Editorial

The Unsaddled Annulus
Biomechanical Culprit in Mitral Valve Prolapse?

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Masterful mitral valve (MV) repair demands thorough understanding of integrated mitral apparatus structure and mechanics.[1,2] One consistently reported feature, the saddle shape of the mitral annulus, was recognized in the process of resolving the contradiction posed by an apparently high prevalence of MV prolapse (MVP) in otherwise healthy individuals: A normal saddle-like shape will show opposite leaflet curvatures with leaflets above or below the annulus in perpendicular 2-dimensional echocardiographic views, leading to the false impression of prolapse based on an assumed planar annulus.[3] Criteria recognizing annular nonplanarity substantially improved diagnostic specificity.[4,5]

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Biomechanical Concepts

Whether this saddle shape, by analogy to architectural structures, best supports ventricular-imposed stresses on the valve compared with a flat annulus[6] was first shown computationally[7] and then confirmed in vitro and in vivo.[8–11]

In this issue of *Circulation*, Lee et al[12] revisit the implications of annular shape. They have used 3-dimensional echocardiography as a powerful technique to explore MV geometry in 100 subjects, 68 with degenerative MVP, with or without important mitral regurgitation (MR ≥ moderate), and 32 normal controls. Their most salient finding is that the mitral annulus of patients with more severe MR is not only greater in area but also flatter, with a decreased ratio of annular height to commissural width. That ratio is strongly associated with chordal rupture, which progressively increases in prevalence from 7% in those with the most saddle-shaped annuli to 42% in those with the most planar. Annular flattening is also associated with increased leaflet billowing volume, and together these variables determine MR severity. The authors therefore propose a potential role of annular flattening in MR pathogenesis.

An initial reaction, acknowledged by the authors, is that annular flattening may simply be secondary to annular dilatation, increasing the denominator in the annular height-to-commissural width ratio. Even the decrease in absolute annular height itself in MR patients may be secondary to out-of-plane annular stretching, reducing out-of-plane height (Figure 1).

On further reflection, though, there may nevertheless be a true physical effect. Annular flattening, whatever its cause, exerts increased out-of-plane tension on the annulus, leaflets, and chords, as shown by Jensen et al[10,11] (Figure 1). With biomechanically weakened tissue, this can elongate the leaflets, promoting prolapse, and increase the likelihood of chordal rupture, leading to flail and more severe MR (Figure 2). Chordal rupture, in turn, increases stresses on adjacent unruptured chordal attachments and leaflet tissue[13]; increasing annular area augments the net force on the leaflets,[14] which is proportional to the product of annular area and transmitral pressure. The altered force distribution on the valve induced by annular flattening also dictates a less effective coaptation geometry.[11] There is further evidence that increased leaflet–chordal tension can in turn cause annular dilatation.[15] These interactions will result in a vicious cycle of increasingly unfavorable mechanics and progressive MR.

Mechanistic Considerations

The finding of decreased annular height in patients with MVP and no or mild MR is new and suggests the possibility of primary annular pathology in myxomatous valve disease—often suggested, with little previous support.[16] The underlying concept of a mechanically linked mitral mechanism extending from annulus to ventricular wall is supported by the evidence for force transmission within that system and provides the rationale for chordal preservation in MV replacement.[17–19]

An alternative geometric basis for progressive MR in this study is suggested by the observation of Lee et al[12] of increased distance from the papillary muscle heads to the leaflet coaptation line in patients with more severe MR. As Otani et al[20] have recently published using 3-dimensional echocardiography, these tethering distances increase in parallel with MR and lead to tethering of leaflet portions that have intact chordal support (Figure 2). Malcoaptation between tethered and prolapsing segments potently increases MR in an additional vicious cycle that may also be active in the patients of Lee et al, as suggested by their Figure 2H (gap between tethered anterior leaflet and flail P2 scallop).[12] Of

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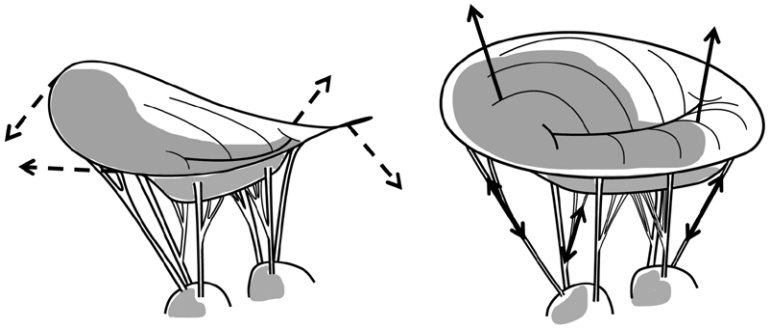

Figure 1. Schematic representation of the biomechanical effects of mitral valve flattening and forces. **Left,** Normal mitral annular saddle shape; dashed **arrows** indicate forces inducing annular flattening. **Right,** Annular flattening with mitral leaflet prolapse; **arrows** indicate increased out-of-plane forces transmitted to chordae and certain parts of the leaflets.

note, mediolateral displacement of papillary muscles may also exert forces that flatten the annulus.

Increased chordal tension may paradoxically be counterbalanced by prolapse itself, which decreases leaflet radius of curvature and therefore local stresses by Laplace's Law.[21,22] Ultimately, however, the increased tension adjacent to flail segments and caused by annular dilatation and flattening will likely cancel any benefit of altered curvature.

Clinical Implications

Considering these findings increases our appreciation of the mechanisms responsible for MR progression in degenerative MV disease; as Carpentier[1] has taught, fixing the lesion requires understanding the mechanisms and mechanics needed to achieve physiological repair. Deliberately saddle-shaped rings are now in use,[23,24] but controlled clinical evidence for superior repair durability is needed. Of note, the MV repair reoperation rate decreased greatly from the 1980s to the 1990s,[25] undoubtedly because of increased repair experience, although that coincides with the introduction of the semirigid and nonplanar Physio ring.

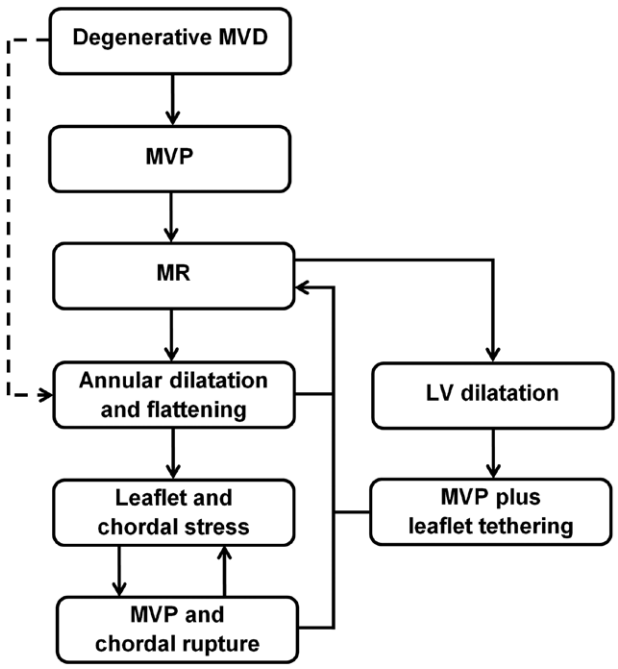

Figure 2. Schema of potential factors promoting MR, with positive feedback loops acting through annulus, leaflet, and chordal stress, and altered papillary muscle tethering. Dashed arrow indicates primary annular change consistent with Lee et al.[12] LV indicates left ventricle; MR, mitral regurgitation; MVD, mitral valve disease; and MVP, mitral valve prolapse.

Annular flattening is also prominent in functional MR,[26,27] and improved coaptation can be expected from restoring nonplanarity to reduce tethering of the vulnerable medial and lateral commissural segments by bringing them closer to the papillary muscles. Although dynamic systolic annular shape change does not preclude degenerative or functional MR,[28] annular shape itself can play a role in the force balance of the mitral mechanism.

Limitations and Future Studies

This study establishes an association but not a causal link between annular flattening and increased MR; the annular geometric changes may still be secondary, although present in patients with no or mild MR. The increased billowing volume may also be a geometric change secondary to the annular flattening. Experimental studies have shown that anterior leaflet strains are influenced by annular rings[29,30]; further modeling is required to explore the mechanisms postulated by Lee et al.[12]

These findings are in a similar direction to others showing decreased nonplanarity[31] and decreased systolic saddle deepening in MVP.[32] The absence of annular flattening in a model of MR created by a MV hole can be explained by the normal tissue substrate and relatively short intervention relative to clinical MVP.[33] The authors discuss MRI findings of nonplanarity in MVP even greater than by 3-dimensional echocardiography, noting possible differences in annular tracing and body mass.[34]

In conclusion, the association between annular flattening and increased MR severity in this substantial population with MVP challenges us to think of the mitral apparatus as an integrated mechanism susceptible to leaflet-annular and leaflet-ventricular interactions. Recommendations for clinical practice will require prospective evidence of causation and ideally controlled clinical testing of outcomes based on annular shape, a potential opportunity for the Cardiothoracic Surgical Trials Network sponsored by the National Heart, Lung, and Blood Institute. Future advances will require synergies between basic and clinical scientists to understand the central role of the altered genetic and biological substrates acted on by altered forces in causing progressively severe MR.[35]

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Disclosures

None.

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