CHAPTER 17 MITRAL ANNULAR FLEXION

Itoh et al.\textsuperscript{1} have pointed out that the mitral annulus can be considered as a hinged structure, with the hinge located roughly along a line between the left (Marker #29, LFT) and right (Marker #24, RFT) fibrous trigones. This hinge, separating the contractile and non-contractile portions of the annulus, can be seen in Figures 17.1 and 17.2 (see captions for the views displayed in these figures). Although the studies described here were conducted in different hearts and employed a different geometric approach to data analysis than those of Itoh et al., the findings described here are consistent with theirs and should be considered as an extension of their findings which should be consulted for a very thorough discussion of this topic.

Figure 17.3 shows the changes in two angles, $\Phi_{X2218}$ and $\Phi_{225418}$, during sequential cardiac cycles in hearts H1-H6. $\Phi_{X2218}$ is a tilt of the mitral annulus with respect to a reference system fixed within the left ventricular chamber. This angle is clearly influenced primarily by left ventricular myocardial contraction, ejection, and filling, not left ventricular pressure. Carlhall et al.\textsuperscript{2} have shown how annular displacements of this sort contribute significantly to left ventricular filling and ejection. Figure 17.2 shows how this angle is greater in systole than diastole, supporting this view. In contrast, $\Phi_{225418}$ appears to not be significantly influenced by ejection and filling, but primarily by left ventricular pressure. $\Phi_{225418}$, maximum at end diastole, falls precipitously with the rapid left ventricular pressure increase associated with IVC. Figure 17.2 shows that this rapid reduction in $\Phi_{225418}$ is produced by a displacement of site 54 (midpoint of the line from LFT #29 to RFT #24) to the left and down, presumably drawn to the left and down by elastic coupling to structures attached to the left and right fibrous trigones. Such displacement may serve to provide continuous 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.

Note that in the discussion of Figure 2.5 it was pointed out that fibrous mitral annular length was minimum during diastole, rose steadily during ejection, then fell abruptly immediately after mitral valve opening, in concert with LV contraction, not LV pressure. This is consistent with the concept that the LFT and RFT are also being pulled apically by myocardial contraction. This appears analogous to the behavior of $\Phi_{X2218}$, possibly reflecting a saddlehorn (Marker #22) held in place by left ventricular pressure and its aortic attachment, while outlying regions (Lateral Annular Marker #18, LFT Marker #29, and RFT Marker #24) are pulled down (apically) away from it. Also in the discussion of Figure 2.5 it was pointed out that the LFT-SH-RFT angle, maximum at end diastole, fell abruptly as LV myocardial contraction began, much like the LVP-induced behavior of $\Phi_{225418}$ during early systole. This suggests that this movement of LFT and RFT sites to the left and down, as in Figure 17.2, happens almost instantly as LVP starts to rise, without initially stretching the non-contractile annulus, which is likely to be important to help bring the lateral mitral annulus (with its attached posterior leaflets) toward the anterior mitral leaflet to facilitate valve closure. Then, once closure is accomplished, this early systolic LFT and RFT translation force is augmented by forces associated with myocardial shortening as ejection proceeds and helps maintain valve closure.

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Figure 17.1 Mitral annulus silhouette at ED for hearts H1-H6. Dimensions in mm. Cubic spline (blue) through non-contractile annulus Markers #29 (left fibrous trigone)-15-30-22 (“saddlehorn”)-24-21-24 (right fibrous trigone). Cubic spline (red) through contractile annulus Markers #29 (left fibrous trigone)-16 (anterior commissure)-28-17-27-18 (lateral annulus)-26-19-25-20 (posterior commissure)-24 (right fibrous trigone). Marker #22 at origin (0,0,0), Z-axis from #22 to #01 (left ventricular apex), Marker #18 in X-Z plane. Site 54 at midpoint of 29-24 line segment.
Figure 17.2 Annular flexion triangles (vertices 22-54-18) during diastole (blue) and systole (red) for hearts H1-H6. View is from Marker #29 (left fibrous trigone) to #24 (right fibrous trigone) with Marker #22 at origin. Left and right fibrous trigones overlap at open circles.
Figure 17.3 Mitral annular angle and flexion for hearts H1-H6. LVP = Left Ventricular Pressure; MVC = Mitral Valve Closure; MVO = Mitral Valve Opening; $\Phi_{2218} =$ Angle X-22-18 (see Figures 17.1 and 17.2); and $\Phi_{225418} =$ Angle 22-54-18 (see Figures 17.1 and 17.2).
Jensen et al.\textsuperscript{3} have provided important information regarding such potential systolic forces acting on the mitral annulus. They sewed a flat annuloplasty ring (instrumented with strain gages to measure bending forces about the saddlehorn, left and right commissures, and lateral annulus) to the mitral annulus in the beating porcine heart and found that systolic torques tended to bend the annulus from a flat configuration in diastole to the curved configuration shown by the dashed line in Figure 17.4.

Their finding, illustrated in Figure 17.4 is consistent with the findings of our marker studies shown in Figures 17.1-17.3, provided that we include the dynamics of the basal endocardial LV septal Marker #7 (shown in Figure 17.5) that is coupled to the LFT and RFT.

With this inclusion, our provisional explanation for this aspect of annular mechanics is:

- The saddlehorn region (Marker #22) is firmly attached to the main body of the collagen “skeleton” of the heart and further constrained by its attachment to the rather rigid aorta that is always subjected to at least diastolic arterial pressure. Thus the saddlehorn region is quite immobile relative to other annular regions.

• Unlike the saddlehorn, however, the LFT and RFT regions are not as rigidly bound to the stiff collagen skeleton and continuously pressurized aorta; they are at the outer extremities of the collagen skeleton and exposed to the full range of LV pressure fluctuations in the outflow tract.

• The LV pressure rise and LV volume shifts during IVC dilates the outflow tract, increasing the distance between Markers #22 and #07, and increasing the tension in the outflow tract connections to the LFT (from Marker #07 to #29) and RFT (from Marker #07 to #24).

• This dilation and tension pulls the LFT and RFT laterally towards the interventricular septum and down towards LV apex, rotating and translating them both around the essentially fixed saddlehorn. This can be seen in the correlations between $\Phi_{225418}$ and $(D_{2207}-D_{2407})$ and $(D_{2207}-D_{2907})$ during systole in Figure 17.6 and the behavior of D2207, D2907, and D2407 during IVC in the summary Figure 17.7. Note that while both the LFT and RFT displace during IVC, the displacement of the RFT is typically considerably greater than that of the LFT, perhaps reflecting the left-right asymmetry of the attachments to the collagen skeleton and myocardium of these trigonal regions as can be seen in Figure 1.3. Figure 17.8 illustrates schematically how aortic root expansion is coupled to trigone displacements during IVC. As discussed in Chapter 22, both the magnitude and change of total left and right papillary forces are very small during IVC, thus chordal force is unlikely to underly these LFT and RFT displacements during IVC.

• The outflow tract dilation and tension appear to be the primary forces underlying the rotations of the LFT and RFT around the saddlehorn; the strut chords do not appear to participate meaningfully in these displacements as can be seen in the poor correlations between $\Phi_{225418}$ and $(D_{2233}-D_{2433})$ and $(D_{2231}-D_{2931})$ during systole in Figure 17.6.

• As indicated earlier in this chapter, these displacements of the LFT and RFT as LVP increases during IVC initially help pull the annulus toward the septum, thereby facilitating valve closure, these displacements are then firmly held throughout systole to provide continuous annular tension and help maintain leaflet coaptation.

• An additional force, from myocardial contraction as ejection proceeds, pulls the LFT and RFT toward the left ventricular apex and interventricular septum, while left ventricular pressure and aortic attachment hold the saddlehorn in a relatively fixed position, thereby increasing the tension in the LFT-SH-RFT collagen band and buttressing the effects of outflow tract dilation acting along almost the same force vectors.

A theme that we introduce here and attempt to support additionally in other chapters is that the annulus should not be considered as a continuous entity, rather as two interconnected almost independent parts. This is tacitly assumed in the terminology in this field when reference is made to the “contractile” portion of the annulus, as differentiated from the “non-contractile” portions of the annulus. The “non-contractile” portion of the annulus (which could be considered basically as an extension of the aorta into the LV) provides the fairly rigid hinge for the anterior leaflet, but has almost no connections to the posterior leaflets. The “contractile” portion of the annulus is tightly associated with the posterior leaflet hinges, but almost completely independent of the anterior leaflet. These two annular regions interact, of course, at the LFT and RFT regions, but the influence of trigonal region displacements seems likely to dwarf the influence of the contractile region displacements on trigonal region displacement. Considering these two annular regions as almost separate entities could have important implications in our understanding of valve physiology, and, importantly, potential approaches to valve repair and tissue engineering.

Figure 17.5 Same views as H4 in Figure 17.1 during diastole (top) and systole (bottom), but with the addition of the basal endocardial LV septal Marker #7 coupled to the LFT (#29) and RFT (#24).
Figure 17.6 Mitral annular angle and flexion for hearts H1-H6. LVP=Left Ventricular Pressure; MVC=Mitral Valve Closure; MVO=Mitral Valve Opening; Φ22518=Angle 22-54-18; Dxxys=distance (mm) from Marker xx to yy.
Figure 17.7 Mitral annular angles and flexion summary for hearts H1-H6. LVP=Left Ventricular Pressure; MVC=Mitral Valve Closure; MVO=Mitral Valve Opening; ANGLE225418=Angle 22-54-18 (degrees); ANGLE292224=Angle 29-22-24 (degrees); LFT TO RFT=Perimeter Length (mm) of the Non-Contractile Annulus (connecting Markers #29(LFT)-15-30-22-23-21-24(RFT)); Dxxyy=distance (mm) from Marker xx to yy; FPS=Frames per Second.
Figure 17.8 Schematic illustration of the coupling between aortic root expansion and trigone displacements during IVC. LFT=Left Fibrous Trigone (Marker #29); SH=Annular Saddlehorn (Marker #22); RFT=Right Fibrous Trigone (Marker #24); SEP=Outflow Tract Septum (Marker #7). Dashed lines show schematic “shape” of the non-contractile annulus at LVP onset (black) and end-IVC (red). As shown in Figure 17.7, the distances between Markers #24 and #7 (D2407), #22 and #7 (D2207), and #29 and #7 (D2907) are of the same order of magnitude at LVP onset (illustrated by the 3 black lines of equal length in this illustration). During IVC, D2207 and D2907 both increase by similar amounts (the two red lines on the right), but D24’07’ (the red line on the left) ≅ D2407 (the black line on the left), resulting in a deformation of the non-contractile annulus as illustrated by the dashed red line.