CHAPTER 43 THE NORMAL VALVE-CONCEPT SUMMARIES

The following are brief summaries of concepts underlying normal mitral valve mechanics that we find most compatible with the currently available data. Chapters developing and supporting these concepts are identified at the end of each summary.

FIBROUS ANNULUS

At the onset of each beat, immediately before valve closure, increasing LVP dilates the LV outflow tract which abruptly displaces the left and right fibrous trigones laterally towards the interventricular septum and down towards the LV apex (decreasing the fibrous annulus angle (LFT-SH-RFT)). These displacements produce tension in the contractile portion of the mitral annulus; much as pulling on the reins of a horse provides tension in the reins and tightens the bit. As ejection proceeds, myocardial contraction (not LVP) pulls the trigones further in these directions. CHAPTERS 02, 17

PAPILLARY TIPS

Papillary tips rotate around their respective trigone axes throughout the cardiac cycle, thereby maintaining their positions constant with respect to the mitral annulus to within a few millimeters in three-dimensional space throughout the entire cardiac cycle. In many respects, the papillary tips can be considered as suspended, parachute-like, below an annular “canopy” by rather stiff chordal “suspension lines”, while the papillary bases accommodate left ventricular wall motion via papillary muscle length changes. Papillary tip positional constancy is needed to properly set the initial geometric conditions for the leaflets (i.e., shape, position) at the instant of valve closure, thereby allowing the valve to be nearly self-supporting. CHAPTERS 03, 19, 20

ANTERIOR LEAFLET STRUT CHORDAE

Anterior strut chordae are always in tension and remain at roughly constant length. During diastole, they prevent the anterior mitral leaflet, particularly its leading edge, from encroaching beyond a certain point into the LV outflow tract. At the moment of valve closure, they help set the annular half of the anterior leaflet into a specific initial 3D geometric configuration (stiff hyperbolic paraboloid “saddle” shape, radially convex, circumferentially concave to the LV), after which the leaflet becomes locked into this rigid 3D configuration by LVP loading throughout the rest of systole and IVR. CHAPTERS 03, 04, 06, 07, 19, 21

ANTERIOR LEAFLET MOBILITY

Anterior leaflet opening takes place primarily at the leaflet edge; the annular half of the leaflet has severely restricted mobility. CHAPTERS 05, 24

ANTERIOR LEAFLET SHAPE

The annular two-thirds of the anterior leaflet is set in a hyperbolic paraboloid “saddle” shape (radially convex, circumferentially concave to the LV; not associated with annular shape) at the moment of valve closure. Subsequent loading of this structure produces an offsetting combination of radial compression and circumferential tension that dramatically decreases load-induced anterior leaflet deformation. Anterior mitral leaflet shape is maintained with sub-millimeter precision the entire time the mitral valve is closed, in spite of changing LVP. The anterior leaflet behaves much like a canvas sail that can bend to its near-final shape in a light breeze, yet hold this shape, with very little displacement or surface strain, in a gale. Because the anterior leaflet is an important component of the LV outflow tract, this invariant shape is important for efficient outflow patterns. During diastole, the anterior leaflet flattens considerably and its free edge takes on very complex shapes, including sometimes folding back on itself. CHAPTERS 06, 08, 09, 11, 18, 30
ANTERIOR LEAFLET STIFFNESS

The anterior mitral leaflet owes its systolic stiffness to both its shape and highly active material properties. In the closed valve, its saddle shape provides radial leaflet compression and circumferential leaflet tension that offset to minimize deformation with pressure loading. In response to A-wave excitation, cardiac myocytes in the annular half of the leaflet provide a stiffening twitch at the beginning of each ventricular systole. This stiffness-twitch is abolished by beta-blockade, but insensitive to neural stimulation. The bulk of steady-state leaflet stiffness is provided by contractile cells (likely VICs, cross-linking collagen throughout the leaflet), insensitive to beta-blockade, but responding to neural stimulation with rapid increases or decreases of overall leaflet stiffness. The stiffness of this leaflet may be under reflex and/or central control, providing leaflet stiffness changes to maintain appropriate outflow-tract geometry under widely-varying hemodynamic conditions. CHAPTERS 11, 29, 30, 31, 37

ANTERIOR LEAFLET LV POSITION

The position of the anterior leaflet edge in the LV, once established at end IVC, exhibits unchanging 3D positional stability throughout ejection in each beat as well as sub-millimeter reproducibility from beat-to-beat. Its 3D position is virtually independent of changes in left ventricular pressure, the changing geometry of the LV throughout ejection and isovolumic relaxation, and pressure from coapting posterior leaflets in the closed valve. CHAPTERS 13, 28

ANTERIOR LEAFLET AREA

Anterior leaflet surface area is constant to within a few percent over the wide range of left ventricular pressures from mitral valve closure to end IVR. CHAPTER 10

ANTERIOR LEAFLET PERFUSION

The myocyte-containing annular half of the anterior leaflet has a rich vascular supply arising from the mid- and distal left circumflex coronary artery, entering the leaflet near the trigones, particularly near the commissures. Additional leaflet perfusion is possibly provided through both strut and edge chordae. CHAPTER 32

ANNULAR SIZE VARIATION

The mitral annulus exhibits a large variation in size during the cardiac cycle and these dimensional changes occur rather uniformly throughout the entire contractile (non-trigonal) portion. Annular area, greatest in diastole, begins to fall, driven by annular contraction (triggered by atrial excitation) well before the onset of left ventricular pressure rise and valve closure. Systolic pressure on the LV side of the posterior leaflets is fully capable of creating and maintaining the reduced annular dimensions throughout ventricular systole. Annular area begins to increase during isovolumic relaxation, as left ventricular pressure is falling rapidly, well before mitral valve opening. CHAPTERS 14, 15, 16, 24

LV-ANNULAR COUPLING

The contractile mitral annulus and the LV basal myocardium are elastically tethered but their movements are out of phase, with the connecting tethers shortening during ventricular systole and stretching during ventricular diastole. CHAPTER 16

ANNULAR SHAPE AND FLEXION

The mitral annulus is a hinged structure, with the hinge (separating the contractile and non-contractile portions of the annulus) located roughly along a line between the left and right fibrous trigones. At the beginning of each beat, the mitral annulus is rapidly driven towards its mean systolic shape by the increase in LVP during IVC, starting immediately with the rapid LVP increase, continuing during and after mitral valve closure, and reaching a minimum in mid-to-late systole. Mitral annular shape is constant throughout systole in each beat and exhibits
sub-millimeter beat-to-beat repeatability. Annular shape begins to be driven back towards its diastolic value as LVP falls during the last half of IVR but before mitral valve opening. During systole, annular shape is dictated principally by LV pressure, not LV volume. During diastole, annular shape is dictated principally by LV volume, not LV pressure. The complete mitral annulus (trigone region plus contractile annulus) increasingly flattens throughout diastole, reaching its flattest configuration at the onset of the LVP increase at the beginning of each beat. It immediately becomes more curved in concert with the rising LVP during IVC, reaching its maximum curvature in mid-to-late systole then begins to flatten again in mid-to-late IVR as LVP falls. The contractile annulus, however, is much flatter than the complete mitral annulus and exhibits less curvature change throughout the cardiac cycle. CHAPTERS 17, 18

HINGE CHORDAE

Chordae from the papillary tips to the mitral annulus (leaflet hinge sites) maintain constant 3-D mitral valve geometry as LV dimensions change throughout the cardiac cycle. This constant geometry provides precise leaflet shape and edge positioning at the moment of valve closure and positions strut chordae to prevent diastolic anterior leaflet incursions into the outflow tract. Papillary forces, transmitted through the hinge chordae, limit annular displacement towards the left atrium (along with tertiary chordae) and help pump blood, particularly in the last half of systole. If precise leaflet 3-D geometry at the instant of valve closure is set properly, the valve becomes almost self-supporting as LVP presses on its leaflet surfaces (drawing the annulus inwards and the posterior scallops against the stiff anterior leaflet) as well as creating internal load-bearing rigid leaflet coaptation regions and folds. CHAPTERS 19, 40

PAPILLARY FORCE AND CONTRACTION

The long axis of the posterior papillary muscle is aligned with the region near the right fibrous trigone and the anterior papillary muscle is aligned with the region near the anterior commissure. As papillary muscle fibers are aligned with the papillary long axis, the greatest force generation will be in this direction. The papillary tips are held in a precise and relatively fixed 3D geometric relationship to the mitral annulus throughout the cardiac cycle by stiff chordae subjected to rather small forces. This fixed geometric relationship allows the leaflets to close gently during IVC (with almost no tension in the chordae or their associated papillary muscle), with leaflet shape and position established at the moment of closure in very nearly the geometry that will be maintained throughout systole. At the moment of mitral valve closure, with near-maximum LVP pressing on the closed leaflets, the chordae experience very little force, about 8% and 1%, respectively, of the maximum force developed in mid-systole by the anterior and posterior papillary muscles. This supports the concept that the mitral valve leaflets in the closed valve are nearly self-supporting, without requiring major chordal/papillary forces to maintain valve closure. Papillary force development, transmitted through the hinge chords, contributes about 10% to the total force of contraction, particularly in mid-to-late systole. Papillary muscles can shorten up to 30% and shortening continues throughout IVR. Such late papillary force and shortening, potentially supplementing the primary opening force associated with the reversal in the LVP/LA pressure gradient, may well play an active role to aid quick and reliable valve opening at end IVR. CHAPTERS 20, 21, 22

POSTERIOR LEAFLETS

The maximum posterior leaflet edge opening silhouette is virtually identical to the annular silhouette as viewed from LA to LV. Thus, flow from the left atrium into the left ventricle does not encounter significant restriction associated with a narrowed opening due to the posterior leaflet. The P1-P2 and P2-P3 junctions are capable, almost entirely, of providing the large change in posterior leaflet perimeter needed to open the valve widely during left ventricular filling and close it tightly during ejection. In many respects, these regions provide junctions similar to pleats used to gather a wide piece of fabric to a narrower circumference. Posterior leaflet pleats are greatly flattened during diastole and gathered tightly during systole. Folded pleats in the closed valve are pressed tightly together by systolic left ventricular pressure acting on their outer (ventricular) surfaces,
helping to align and position adjacent leaflet coapting surfaces precisely at the moment of valve closure and providing a rib-like structure that helps stiffen the posterior leaflet to resist systolic deformation. The posterior leaflet belly has tertiary chordal support. The very wide opening of the posterior leaflets has flow consequences. Such opening squeezes most of the blood out from behind these leaflets because they nearly contact the LV endocardium. This “squeezed” blood flows in the same direction as, and contributes to, central LV inflow. When the posterior leaflets close again, a fresh charge of blood enters this space, preventing stasis behind the leaflets. In contrast, the anterior leaflet, when maximally open, leaves a large space behind itself in the outflow tract. Indeed, the anterior leaflet region near the annulus is like a drumhead, supported by the stiff trigone regions, which guides diastolic inflow away from the LV outflow tract. Even the anterior edge region is prevented from entering too far into the outflow tract by the strut chordae. As a result, the anterior leaflet can be thought of as a flow-guiding boundary for both LV inflow and outflow, while the posterior leaflets serve the primary role of offering a minimum impediment to LV inflow during filling, then closing against the anterior leaflet to prevent regurgitation, but having a lesser impact on flow during ejection. CHAPTERS 24, 25, 26, 27, 37, 39, 41

**COAPTATION**

The contact regions of the anterior and posterior leaflets exhibit three geometric configurations: folding near the annulus; 2-curve coaptation in 5 regions further from the annulus; and 3-curve coaptation (similar to the aortic valve) in 2 regions further still from the annulus. Specific sites on the leaflet edges are reproducibly aligned at the beginning of each beat with mm (and typically sub-mm) precision and this alignment precision is preserved (rigid coaptation region) in the closed valve for the duration of each beat. At the instant of valve closure, the 3-D geometry of the leaflets is first established by the chordae, then the posterior leaflet folds are forced toward one another and toward the anterior leaflet by LVP which tightens the posterior leaflet perimeter against the anterior leaflet. The higher the left ventricular pressure, the greater the stiffness of the anterior leaflet (via the interplay between compression and tension in the saddle-shaped anterior leaflet) and the more forcefully the posterior leaflet perimeter is tightened about the stiff anterior leaflet perimeter. Spreading coaptation over a large surface “rough zone” contact area reduces crushing forces below the threshold required to damage blood cells trapped in the coaptation region, thereby preventing blood cell damage, yet maintaining tight closure. Microscopic spaces distributed throughout the rough zone contact areas could allow protected regions where the blood cells are not subjected to crushing forces associated with leaflet coaptation. Frictional interactions between the “rough zones” in the coaptation regions at the edges of the anterior, P1, P2, and P3 leaflets lock the leaflet edges in place, thereby preventing the leaflets from slipping past each another toward the left atrium. The folds and coaptation regions in the closed valve form a structurally rigid supporting “skeleton” that resists displacement of the assembly towards the annulus. The higher the left ventricular pressure, the more these regions press together, the stiffer and more extensive this structural support becomes, thereby further resisting the tendency of the leaflet assembly to displace towards the mitral annulus as LVP increases. CHAPTERS 26, 27, 28, 29, 30, 36, 37, 39

**FLOW**

Initial LV inflow occurs slightly before mitral valve opening (i.e. leaflet separation). This results from leaflet shape changes as LVP falls to low values immediately before valve opening. Because the anterior leaflet is so stiff, the elastic change in posterior leaflet geometry is a prime candidate for this volume change. Although E-wave inflow kicks both the anterior and posterior leaflets toward open positions, they swing back towards their closed positions as early filling wanes. This could result from at least two forces acting on the leaflets. The collapse of the lowered pressure in the inflow stream from the Bernoulli Effect may tend to pull the leaflets back towards closed positions. Perhaps even more important might be the strut chord forces tending to gently close the leaflets at all times. The vortices shed behind the leaflets are possible factors, but they may be too brief to have a major effect driving the leaflets toward closure. Regurgitation volume associated with valve closure ranges from 0-18% of SV. Being in a nearly closed position as LVP just starts to rise does not seem to confer an
advantage toward efficient closing as measured by closing regurgitation. Some valves are in nearly closed positions at the onset of LVP increase, but exhibit large (seemingly inefficient) closing regurgitation. Energy storage in the left atrial wall plays a very minor role in either E-wave or A-wave left ventricular filling. By far, the dominant role in LV filling is played by the direct conduit function of the left atrium as a straightforward connector between the pulmonary veins, the atrial reservoir, and the left ventricle. CHAPTERS 34, 37, 41

COMMISSURES

The anterior and posterior commissure membranes allow the anterior leaflet and the P1 posterior scallop, as well as the anterior leaflet and the P3 posterior scallop, to swing freely around nearly orthogonal hinge axes in response to the very small internal LV pressure gradients when the valve is open, yet fold to form precise, rigid, tight seals between the anterior leaflet and the P1 posterior scallop and the anterior leaflet and the P3 posterior scallop as the rising LVP compresses each fold at the instant of valve closure and thereafter throughout systole. They provide part of the rigid “skeleton” support for the leaflets in the closed valve. CHAPTER 38

MITRAL “SKELETON”

In the closed valve, the stiff fold and coaptation regions form a skeletal, tent-like support structure that helps maintain valve geometry without requiring chordal support as systolic LVP presses on the leaflet surfaces. CHAPTERS 22, 39, 40

OVERVIEW

Initial leaflet geometry at the moment of valve closure is crucial to systolic valve mechanics. If the initial geometric conditions are set properly at this moment (i.e., the complex anterior leaflet curvatures are set precisely and all leaflet edges are positioned precisely with respect to one another in the LV chamber at this time), the resulting leaflet assemblage is nearly self-supporting, becoming nearly a rigid body whose geometry is virtually independent of subsequent flow and pressure throughout systole. This concept is supported by the small papillary forces measured at the moment of valve closure, as discussed in Chapters 21 and 22, and the beat-to-beat repeatability and leaflet systolic positional stability discussed in Chapters 9, 13 and 18. Such initial leaflet shape and positioning is achieved by positioning the papillary tips at precise 3D locations at the moment of valve closure, as discussed in Chapters 3, 4, and 19, with all the chordae distributed from these tips to the many leaflet attachment sites having exactly the right lengths to place the leaflet edges to within a millimeter of their closed positions at the moment of closure, as discussed in Chapter 13. In this view, the papillary muscles and chordae act primarily to keep the anterior leaflet out of the outflow tract during diastole and to gently and precisely position the leaflets into a precise geometric configuration at the moment of closure; exerting about 10% of ejection force during the last half of systole, as described in Chapter 22. As left ventricular pressure just begins to rise during the ECG R-wave, the slightest regurgitant pressure gradients force the large-area anterior leaflet and P1, P2, and P3 scallops inward relative to the smaller areas exposed in the clefts between these leaflet regions, thereby assuring proper folding geometry, similar to the sequence shown in Chapter 37. The precise initial positioning associated with all of these mechanisms also prevents the leaflet from colliding forcefully at the beginning of each beat, allowing gentle closing mechanics that spares both valve and blood components from damage.

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