Each of the components can be synthetically described.

The leaflets represent a continuous (uninterrupted) structure but showing some regional differences, being consequently subdivided in an anterior and a posterior segment separated by the two commissural areas. The anterior mitral leaflet (AML) occupies roughly one third of the annular circumference and is wider than the posterior leaflet. Due to its relationships with the aortic valve and septal structures, the term "*aortic leaflet*" will be more suited. The posterior mitral leaflet (PML) occupies the remainder roughly two-thirds of the annular circumference, is narrower and presents a scalloped appearance with three or more segments separated by clefts. The commissures and the clefts are the areas of the mitral valve with less and thinner leaflet material, rendering pliable the posterior segment of the mitral valve and thus allowing the dilatation and reduction of the valvar circumference *("the sphincteric mechanism").*

The leaflets are non-homogenous structures and show a nonlinearly anisotropic behaviour (2). Both anterior and posterior leaflets are less extensible in the circumferential than in the radial direction. The PML shows greater extensibility in both directions, possibly due to the more abundant chordal sustain.

On microscopic examination, the leaflets have a fibrous skeleton *(the fibrosa)*, covered toward the atrial side by a layer of myxomatous connective tissue *(the spongiosa)*. The atrial and ventricular endocardium are continued over the leaflet surface, the so-called "*atrialis*" being a thin layer of collagen and elastic tissue covering the atrial aspect of the leaflets.

For a correct interpretation and orientation, the following coordinates characterize the leaflet anatomy (Figure 1):

- *atrial and respectively ventricular surface (aspect)*
- *leaflet thickness: between the atrial and ventricular surface*
- *peripheral (annular) insertion*
- *circumferential length*
- *free margin (free edge)*
- *leaflet width ("height"): between the peripheral insertion and the free margin*
- *coaptation region (line of leaflet closure*)

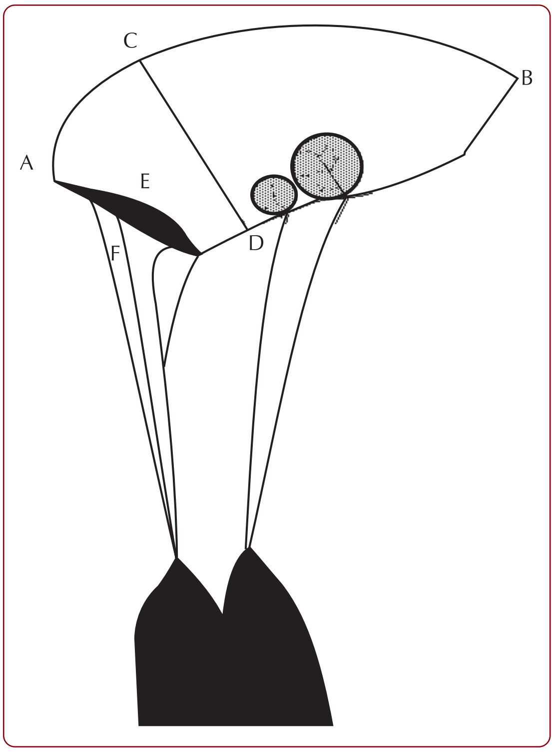

FIGURE 1. Schematic drawing of mitral valve leaflets and subvalvar apparatus; definition, coordinates

A-Bcircumferential length (following the peripheral insertion); C-Dwidth ("height"); E-Fthickness; Red line: coaptation region; arrow: free margin

The AML has a reduced circumferential length but is wider than the PML and has no clefts. The conspicuous and less pliable *rough zone* marks the line of leaflet coaptation. More peripherally, *the clear zone* of the AML is thinner and more malleable.

The PML is a partially divided structure with three or more scallops and the corresponding clefts. In spite of their different shape, the AML and PML have similar areas. Besides a rough and a clear zone analogous to the AML, the PML has a *basal zone* reinforced by atrial myocardium.

Starting from the antero-lateral commissure, towards the opposite postero-medial one, the scallops of the mitral valve can be designated as: P1, P2, and respectively, P3. The corresponding areas of the AML (in spite of the fact that the AML is an undivided structure) are designated as A1, A2 and A3. Due to the fact that papillary and chordal sustain is distributed to corresponding areas of the mitral valve leaflets – areas that will coapt during valve closure, 6 anatomic-functional scallops eventually result. This anatomic-clinical nomenclature allows a more precise definition of mitral valve leaflets, both in normal cases as well as in disease (Figure 2). For example various degrees and patterns of severity of mitral valve prolapse can be defined, from 1 out of 6 scallops through 6 out of 6 (1/6-6/6)., reflecting not only the severity of the disease, but also allowing a more precise orientation during diagnostic interrogation and surgery. ❑

The annulus represents a concept and not an anatomical well-defined structure. It is differently defined from the anatomical, echographical and respectively the surgical points of view. Following different landmarks, the annulus appears either planar or saddle-shaped. Anatomically, at the level of the atrioventricular junction, fibro-elastic tissue extends posteriorly from the left and right fibrous trigones forming a partial ring, otherwise completed by myocardium. The annulus is deficient anteriorly at the level of the aorto-mitral curtain. Echographically, the annulus is identified at the level of the valvar hinge resulting in a saddle-shaped form (a hyperbolic paraboloid) with "the lowest points" at the level of the commissures (3). Surgically, the annulus is identified at the level of the visible transition

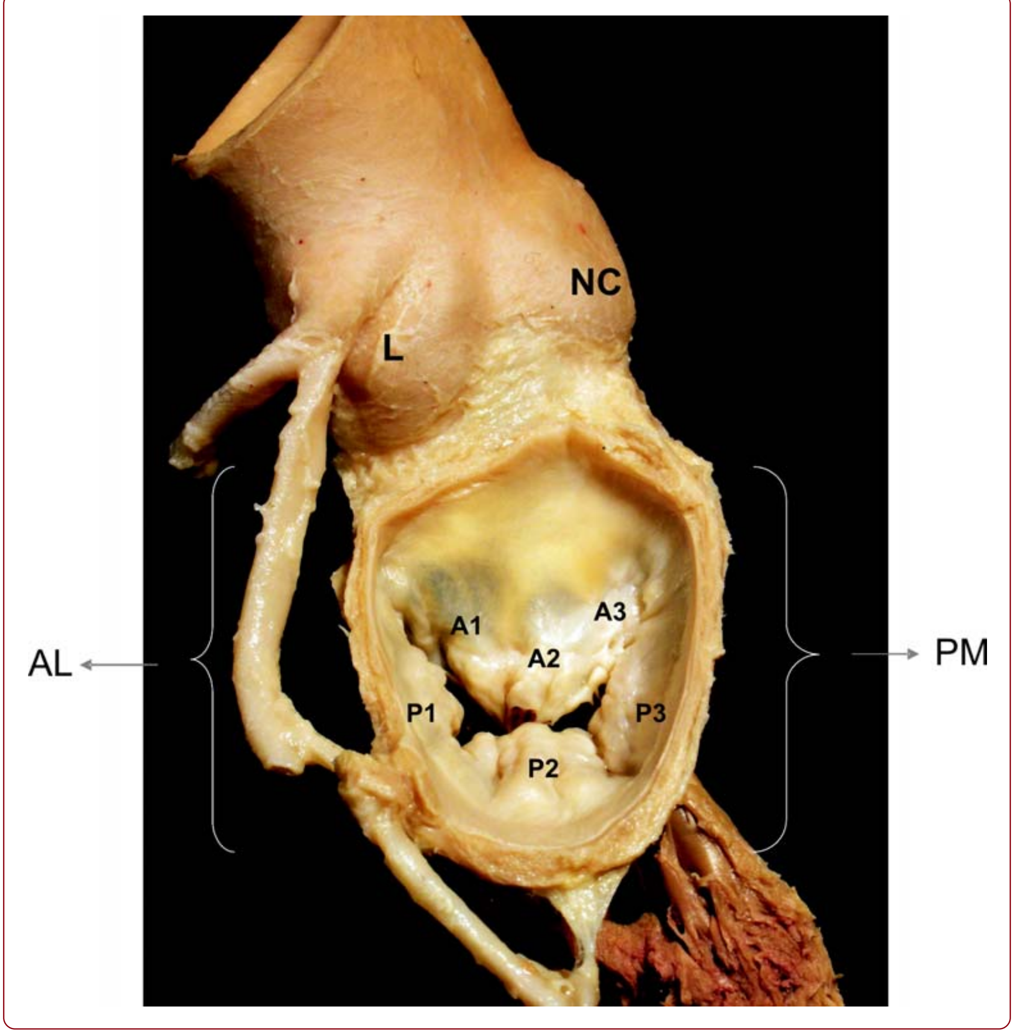

FIGURE 2. Anatomic-clinical nomenclature of scallops
Left atrial view of the mitral valve. Note the un-interrupted nature of mitral leaflets and the mitral-aortic continuity.
P1-P3 the scallops of the PML; A1-A3: the corresponding scallops of the AML; AL and PM: the areas of the valve sustained by the antero-lateral, and respectively, the postero-medial papillary muscles; L and NC: the left and non-coronary sinuses of the aorta.

between the left atrial endocardium and the whitish leaflet *atrialis*. No matter what definition of the annulus is chosen, the orifice at the level of the left atrioventricular junction is ovoidal with a longer intercommissural (IC) and a shorter septal-to-lateral axis (SL). Body-weight-corrected data are: 0.39-0.59 mm/kg for the IC and 0.32-0-48 mm/kg for the SL diameters respectively (4). However, dimensions are underestimated *"in vivo"* by two-dimensional echography as compared by three-dimensional echocardiography and with magnetic resonance imaging (5). Discordant findings regarding annular dimensions and dynamics are the result of the various and different methods of measurement (6).

The annulus depicts complex modifications during the cardiac cycle. The widening and narrowing define *the annular flexion*. There is a 23-40% variation in the annular circumference between the systolic and diastolic configuration (7). *The excursion* or *annular descent* is the movement in apical-to-basal direction. Mitral annulus excursion toward the apex can be better evaluated by using the two-dimensional strain imaging technique (8). Mitral annulus excursion (annular excursion volume) strongly correlates with left ventricular stroke volume (9). *The rotation* represents the torque movement while the complex three-dimensional modifications in shape are called, *folding* of the annulus. All such modifications are reduced or disappear with the use of rigid annuloplasty rings, postoperative fibrosis or extensive reduction of the posterior annulus.

The annulus shows a dynamic behaviour including its anterior (intertrigonal) portion; this latter also changes in response to modifications in haemodynamic loading and ventricular contractility (10).

Aortic and mitral annular areas change in a reciprocal fashion during late diastole and late systole (32 ± 8% for aortic annular area and 13 ± 13% for mitral annular area) but such dynamic changes seem not mediated through the anatomic fibrous continuity (11). ❑

The papillary muscles and **the chordae tendineae** represent the connection between the valvar leaflets, annulus and the ventricular wall. Different from the tricuspid valve, there is no direct attachment of the mitral valve to the ventricular septum. The length and the reciprocal ratio between papillary muscles and chordae, show individual variations, but studies demonstrated similar annular-to-papillary muscle tip distances in the 2-, 4-, 8- and 10-o'clock positions that also correlate with mitral annular diameter (12). and which are relevant for the proper choice of chordal length during reparative surgery.

Mitral valvar leaflets, scallops, clefts, commissures – on one hand, and chordae tendineae on the other, are reciprocally definable. The AML, and each of the scallops of the PML, have a convex free margin and receive chordal support from two distinct papillary muscles or papillary muscle fascicles (*"heads"*) (Figure 3), in such a manner that chordae from different papillary muscles, converge toward the leaflet. On the other hand, the clefts and commissures have a concave free margin and receive from a papillary muscle or fascicle situated immediately underneath, a chordal support that diverges (dichotomously or in a fan-like manner) toward the leaflet. Following their shape and chordal distribution, each scallop of the PML can be considered as a *"mini-AML"*.

The chordae tendineae represent complex structures. Their inner layer is composed of tightly bound collagen; the outer layer consists of loose collagen and elastic fibers and contains blood vessels. Chordae tendineae are covered by a layer of endothelial cells (endocardium). Fibroblasts are evenly distributed through both the inner and outer layers. The presence of blood vessels suggest an additional nutritional role for the leaflets (13). The chordae depict different microstructures according to their type, with higher levels of DNA and collagen at the level of the anterior and posterior marginal chordae (for a comprehensive classification of the chordal types, see Table 2). The complex three-dimensional arrangement of the collagen fibers offers a built-in elasticity to the chordae, mitigating the peak stress developed during ventricular and papillary muscle contraction (14). Extensibility of chordae increase with chordal size and decrease with age (15).

Chordae tendineae intermingle within the very substance of the leaflets, contributing to their fibrous skeleton. Intraleaflet extensions of some chordae, reach the level of the annulus.

The papillary-chordal-annular continuity is of notable importance in maintaining the dynamic shape of the left ventricle; the role of strut chordae integrity as *"active ligaments of*

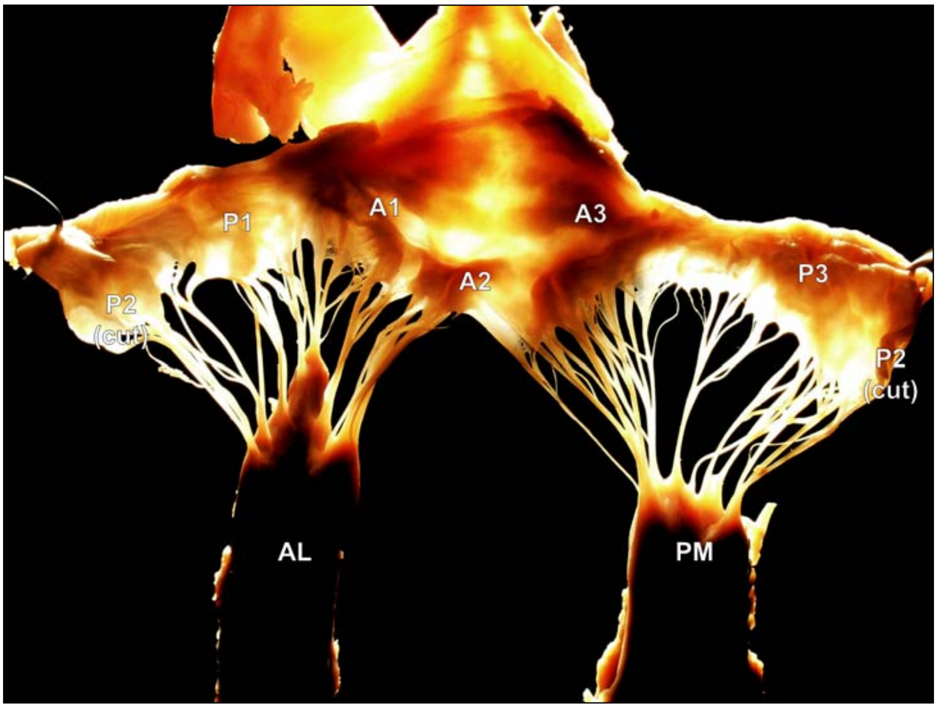

FIGURE 3. Mitral valve anatomy
The mitral valve has been opened at the level of the P2 scallop of the PML. The A1-A2-A3 scallops belonging to the AML are centrally-located. Note the convex free margin of the AML and of the scallops of the PML., the concave free margin of the commissural areas and clefts and the disposition of the corresponding chordal sustain (see txt for further details). The antero-lateral commissure is located between A1 and P1 while the postero-medial commissure, between A3 and P3. The mitral valve is backlit rendering evident the clear and the rough zones of the leaflets. Following their general contour and chordal distribution, each of the scallops of the PML resembles a *"mini-AML"*.

Old terminology	Lam et al. (1970) (34)	Ritchie et al. (2005) (35)
First order[A]	Commissural Rough zone chordae of AML and PML that insert into the free margin Branches of the cleft chordae of the PML	Commissural Posterior marginal chorda Anterior marginal chorda
Second order[B]	Rough zone chordae of AML and PML that insert beyond the free margin Strut chordae AML Main stem of cleft chordae of the PML	Posterior intermediate chorda Anterior strut chorda
Third order[C]	Basal chordae of PML	Basal posterior chorda

TABLE 2. Classification of mitral chordae tendineae
[A] Inserting on the free edge of the leaflet
[B] Inserting on the ventricular aspect of the leaflet and contributing to the rough zone
[C] Origin from the posterior left ventricular wall

the left ventricle" is relevant (16,17). The number of papillary muscle fascicles and their spatial relationship has a determinant influence on ventricular geometry and function both in normals and in disease (18).

The position of the papillary muscles and their three-dimensional orientation has an important role in the force distribution and in assisting the proper closure of the mitral valve (19,20,21).

The vascularization of the papillary muscles shows many individual variations and depends also on coronary typology and dominance. However, the posterior papillary muscle is vascularized by posterior left ventricular branches that may have origin in the right, left or both coronary arteries. The anterior papillary muscle is vascularized by branches from diagonal, circumflex or even acute marginal branches of the left coronary artery. Arterial branches for the papillary muscle have a recurrent tract toward their apices and represent the most distal coronary territory (both as length from the aortic origin and as number of bifurcations). The vascularization of the posterior left ventricle and the posterior papillary muscle are specially dependent on coronary typology and inter-coronary anastomoses. Papillary muscle ischemia is concomitantly an ischemia of the adjacent ventricular wall. ❑

Normal valve closure

The leaflets normally coapt by apposition of their rough zones. Proper inter-scallop coaptation is as important as coaptation between the AML and the PML (22). Coaptation takes place in a more apical plane *"under"* the level of the annulus. The resultant coaptation triangle, tenting area and tenting volume, are all parameters of diagnostic and surgical relevance (23). By joining their rough zones, the valvar leaflets overlap for about 5 mm. The quantification of the resultant coaptation surface has also diagnostic relevance.

The mechanisms of normal valve closure are complex and still incompletely understood. The major processes are: annular reduction (sphincteric mechanism), with the consequent apposition of the PML against the elevated AML (that functions as a trap door), reduction of all left ventricular dimensions and the subsequent creation of a pressure gradient between the ventricle and atrium that brings the leaflets toward the annular plane. Many interesting details are emerging, such as the presence of a rich innervation (24) and contractile elements within the leaflets, the contribution of left atrial myocardium to annular dynamics (25,26), the architecture of the left ventricular myocardium, the spatial disposition of the left ventricular trabeculae and papillary muscles, the presence of receptors in the structure of the leaflets.

The greater stress during valve closure is borne by the PML. The AML shifts between the closed and respectively, the open position, offering a transitory support against which, the PML abuts. The commissural (and cleft) areas, allow the apposition and concomitant reduction of the posterior leaflet and annulus. The submicroscopic structure of the commissural areas and the disposition of the fibrous skeleton, are fan-like, allowing successive expansions and reductions (thus eliminating the shearing stresses) (Figure 4). Mitral valve plasty with excessive PML reduction and/or immobilization of the PML, generate scissoring stresses over the commissural zones that might be responsible for the earlier failure of such techniques.

FIGURE 4. Commissural area
A close-up of a backlit commissural area reveals its submacroscopic structure and the fan-like disposition of its fibrous skeleton. Dilation and reduction of the leaflet material at this very level, enables the sphincteric mechanism characteristic for the PML. Note also the thinner leaflet material as compared with the rest of the valve.

The anatomic aperture of the valve between the two leaflets does not represent the sole orifice to be traversed by the blood column from atrium to ventricle; blood must cross the interchordal spaces and the space between the papillary muscles and the inferior aspect of the AML (this latter separates the left ventricular inflow from the left ventricular outflow tract). Chordal and papillary muscle agglutination occurring in rheumatic disease or hypertrophic cardiomyopathy will impede the passage of blood through these secondary spaces. Echographic interrogation allows to define an anatomic and a functional mitral area. The anatomic (planimetric) area represents the measurement of the virtual aperture of the valve leaflets and this largely depends on the cutting level, the mitral valve being approximately funnel-shaped. Measurement of the anatomic area requires a skilled operator and a good knowledge of the modified mitral valve anatomy in various disease states. The functional area (pressure half time) does not have a precise anatomic equivalent: this parameter designates the passage of blood from atrium to ventricle, through the main orifice and through all the secondary spaces mentioned above (interchordal, interpapillary). It can be altered with high cardiac output states, anemia, dysrhythmias etc. The anatomic and the functional areas must be similar though not identical. ❑

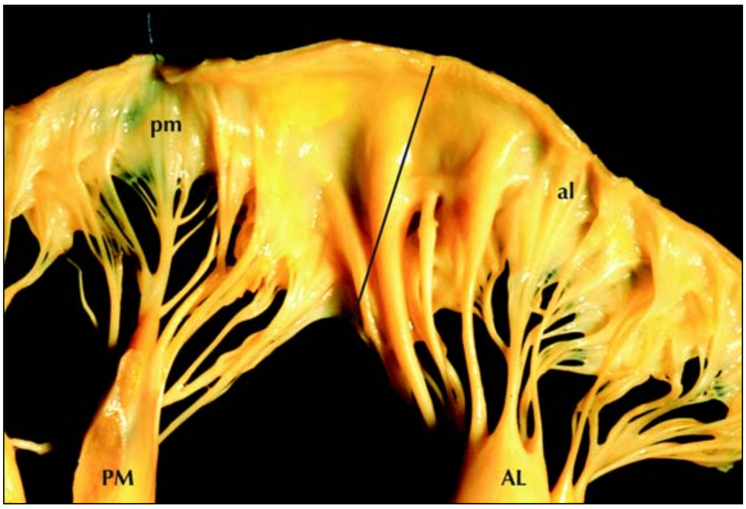

FIGURE 5. The asymmetry of the mitral valve
An endoventricular view of the open mitral valve. Note the important contribution of the chordal elements to the very structure of the leaflet. The asymmetric distribution of the chordae is evident, some crossing the imaginary line that divides the valve in two halves. The clinical impact is quite different, depending on the size and distribution of a chorda and its contribution to the fibrous skeleton of the leaflet.

The functional reserve of the mitral valve

The total leaflet area is 1.5-2 times the annular area (27). Generally, values above 2.3 cm/m² BSA are accepted as normal. The valvar aperture between the AML and the PML is ovoid in shape (becoming crescent-shaped after ring annuloplasty). The area of the aperture is roughly 2/3 of the annular area (28). The difference between the leaflet and the annular area characterizes the functional reserve of the mitral valve, allowing the adaptation of the valve to the various haemodynamic conditions.

The mitral valve shows a natural asymmetry. Leaflets are not equal. The scallops of the PML do not share even leaflet material. Papillary muscle and chordal support are not evenly distributed over the two imaginary halves of the valve (Figure 5). Thus, the functional characteristics and behaviour of the valve, both under physiologic and pathologic conditions show important individual variations, of clinical and surgical relevance. The complex physiology of a normally-asymmetrical structure needs further investigation (29,30,31).

A great part of the left ventricular outflow tract is formed by the AML and by the mitral-aortic continuity. The papillary muscles, together with the strut chordae which insert into the AML and which proceed toward the left and right trigones of the heart – not only delimitate the outflow tract, but offer in the mean time an important support to the fibrous part of the aortic root. Any imbalance of this complex structure will be mirrored at the level of the outflow tract too, as in the well-known case of systolic anterior motion of the AML.

Important parallels and comparisons can be drawn nowadays, between data on the structure and function of the mitral valve, on one hand, and the various disease states, on the other. Newer and deeper insights into the clinical anatomy (32) offer a sound basis for an accurate medical practice and for further research as well. Ultrasound examination represents the best and the mostly used diagnostic tool with multiple valences: from patient screening to risk stratification or in the long-term follow-up after surgery (33). With the advent of new imaging techniques in cardiology, the clinical thinking and the practical approach of the surgeon have been completely changed over the few last decades. Thus, mitral valve repair is gaining worldwide more acceptance and surgical skill is improved. A constructive dialogue should be ideally established among all the specialists who diagnose and treat the diseases of the mitral valve. The balance between valve repair versus replacement is shifting towards the first, reaching impressive percentages in dedicated centers, where up to 98% of the regurgitant mitral valves are repaired, including the complex procedures in complex and difficult cases such as those presenting with bi-leaflet or commissural prolapse. (**Diena M** – Personal communication, 2006). ❑

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