(Why) Are Cardiac Valves Inherently Three-Dimensional?

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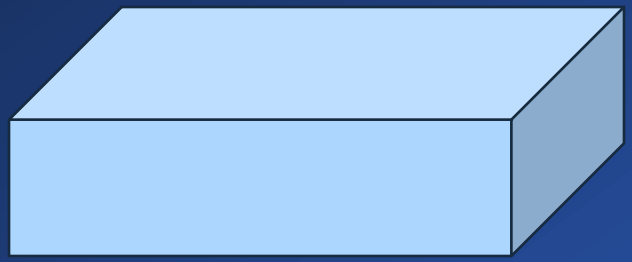
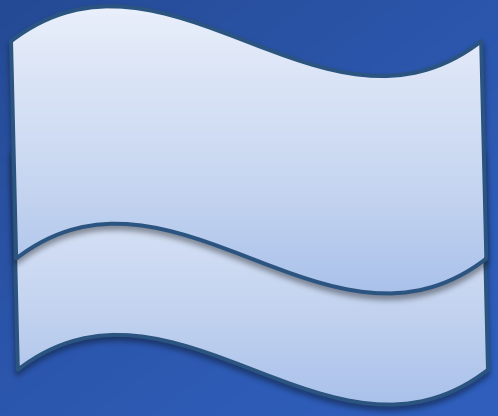
Flat 3D body



Planar

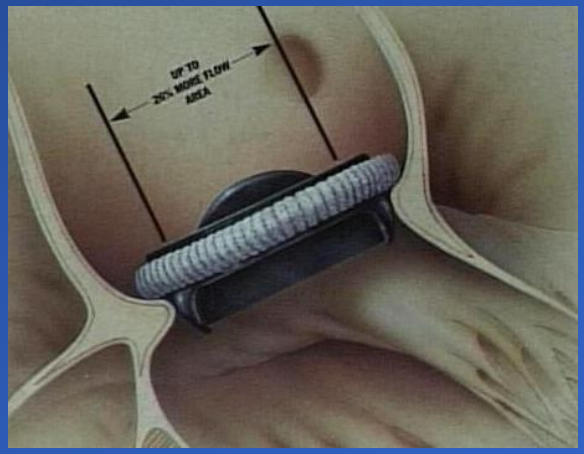
Curved 3D body
(“inherent 3D shape”)



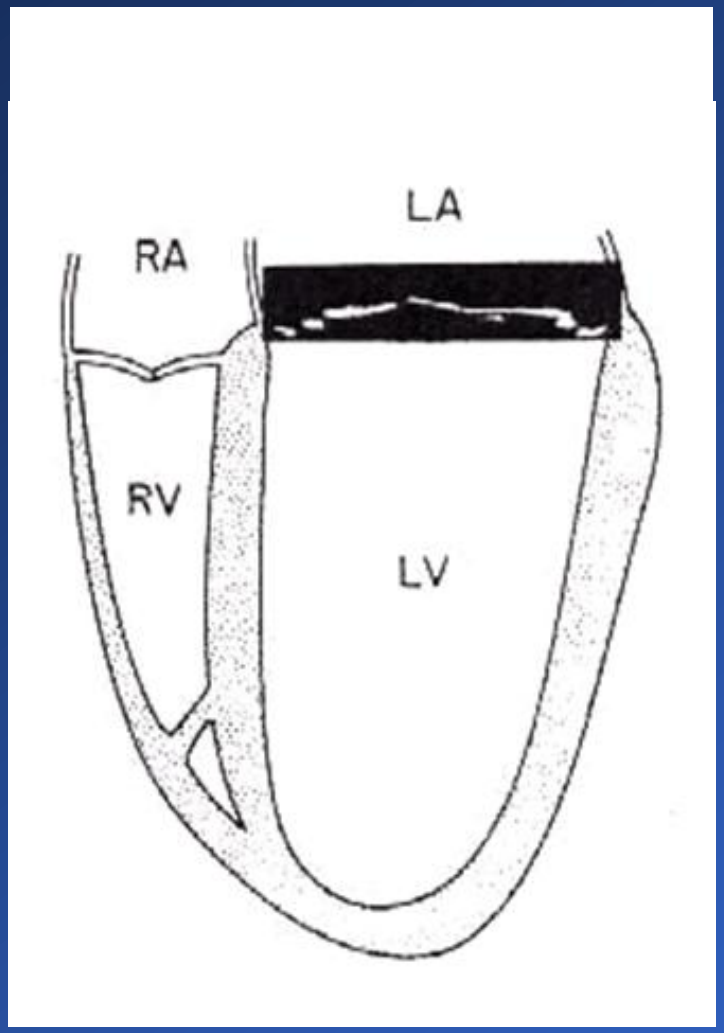
Non-Planar

- Are cardiac valves nonplanar?
- Is there a functional advantage to non-planarity?

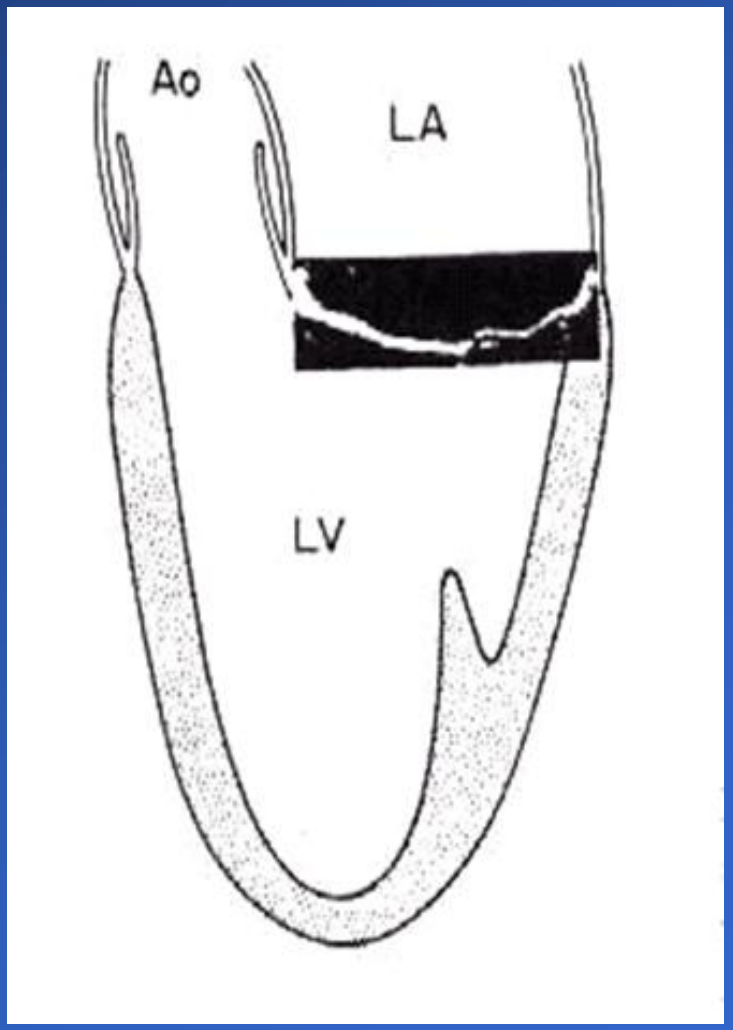
Mechanical valves are essentially flat. Their design reflects our perception of valves and their function



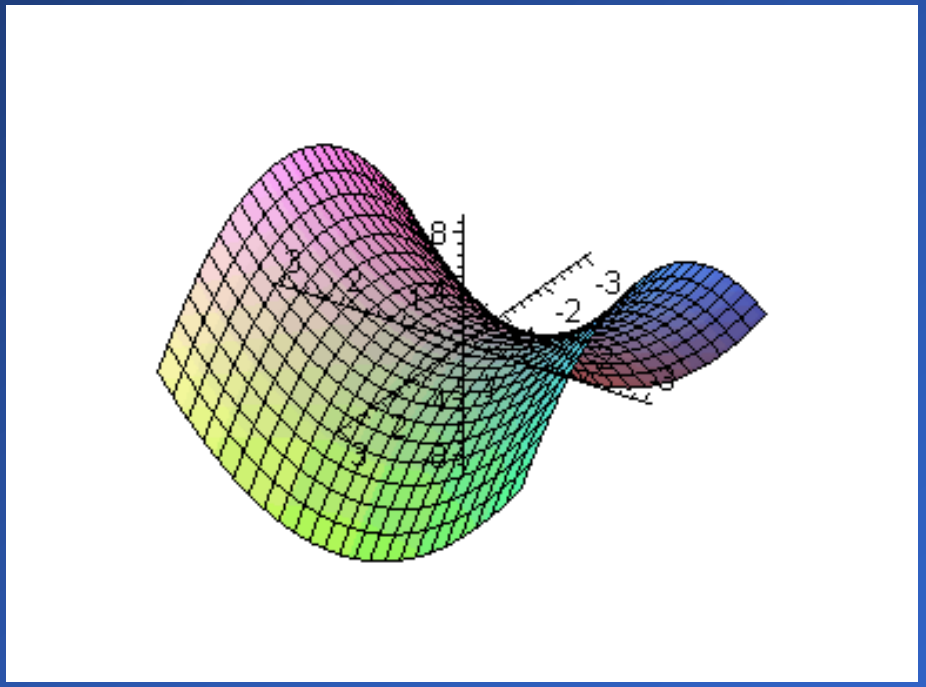
4 Chamber view



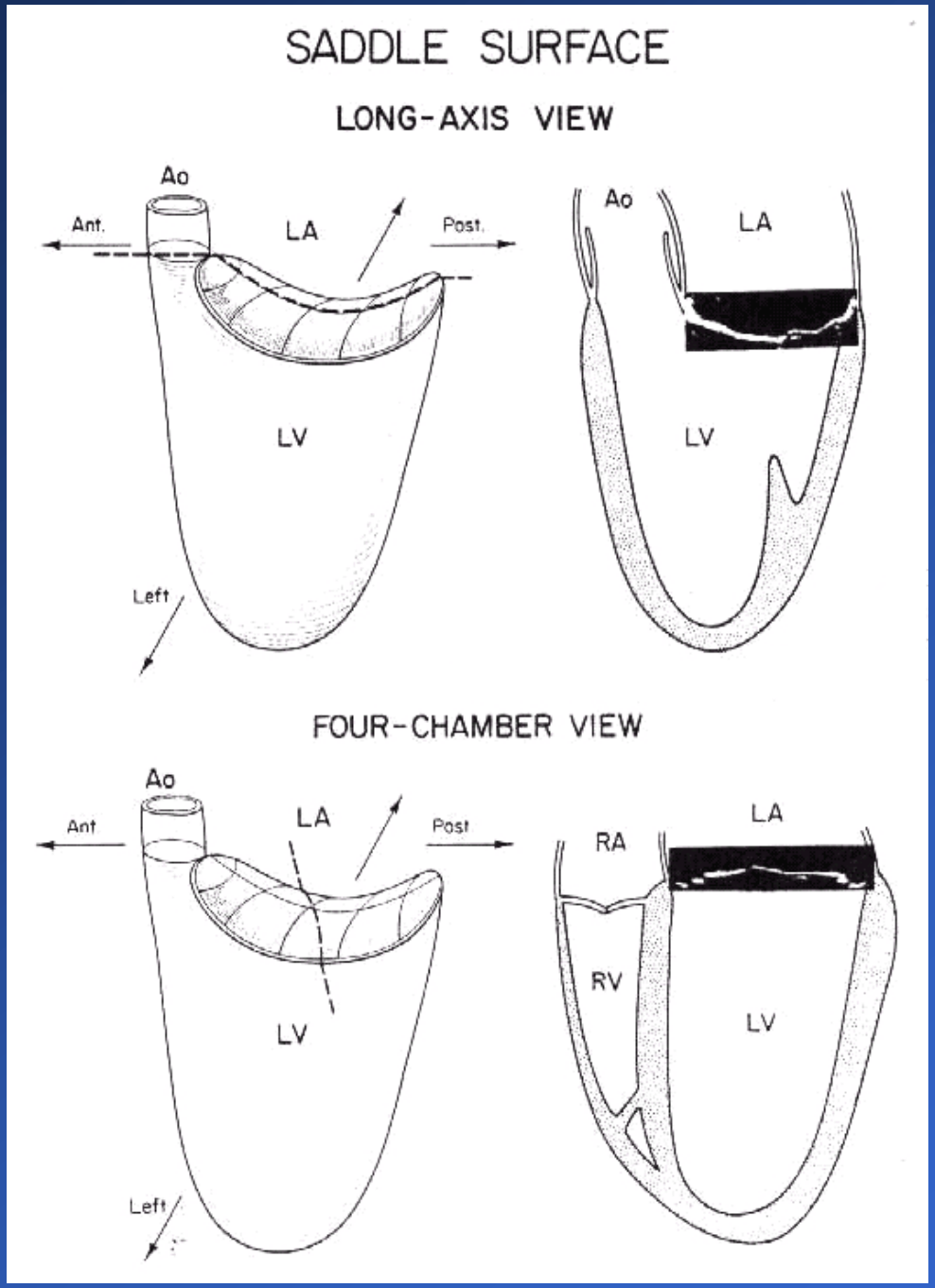
Long-axis view



Levine et al.



Hyperbolic paraboloid



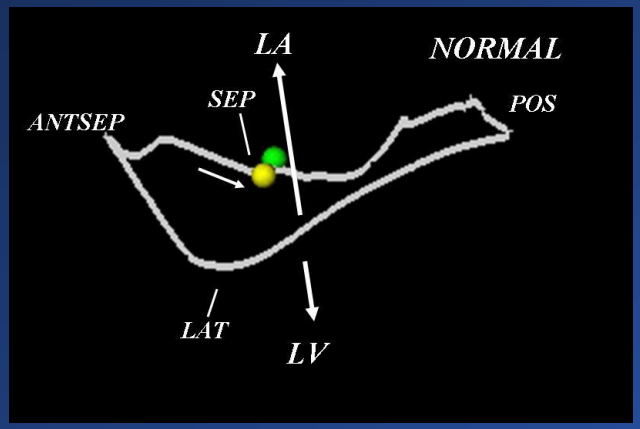
Levine et al.
Circulation 1989,
Am J Cardiol 1992

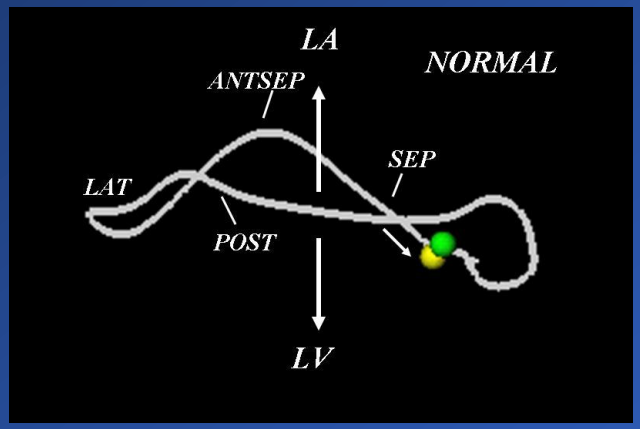
Try to understand the advantages of inherently three-dimensional (nonplanar) cardiac valves

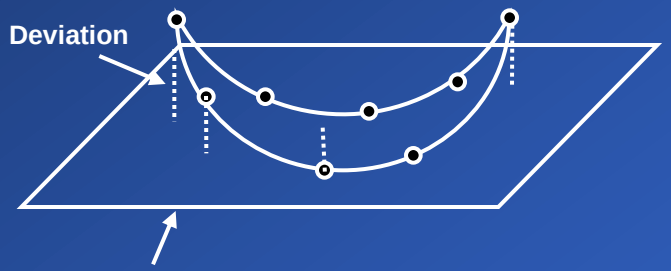
Mitral Annulus (MA)

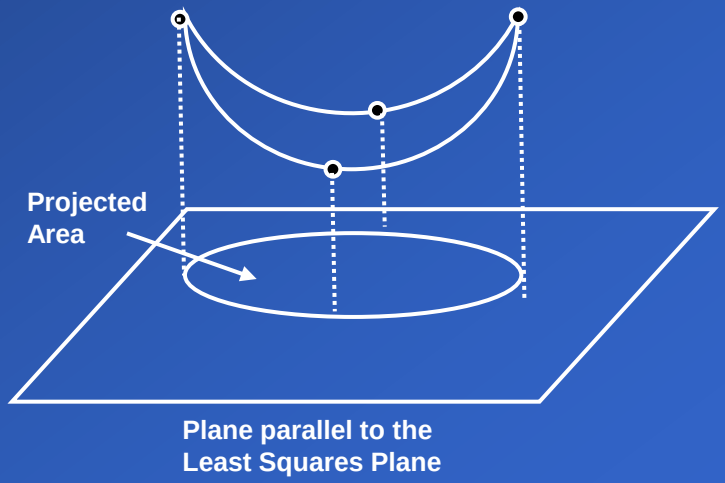
- Shape, size, and motion of the normal MA
- Shape, size, and motion of the MA in dilative and ischemic cardiomyopathy
- Contribution of potential alterations to MR severity

3D Reconstruction of MA Using TEE in 10 normal subjects and 3 patients with DCM





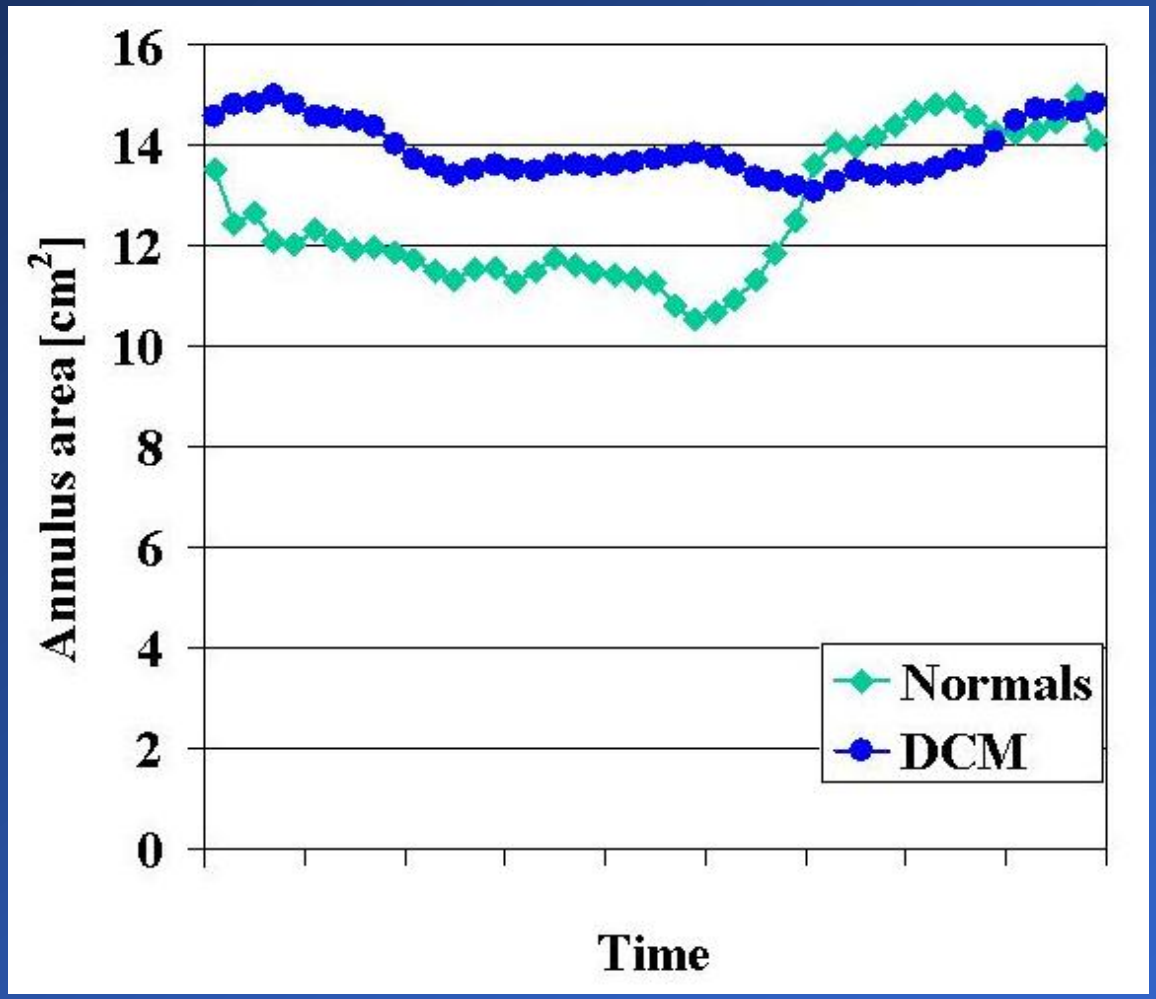




- Degree of nonplanarity by perpendicular distance (z-deviation) of annulus points from a corresponding least-squares plane
- Area as projection of annulus on its least-square plane

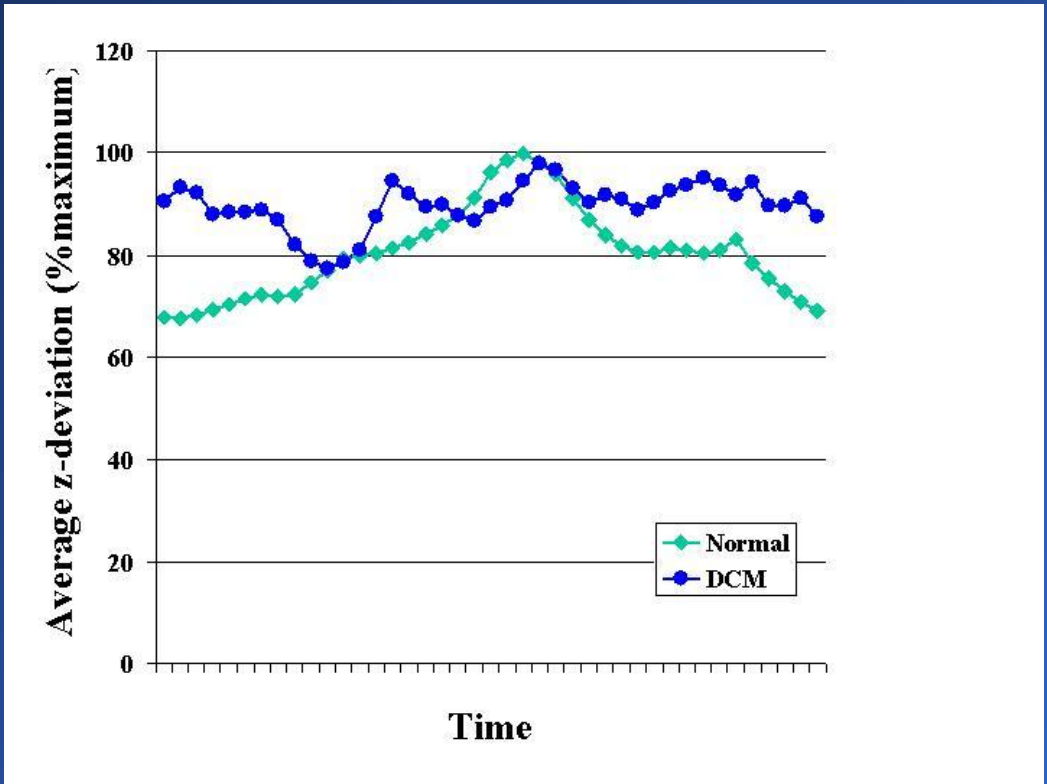
Flachskampf, et al. J Am Soc Echocardiogr. 2000

3D Reconstruction of MA Using TEE
Annular area changes



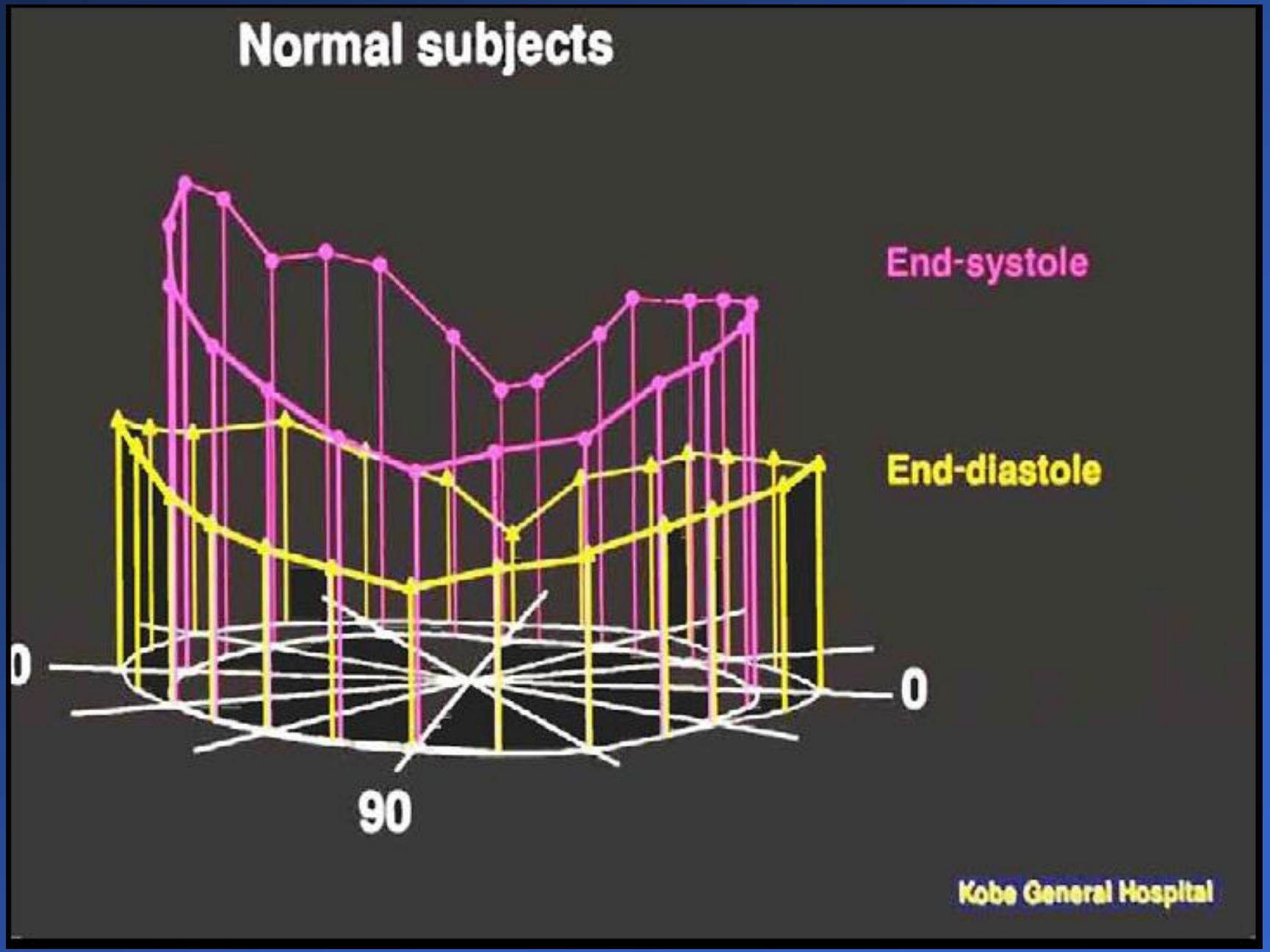
Flachskampf, et al. J Am Soc Echocardiogr. 2000

Temporal variation of nonplanarity in normal subjects and those with DCM



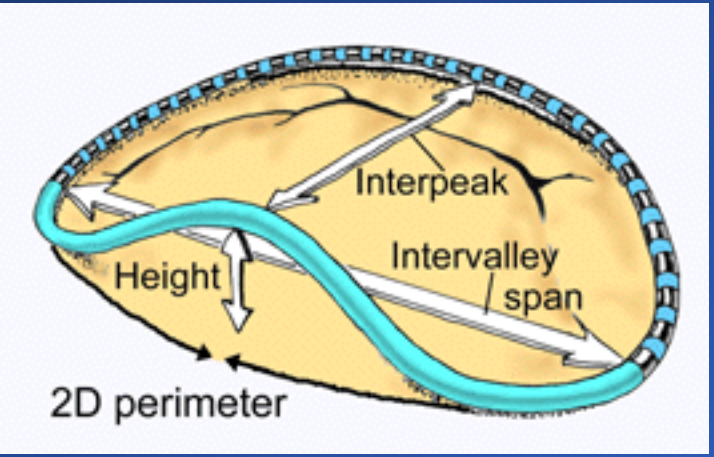
- Circumferentially average z-derivation plotted time indicates systolic folding (peak), and diastolic flattening in normals, but an asynchronous, damped response in patients with DCM

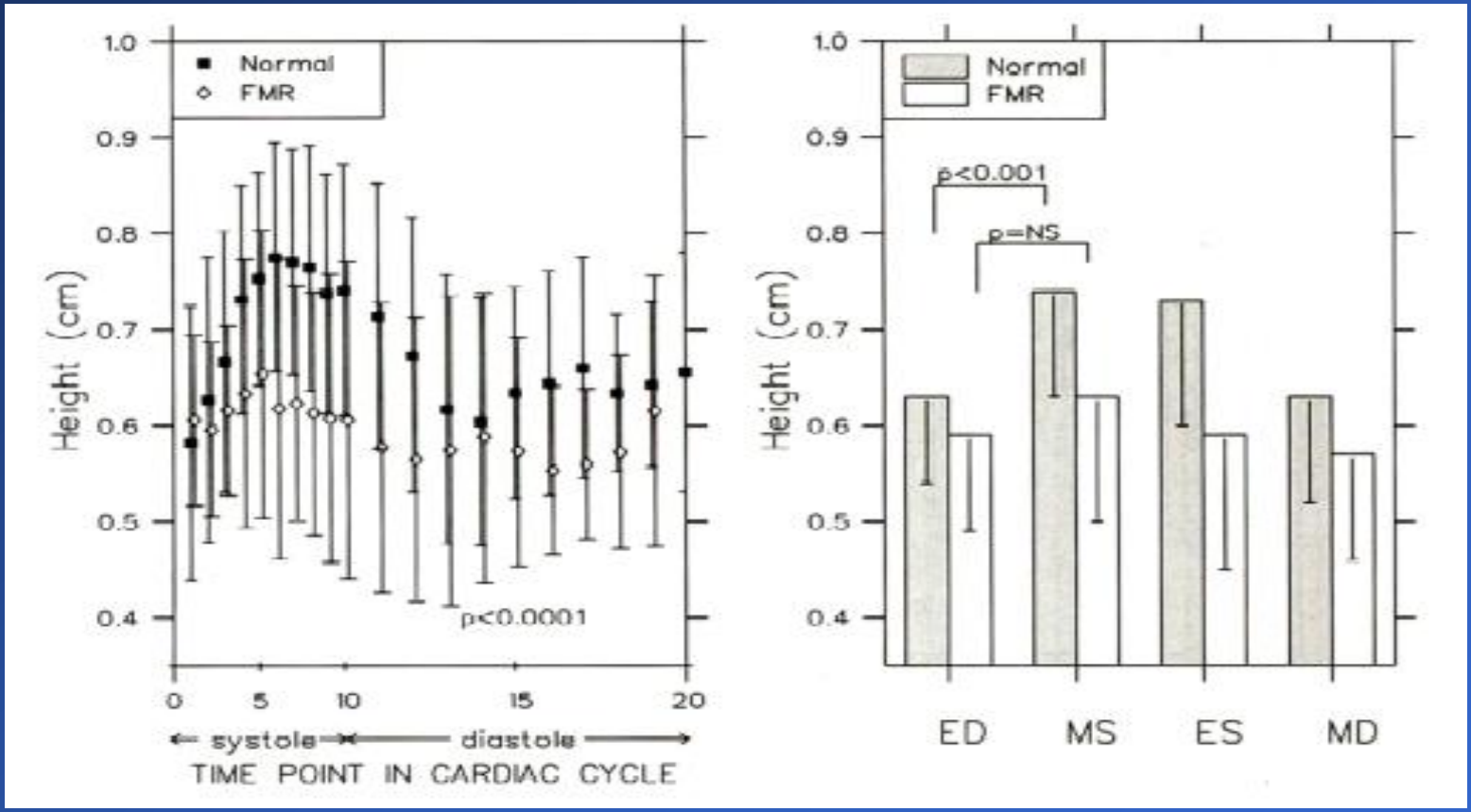
Flachskampf, et al. J Am Soc Echocardiogr. 2000


Normal subjects
End-systole
End-diastole
0
0
90
Kobe General Hospital

3D MA shape in 9 normal subjects and 8 patients with secondary MR:

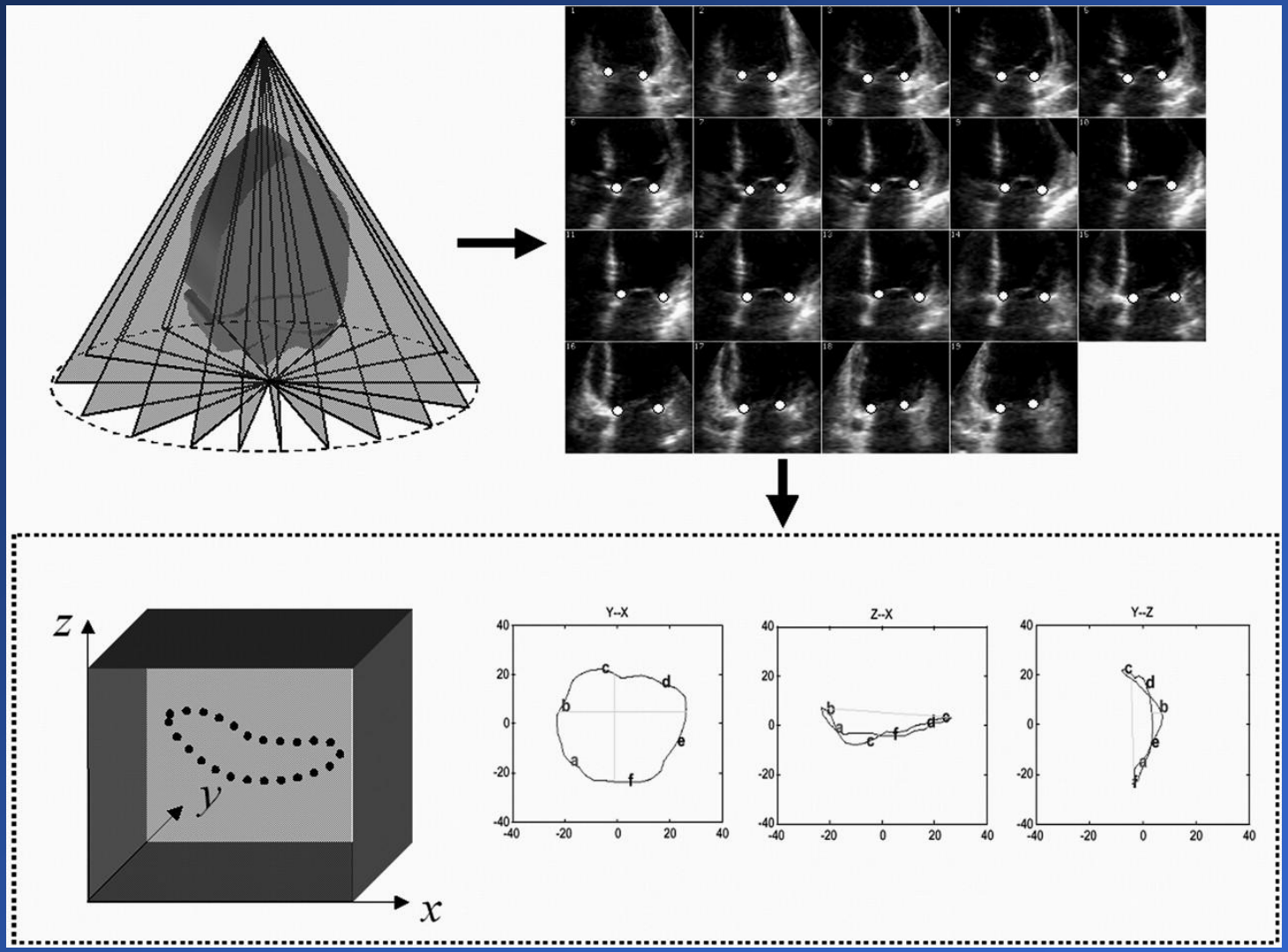
reduced (but preserved) nonplanarity, reduced cyclic variation in MR patients





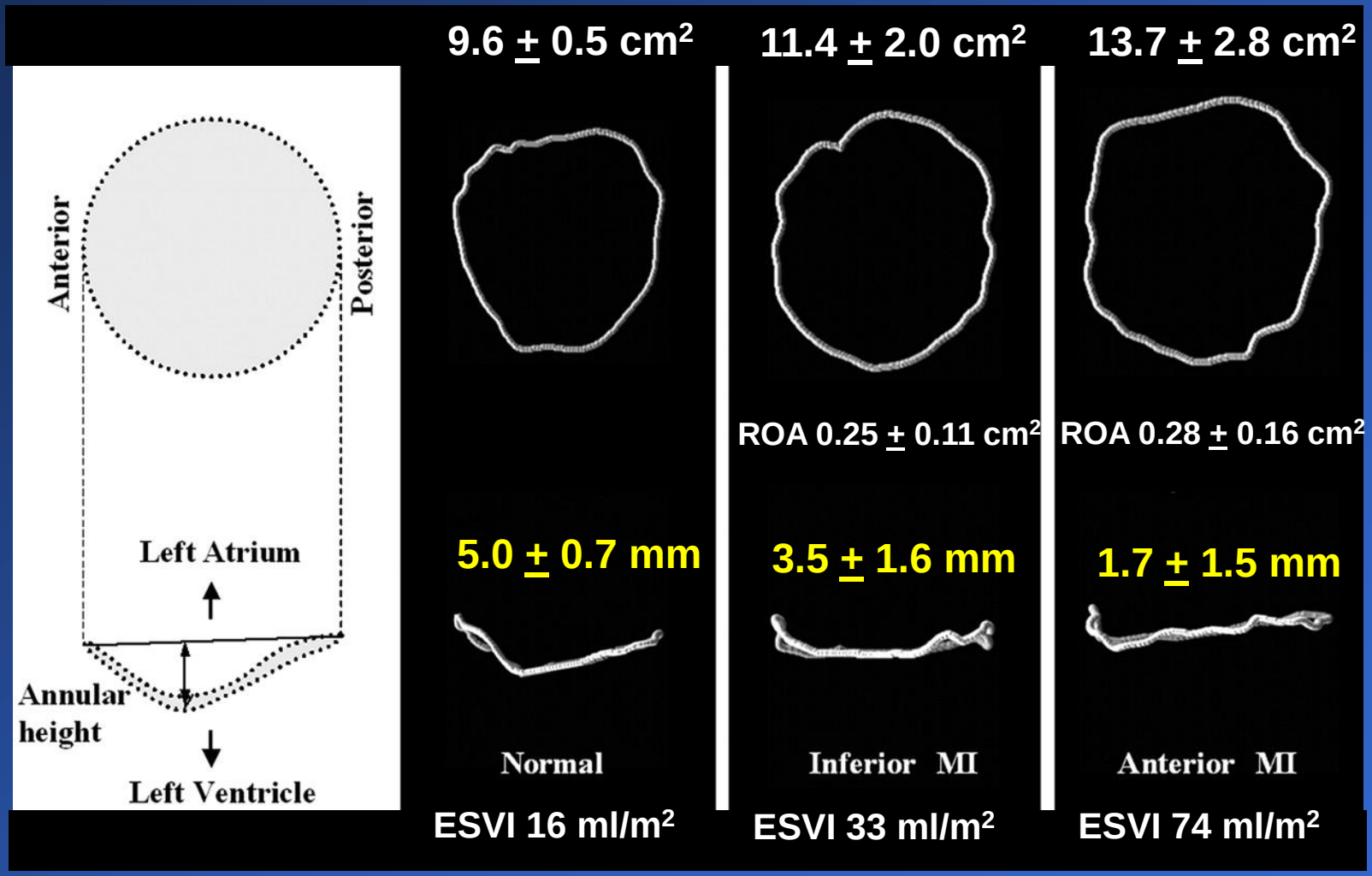
Kaplan, et al. Am Heart J 2000

Real-time 3-D echo in 23 patients with ischemic MR attributable to inferior MI or anterior MI and in 10 controls.



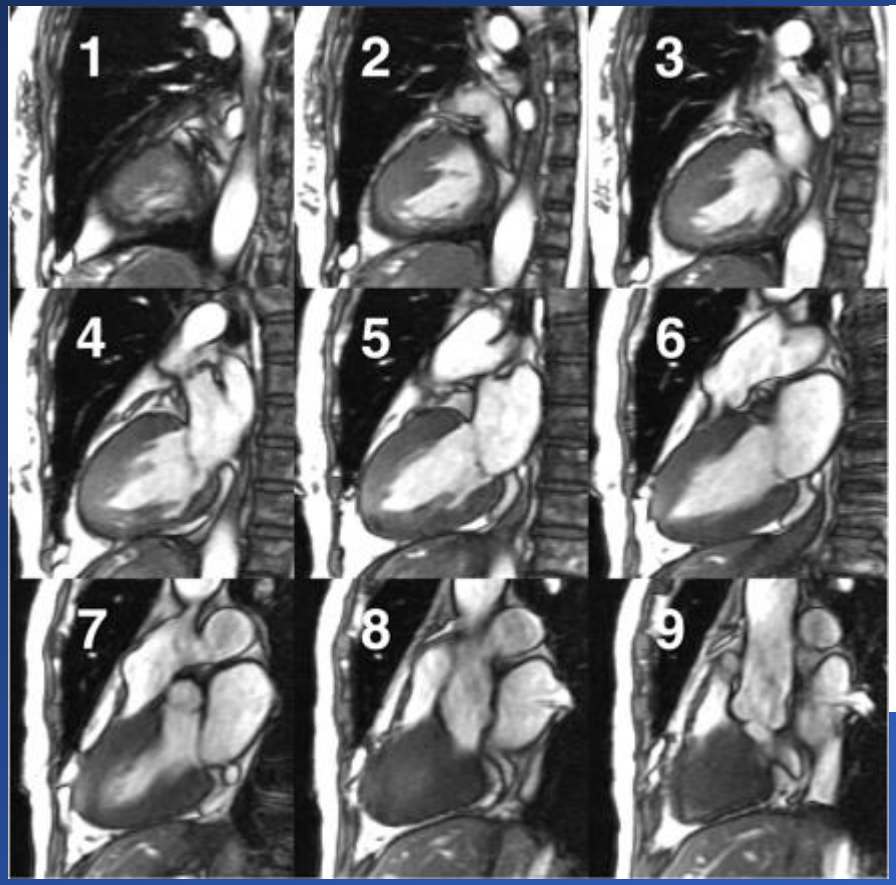
Watanabe, et al. Circulation 2005

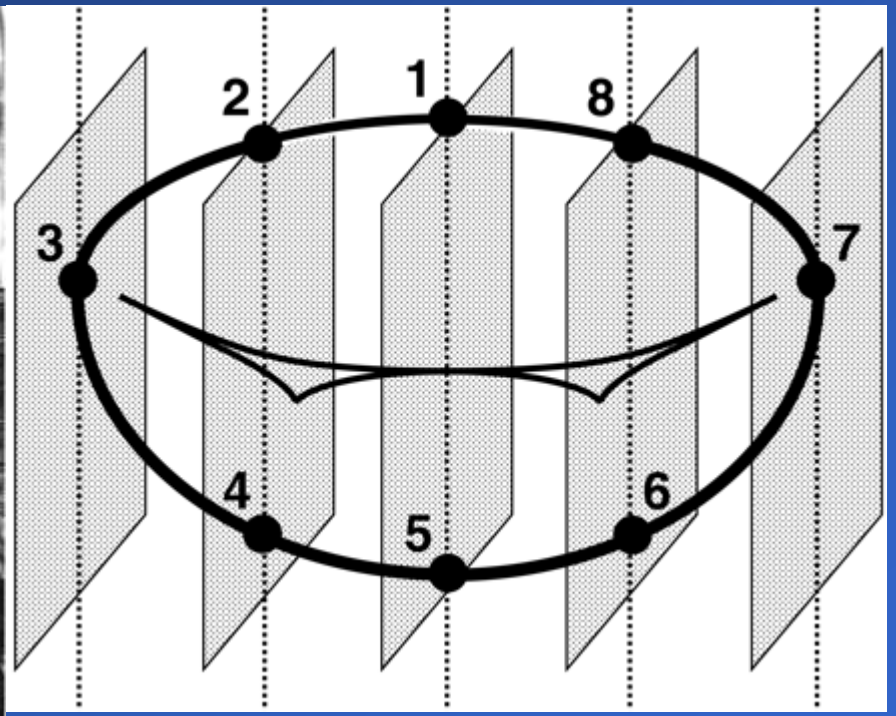
MA Flattens in Ischemic MR: Geometric Differences Between Inferior and Anterior Myocardial Infarction



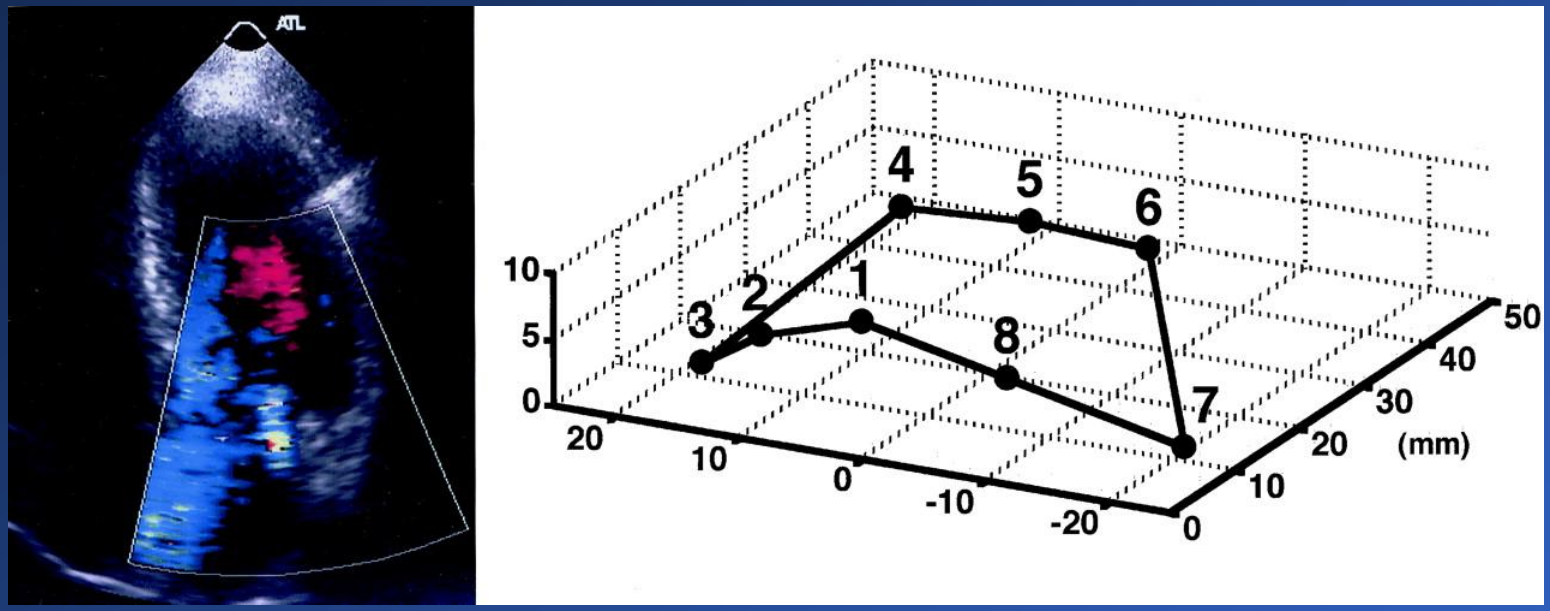
Watanabe, et al. Circulation 2005

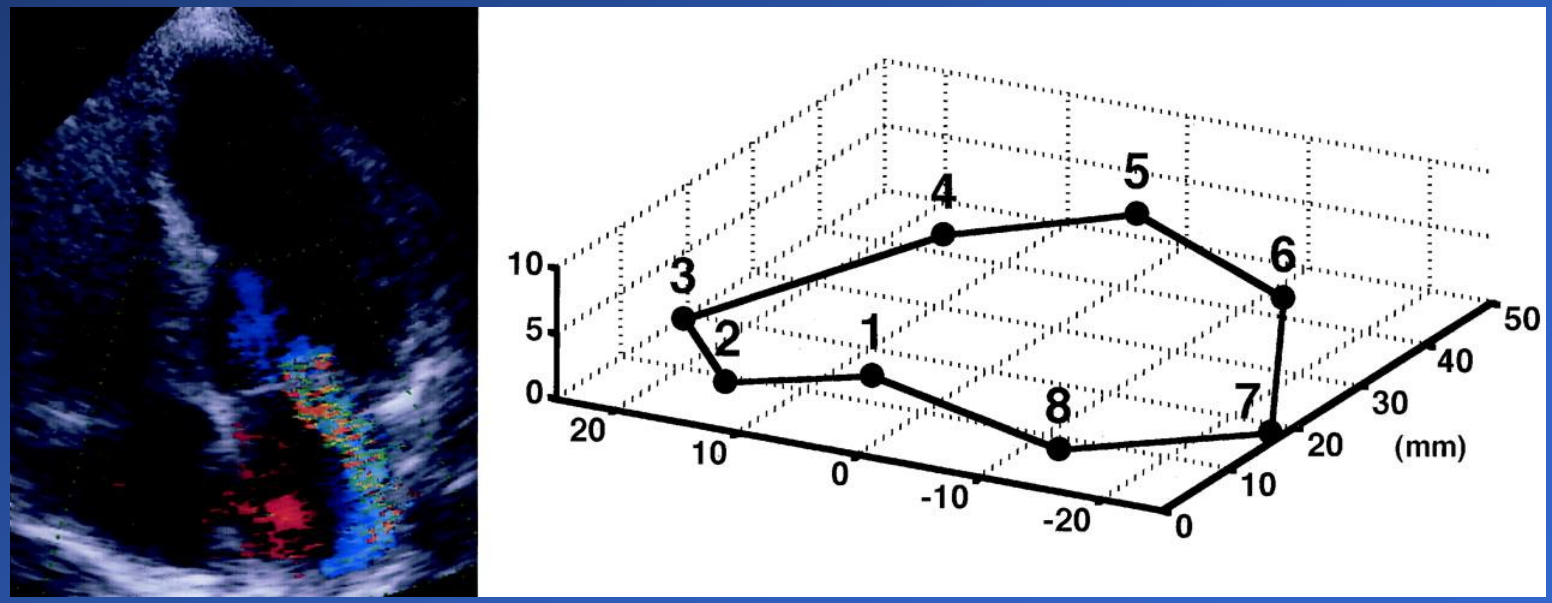
3D-Annular Geometry by MRI in 38 Patients With and W/O Chronic Ischemic MR Following Inferior or Posterior Myocardial Infarction





Kaji, et al. Circulation 2005





Kaji, et al. Circulation 2005

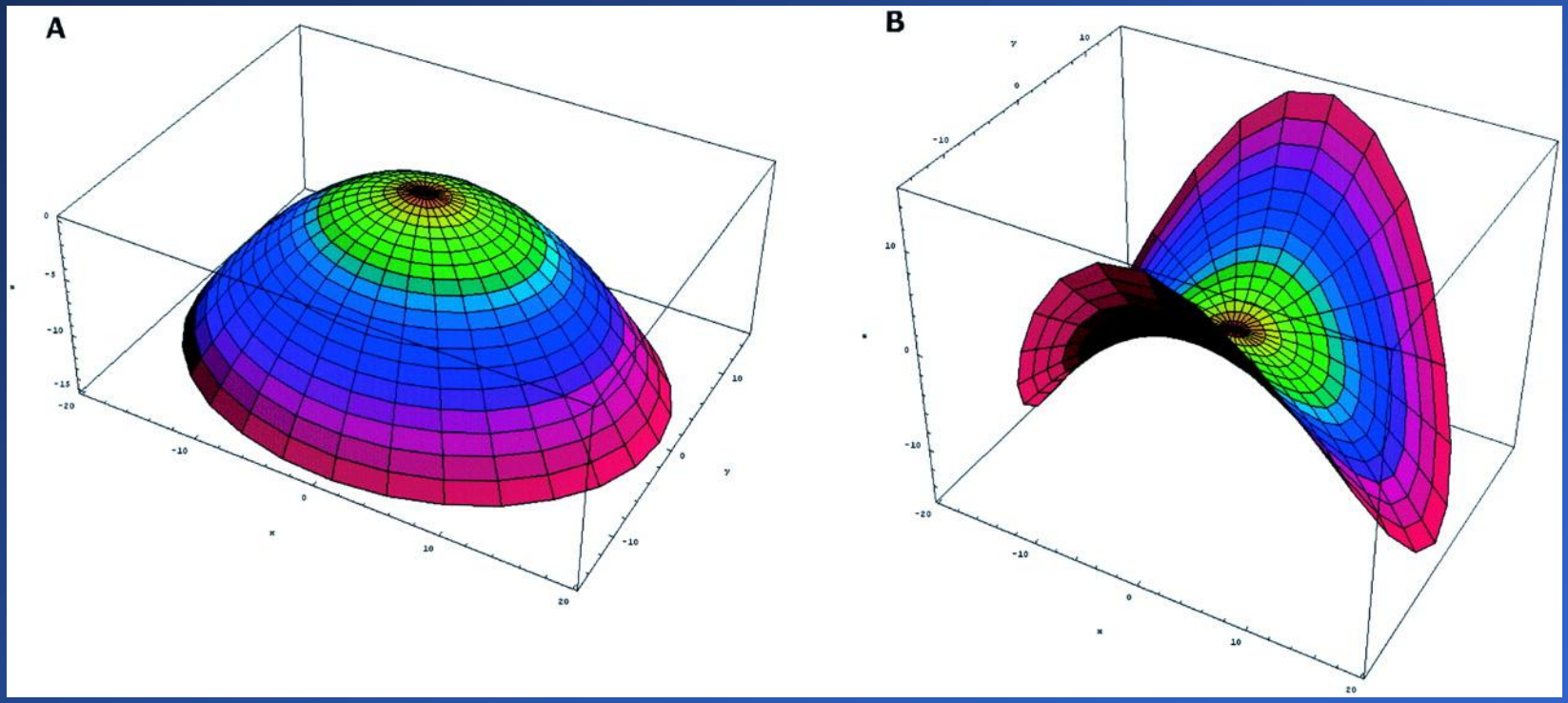
Mitral Annulus in health and disease

- The mitral annulus is nonplanar in normal subjects as well as those with reduced LV function
- Nonplanarity is preserved throughout the cardiac cycle, and as such not just the result of folding secondary to systolic area reduction
- Therefore, nonplanarity appears to be an inherent structural feature of the mitral annulus in health and disease

Mitral Annulus in Functional MR

- However, the mitral annulus clearly flattens with increasing ventriculo-annular remodeling; its nonplanarity is therefore severely reduced in patients with significant functional MR
- Moreover, while there is moderate additional folding during systole leading to more nonplanarity in normal subjects, the latter is absent throughout the cardiac cycle in these patients
- Lack of additional systolic folding is associated with decreased systolic area reduction (MR).
- This will increase the size of the mitral orifice to be covered and increase mitral leaflet stress

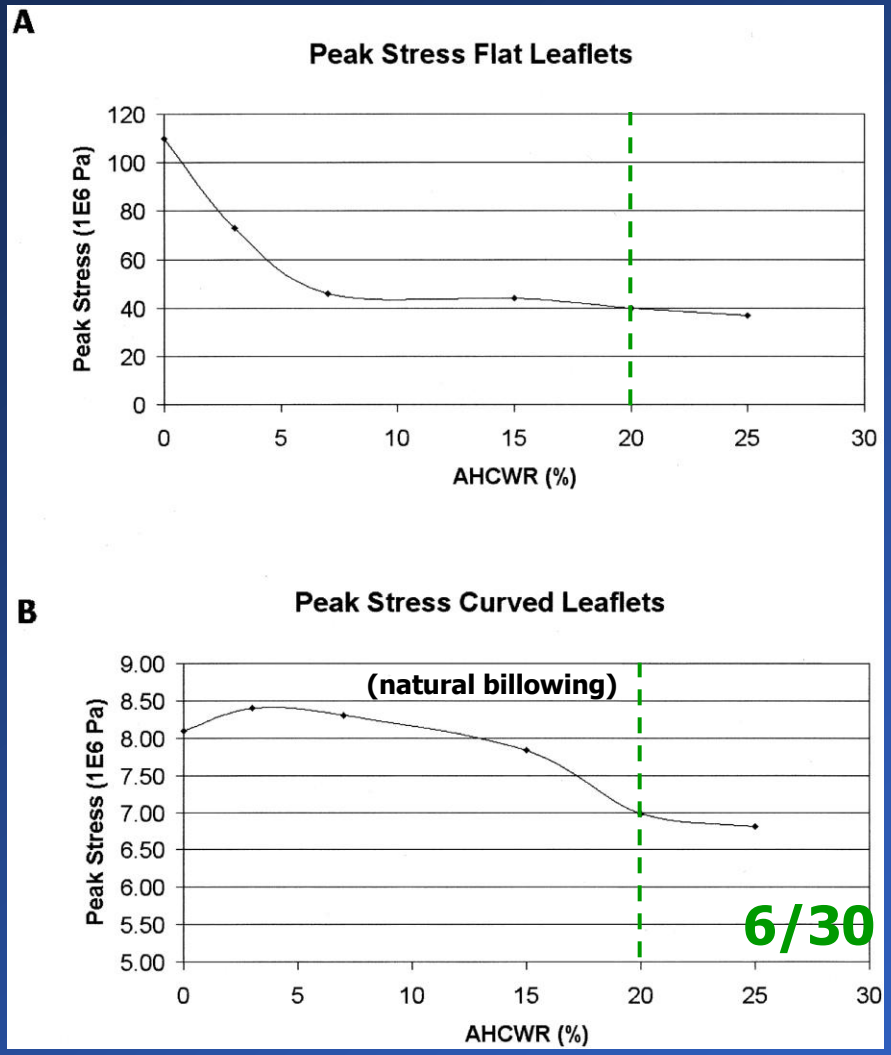
Effect of MA Shape on Leaflet Curvature in Reducing Leaflet Stress

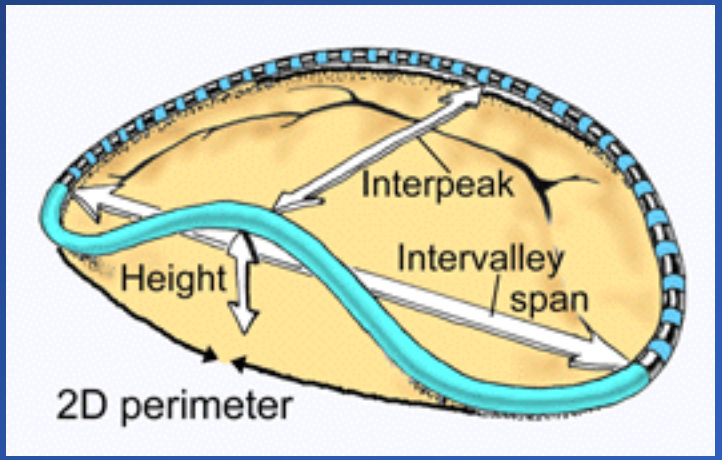


Finite element analysis: leaflet stress is determined by transmitral pressure, leaflet area, and leaflet curvature

Salgo, et al. Circulation 2002

Leaflet Stress decreases with increasing nonplanarity (AHCWR)





- The saddle shape of the mitral annulus confers a mechanical advantage to the leaflets by adding curvature.
- This may be valuable when leaflet curvature becomes reduced due to diminished leaflet billowing caused by annular dilatation.

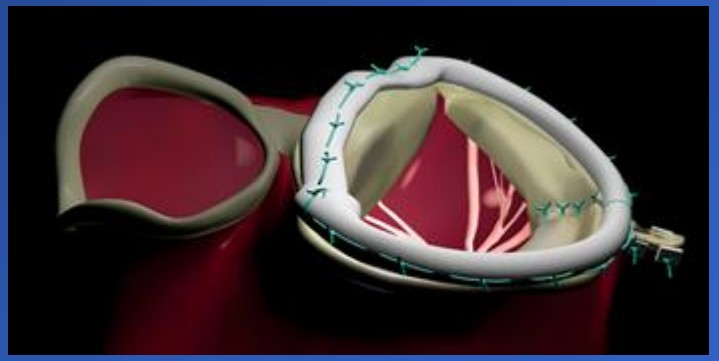
Salgo, et al. Circulation 2002

Saddle shape for stress reduction in unsupported roofs

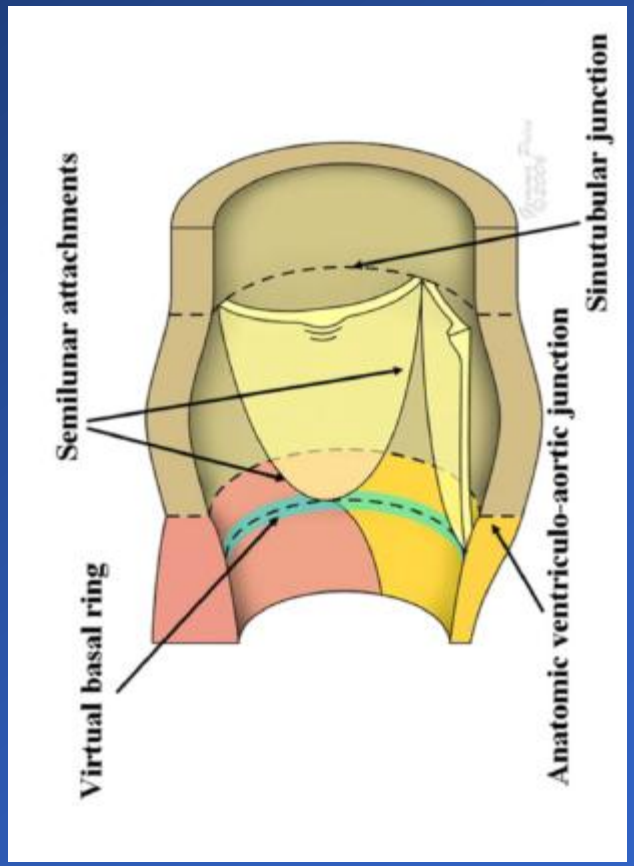
JFK Terminal 5 (TWA)

Saddle Dome Calgary

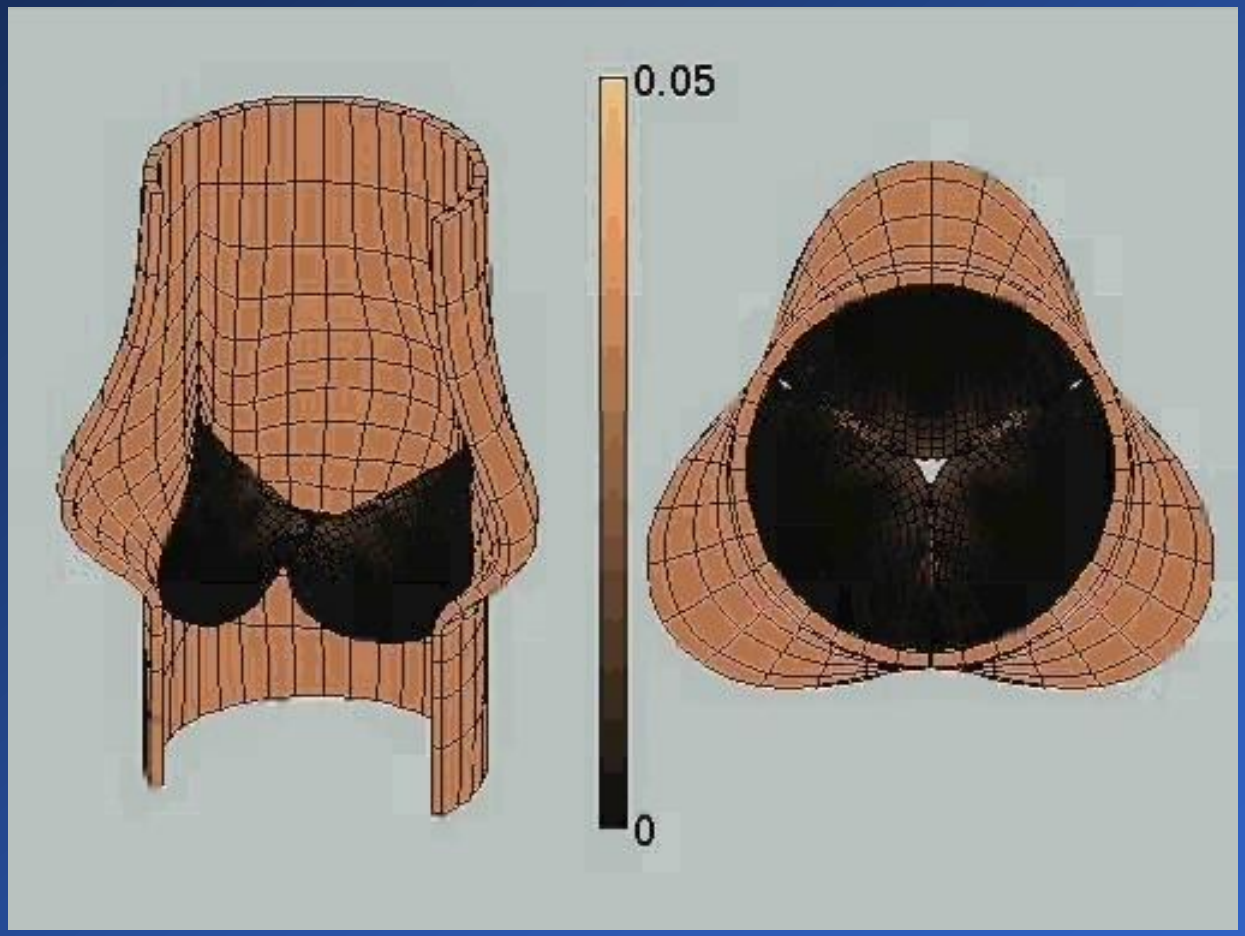
Newly designed mitral annuloplasty rings designed to address three dimensionality of the mitral annulus and its shape change during the cardiac cycle



Mechanical valve prostheses are essentially flat.
The design of biological valve prostheses usually reflects appreciation of the native's valve three-dimensionality



Anderson RH 2006

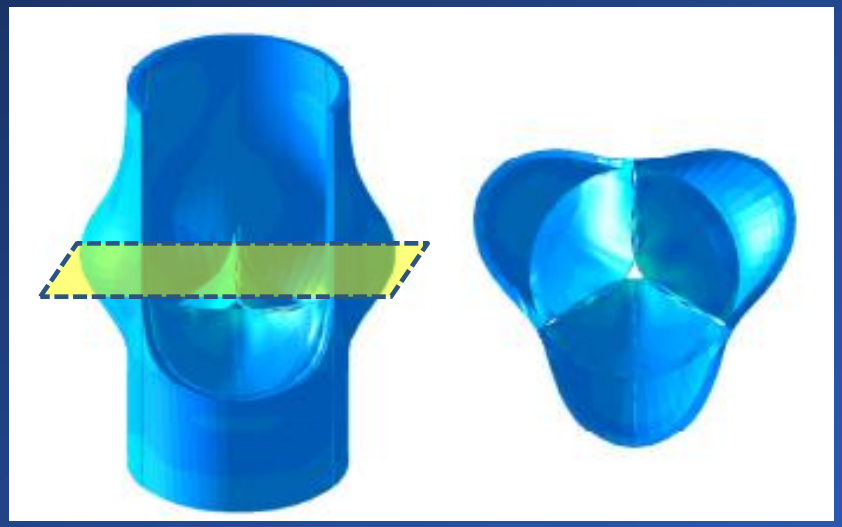


J De Hart

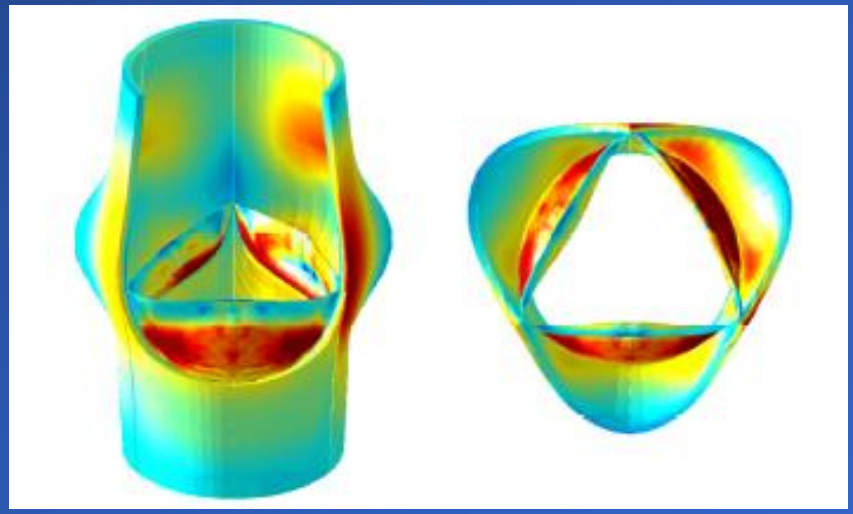
Because of the three-dimensional (3-peak-3-through) geometry of the aortic valve, the bottom of the aortic root is hemodynamically actually part of the LV, and distends with the increase in LV pressure during isovolumic contraction even before aortic valve opening!

"The aortic root is very elastic in young patients and expands considerably during systole…"
T. David. Current Problems in Surgery, June 1999

Diastolic conformation



Systolic conformation



"The commissural points move outward in response to rising internal blood pressures pulling the leaflets towards the sinus cavities. This mechanism is essential for … valve opening"

J De Hart, et al. J Biomech 2003

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3D Shape of the Aortic Valve and Mechanism of Aortic Valve Opening

- **Aortic valve opening is an active process ! It starts with the distention of the aortic root during isovolumic contraction.**
- **The active initiation of aortic valve opening is lost with progressive calcification and decreasing compliance of the ageing aorta**
- **This may actually be one of the initial steps leading to aortic stenosis**

Conclusions

- Cardiac valves have an inherently three-dimensional shape characterized by an equal number of troughs and peaks – two each for the saddle-shaped mitral valve, and three each for the crown-shaped aortic valve
- The three-dimensional shape of the cardiac valves reduces leaflet-stress
- Without stress reduction by their 3D shape the leaflets would have to be much thicker (and consequently less flexible) in order to last a lifetime
- Three-dimensionality may enable to change opening area effectively by conformational changes
- These mechanisms become less effective when affected by disease