CHAPTER 06 ANTERIOR LEAFLET CURVATURES

Anterior leaflet circumferential and radial curvatures were quantified in the six hearts as described in Appendix C. In brief, for each frame a best-fit plane was fit to all the anterior leaflet markers, including the trigonal hinge markers. Coordinate X-Y basis vectors were established in this plane and radial curvature was defined from the radius of a circle passing through the X-Z coordinates of radial marker triplets in this coordinate system (roughly perpendicular to the line connecting the LFT-RFT markers) and circumferential curvature defined from the radius of the circle passing through the Y-Z coordinates of circumferential marker triplets (roughly parallel to the line connecting the LFT-RFT markers). As defined in this fashion, positive curvature was concave to the LV, negative curvature was convex to the LV.

Figures 6.1A and 6.1B plot these radial and circumferential anterior leaflet curvatures for all beats in hearts (H1-H6). Note that when the mitral valve is closed:

- The circumferential trigone leaflet hinge (markers #29-#22-#24), circumferential leaflet belly (markers #50-#41-#53), and radial leaflet central edge (#40-#39-#38) always have concave curvature to the LV, and
- The central radial leaflet annulus (markers #22-#41-#40) and radial belly (#41-#40-#39) always have convex curvature to the LV.

Figure 6.2 illustrates these regions with consistent curvature in the closed valve as gray lines superimposed on the systolic geometry of the anterior leaflet of heart H3.

We think that this is an important function of the strut chordae; e.g. to 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) at the time of the initial systolic increase of LVP. Why is this so important?

In our finite element studies of the anterior leaflet, we found that if our initial condition for the shape of the anterior leaflet was flat or prolapsed (both circumferentially and radially concave to the LV), then the onset of left ventricular pressure loading produced both radial and circumferential tension and the leaflet tended to “balloon” into the left atrium. If, however, we started with the anterior leaflet in a “saddle” shape (radially convex, circumferentially concave to the LV), then the onset of left ventricular pressure loading on the ventricular surface of the leaflet produced an offsetting combination of radial compression and circumferential tension that dramatically decreased load-induced leaflet deformation. Architects have recognized this property of hyperbolic paraboloids for many years. This shape was recently utilized in the roof design for the Velodrome for the 2012 London Olympics. Levine et al. have also invoked this shape in their classic study of the mitral annulus.

What we describe here, however, is considerably different than the boundary conditions involved in architectural roof design and has almost nothing to do with the mitral annulus. The anterior leaflet isn’t a complete saddle shape. As can be appreciated in Figure 6.2, only the leaflet annular and belly regions assume this shape, the leaflet edge does not.

Thus, what we propose is that the curved stiff region between the trigones sets the circumferential concavity of the anterior leaflet at and near the hinge, while supporting the leaflet region between the saddlehorn and the trigones much like a drumhead. Immediately before the onset of left ventricular pressure rise, the strut “trampolines” pull the leaflet on either side to extend this circumferential leaflet concavity further out into the leaflet, while simultaneously acting to pull the leaflet belly against the...
The annular leaflet region between the “trampolines”, although not directly supported by the strut chordae, is tensed by the opposing forces directed toward the APT and PPT. Thus, roughly, the annular half of the anterior leaflet is formed by the very small forces in the strut chords into a taut “saddle” shape at the beginning of every beat. The thickened region near the hinge in Figures 3.2A, B, and C may serve as an anatomical base for this stiff structure; it has the proper shape and has multiple strut chord insertions.

This proposal regarding the function of the strut chords finds support in the second-order chord cutting experiments of Rodriguez et al. When they divided the major strut chords, the compound radial curvature of the anterior leaflet shape during systole was preserved, but the circumferential curvature was altered, and in some cases, even reversed.

At the onset of left ventricular pressure increase at the beginning of each beat, with a proper saddle shape, these annular and belly regions lock into position as a nearly-rigid body during systole. This rigid section of the anterior leaflet serves to anchor one side of the more mobile leaflet edge regions that are supported at their edges, at least in part, by primary chords.

We will have much more to say about the systolic rigidity of the anterior leaflet in later chapters, even demonstrating a burst of extra leaflet stiffness that occurs during IVC in addition to the very stiff in vivo leaflet material properties. But we’ll close this chapter with a homely example illustrating the type of rigidity we are invoking for the annular half of the anterior leaflet.

Figure 6.3 shows an inverted water pitcher, with its saddle-shaped pouring lip which we here take as an analog of the annular half of the anterior mitral leaflet. Note that if pressure (LVP) is applied to the undersurface of the lip, this compresses the belly of the lip (COMPRESSION), while tending to rotate the lip about its base (the “TRIGONE REGION”) and thereby put the edges of the lip in tension (TENSION). Not illustrated is the circumferential tension, normal to the compression arrows, that will be created by the LVP loading. The reason that the lip holds its shape under load, cantilevered into space, is that its stiff spout is anchored to a solid support, the pitcher itself, against which these tensile and compressive forces can act. We suggest that the rigid trigone region provides a similar solid support for the stiff annular half of the anterior leaflet. The strut chords, however, must draw the anterior leaflet into this hyperbolic paraboloid configuration just at the beginning of left ventricular pressure rise in order to insure that the anterior leaflet, less than 2 mm thick, can withstand the full pressures generated by the left ventricular cardiac muscle that is more than 5 times this thickness, without the leaflet becoming, essentially, an aneurysm.

REFERENCES
Figure 6.1A Radial and circumferential anterior leaflet curvatures from marker triplets (color coded: radial triplets #22_#41_#40 (red), #41_#40_#39 (blue), #40_#39_#38 (green); circumferential triplets #29_#22_#24 (red), #50_#41_#53 (blue), #48_40_#49 (green)) for hearts H1-H3. LVP (black line) with black dots denoting the time of mitral valve closure during IVC and mitral valve opening during IVR.
Figure 6.1B Radial and circumferential anterior leaflet curvatures from marker triplets (color coded: radial triplets #22, #41, #40 (red), #41, #40, #39 (blue), #40, #39, #38 (green); circumferential triplets #29, #22, #24 (red), #50, #41, #53 (blue), #48, #40, #49 (green)) for hearts H4-H6. LVP (black line) with black dots denoting the time of mitral valve closure during IVC and mitral valve opening during IVR.
Figure 6.2 Anterior leaflet systolic geometry of heart H3. Mitral annulus (thick black line) defined by annular markers (large filled circles). Leaflet markers (small filled black circles) with possible chordal attachments (thin black lines) from leaflet to APT (left) and PPT (right). Superimposed gray lines denote curvatures that are consistent in the closed valve for all beats in all hearts: circumferential markers #29-#22-#24 and #50-#41-#53 with positive circumferential curvature concave to the LV; radial body markers #22-#41-#40 and #41-#40-#39 with negative radial curvature convex to the LV; and radial edge markers #40-#39-#38 with positive radial curvature concave to the LV.
Figure 6.3. Illustration of a cantilevered structure mimicking the geometry of the annular portion of the anterior leaflet.