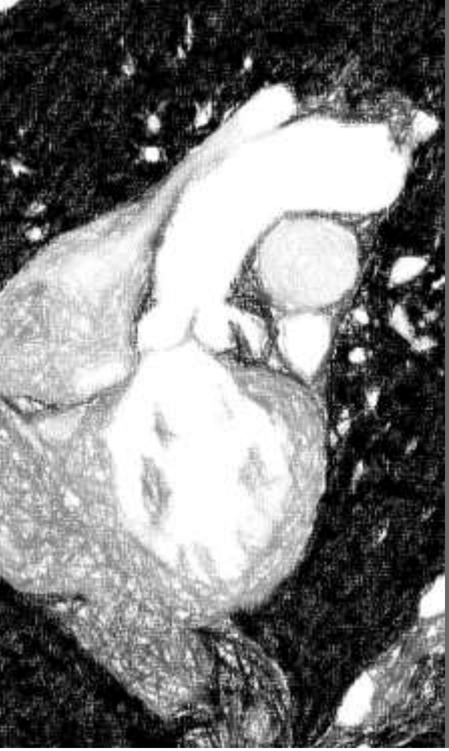
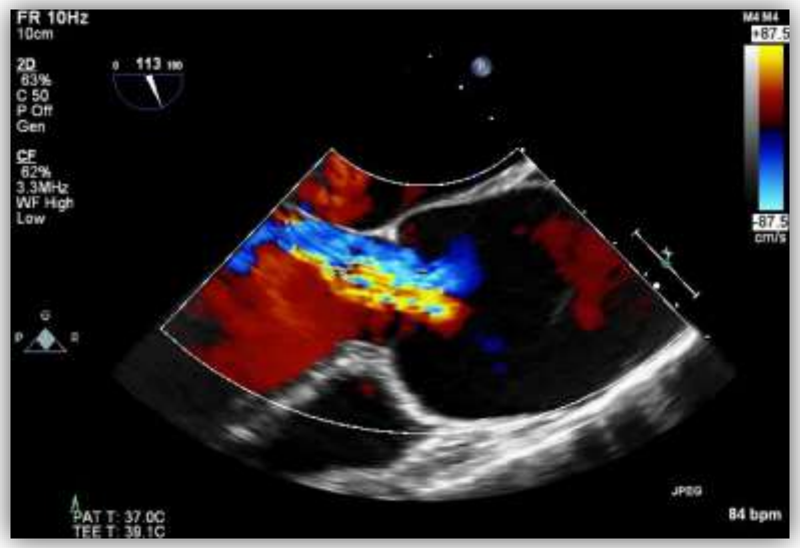


Aortic Cusp Asymmetry and Adaptation in Aortic Regurgitation

Jae-Kwan Song, MD, PhD, FACC
Asan Medical Center Heart Institute
Research Institute for Valvular Heart Disease
University of Ulsan College of Medicine
Seoul, South Korea

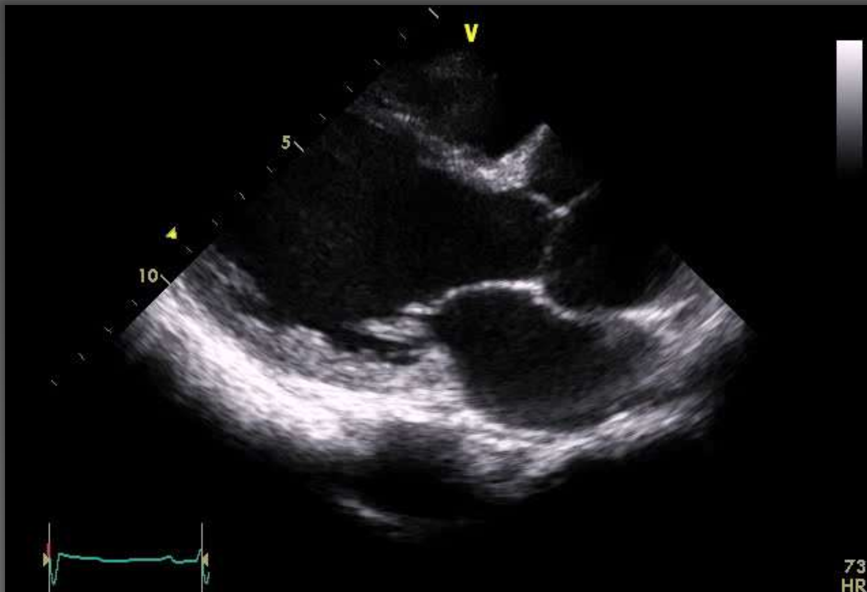
Aortic Root Dilation (ARD)

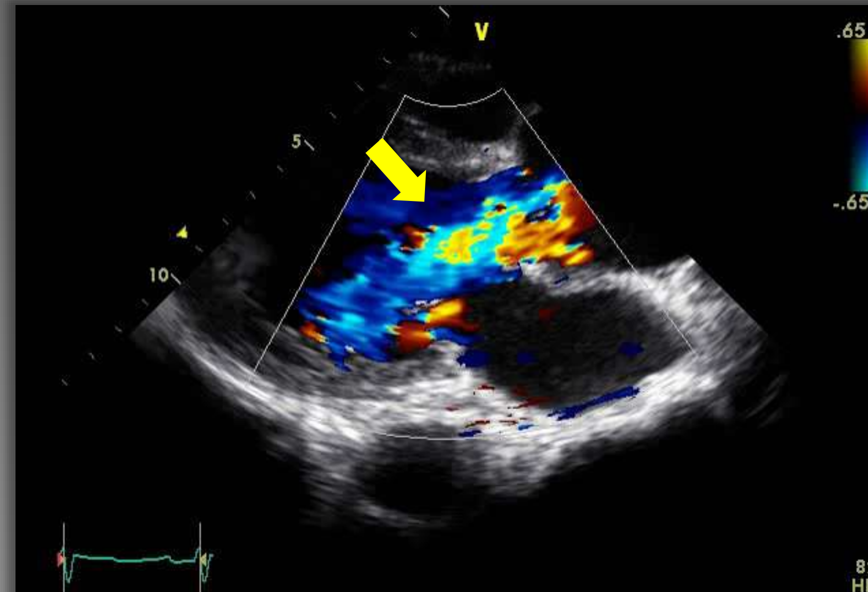
- Can cause functional aortic regurgitation (AR) with anatomically normal AV leaflets

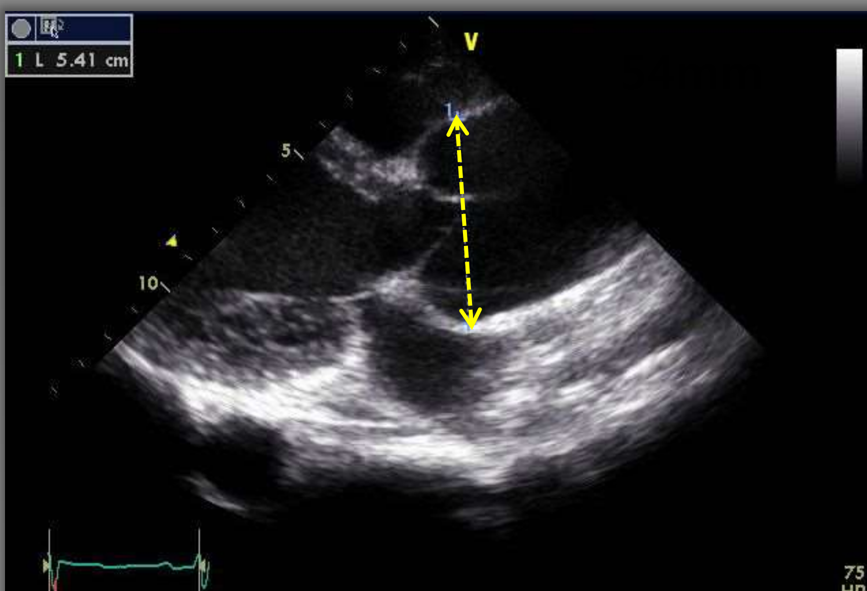


- Aortic valve sparing surgeries:

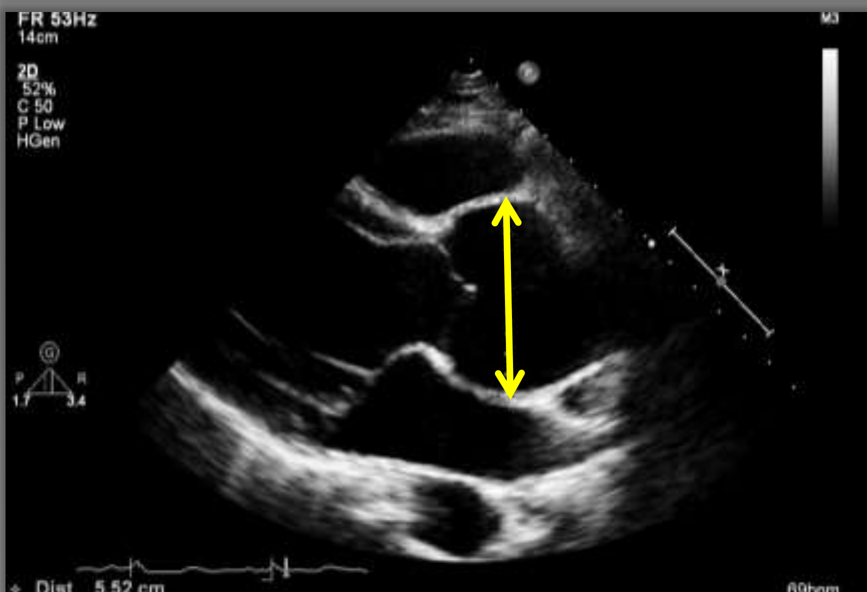
Clinical Observation: case 1

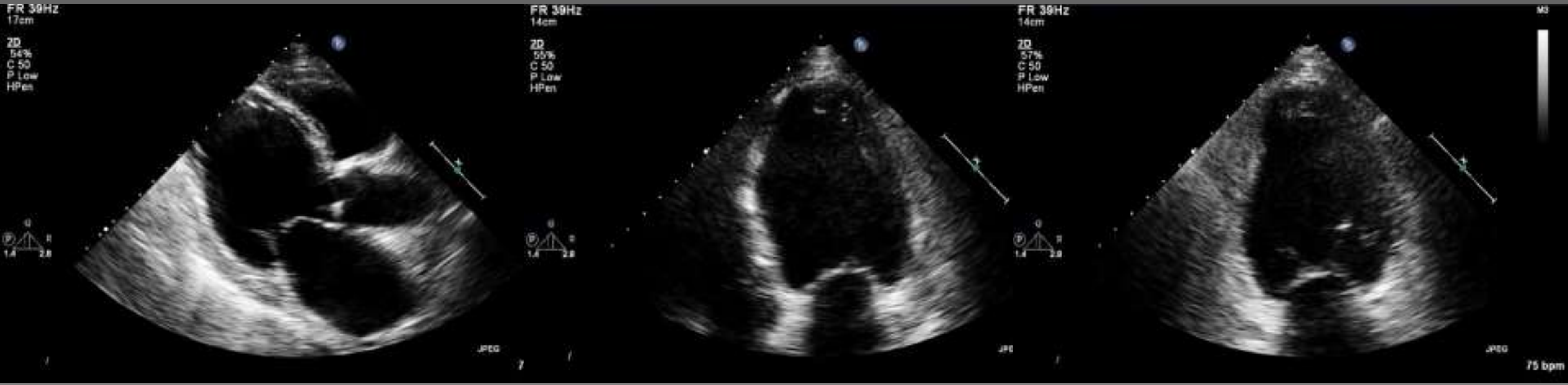






Clinical Observation: case 2

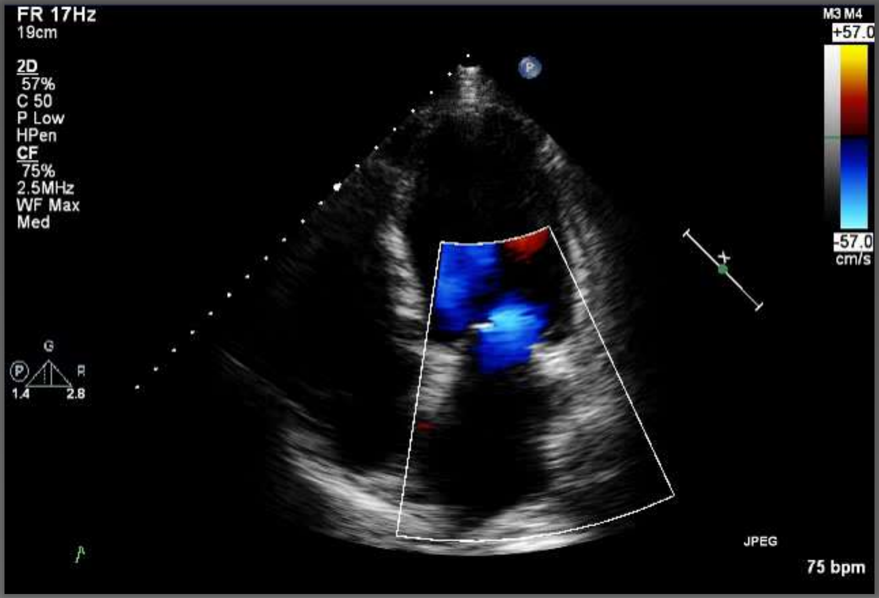




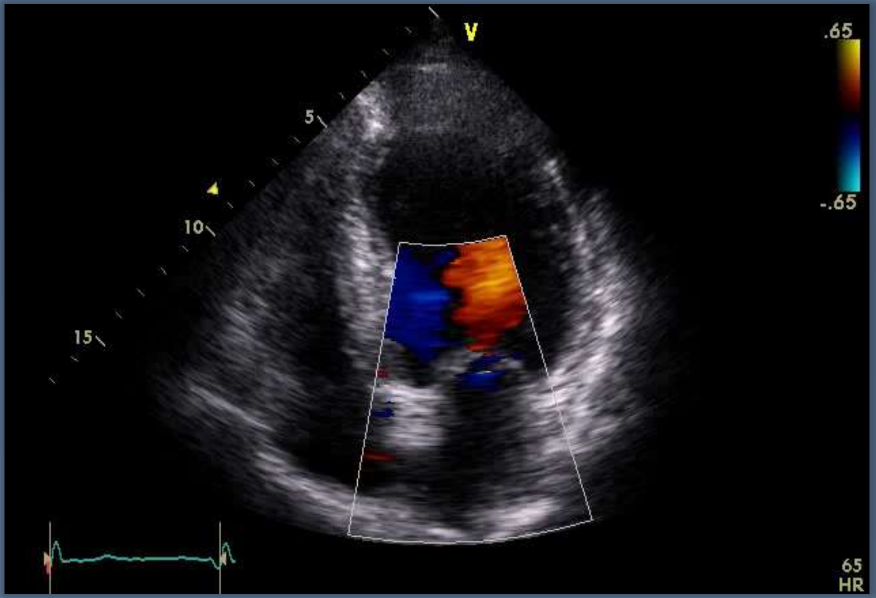
Case 1 3VD LVD: 51/63 EF 33%

Case 2 3VD LVD: 60/67 EF 26%

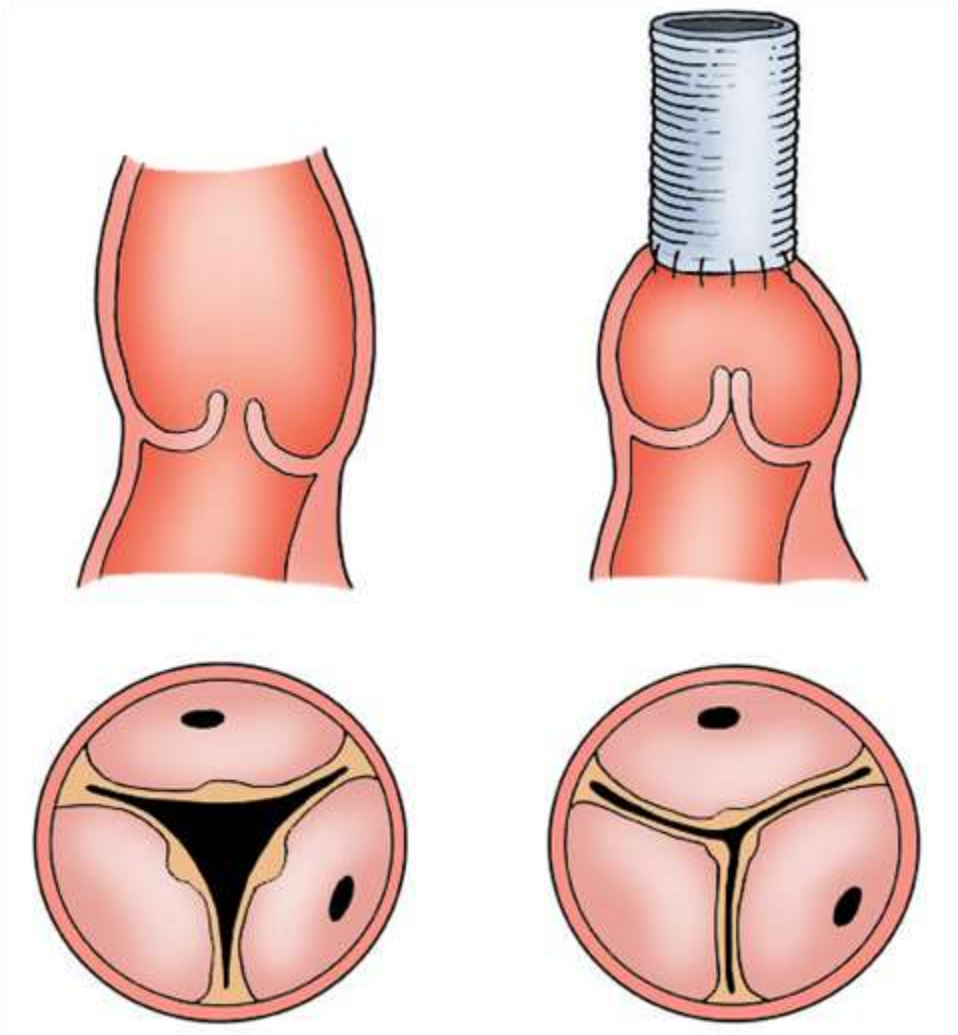
Case 1


FR 17Hz
19cm
2D
57%
C 50
P Low
HPen
CF
75%
2.5MHz
WF Max
Med
M3 M4
+57.0
-57.0
cm/s
1.4
2.8
JPEG
75 bpm

Case 2


V
.65
-.65
5
10
15
65
HR

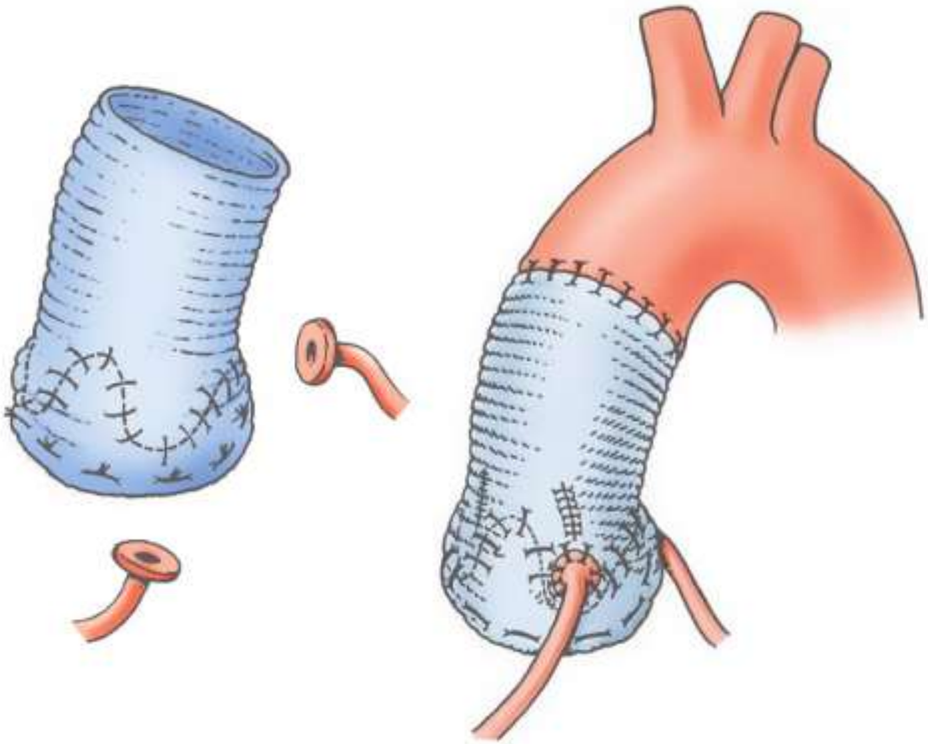
Replacement of the ascending aorta with a graft of appropriate diameter

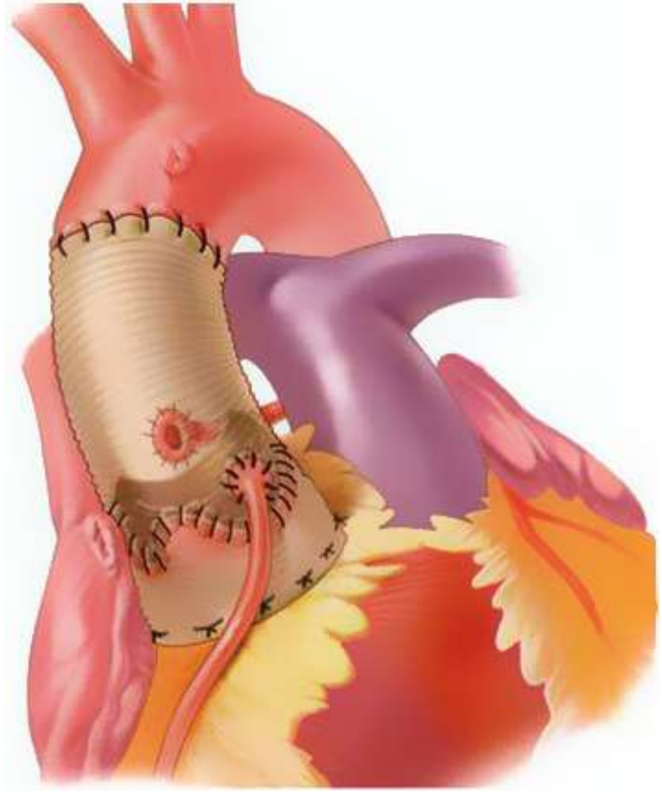


Remodeling of the Aortic Root

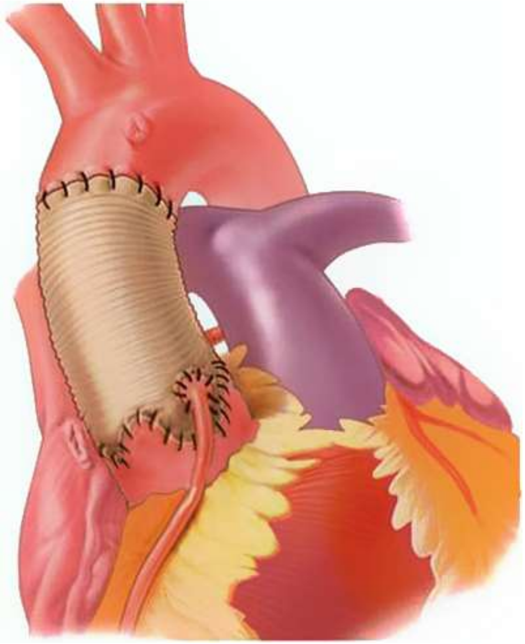
David TE J Card Surg 2011;26:92-99

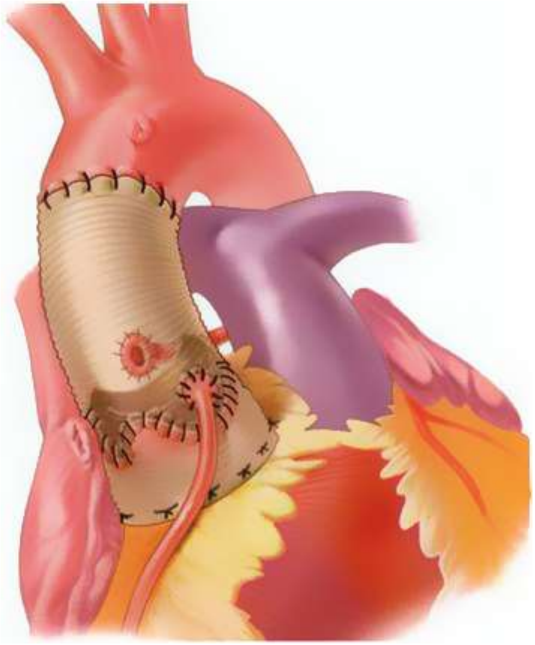
Reimplantation of the Aortic Valve

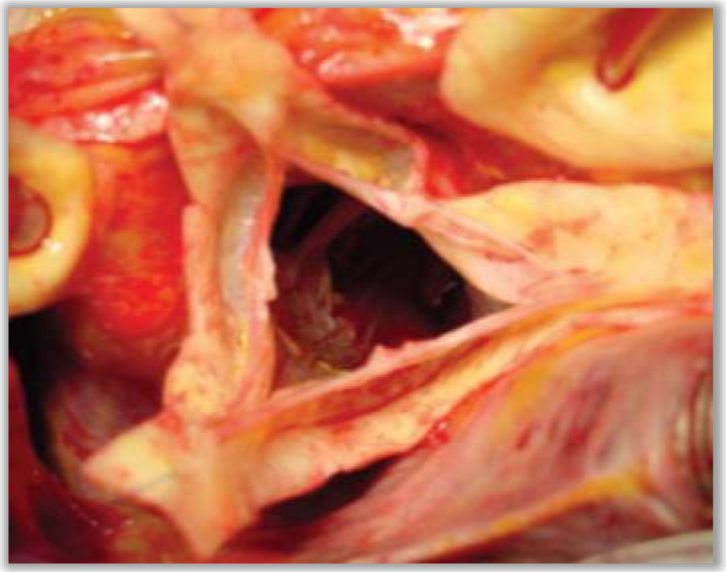




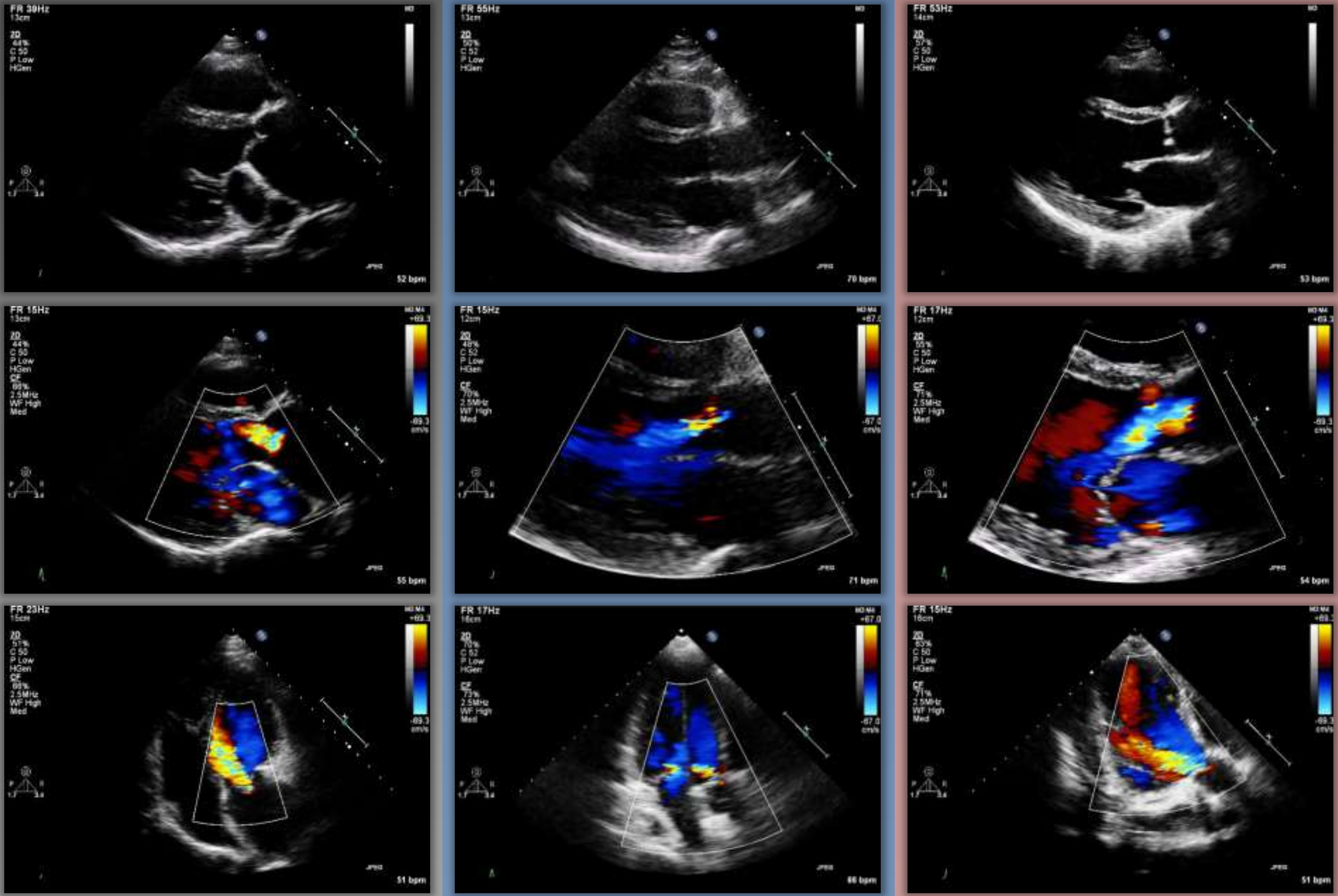
David TE J Card Surg 2011;26:92-99







David TE J Card Surg 2011;26:92-99

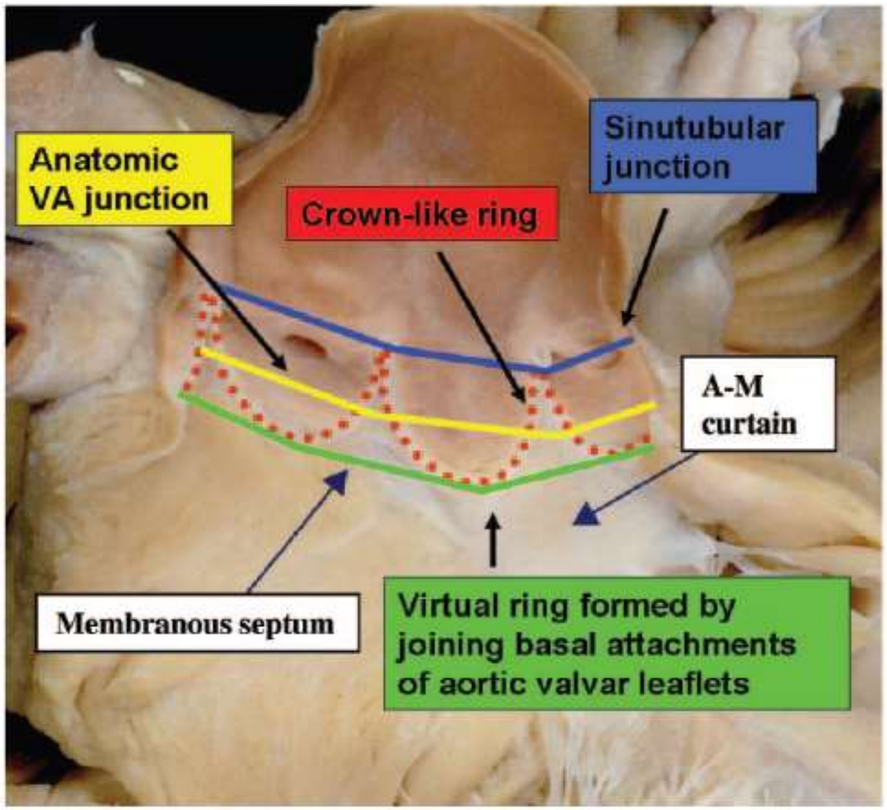


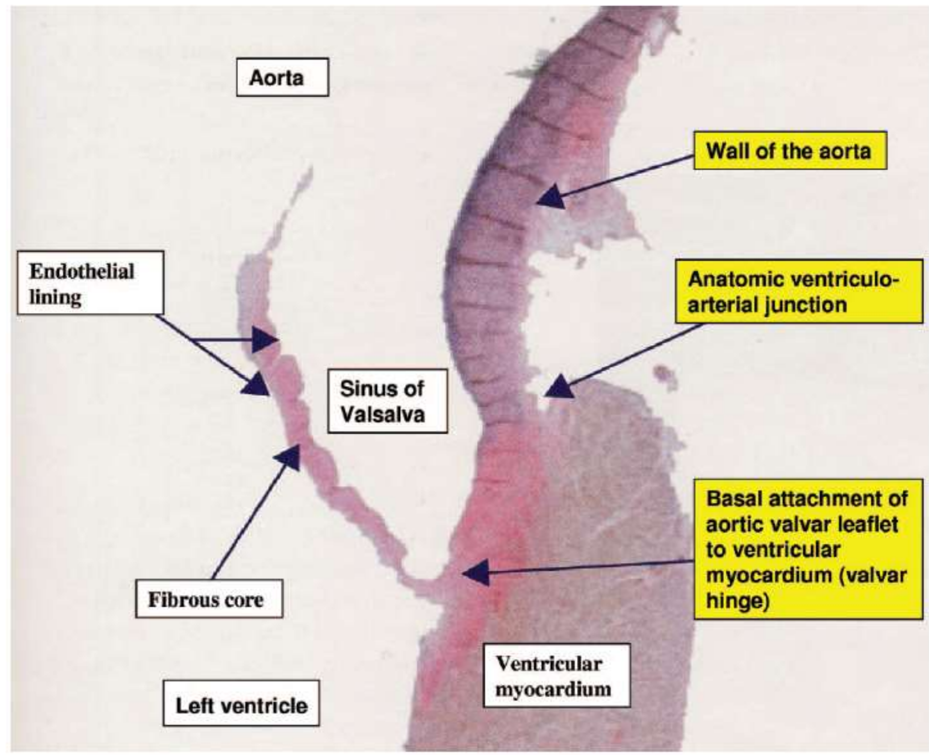
Preop

Post-repair

26 mo later

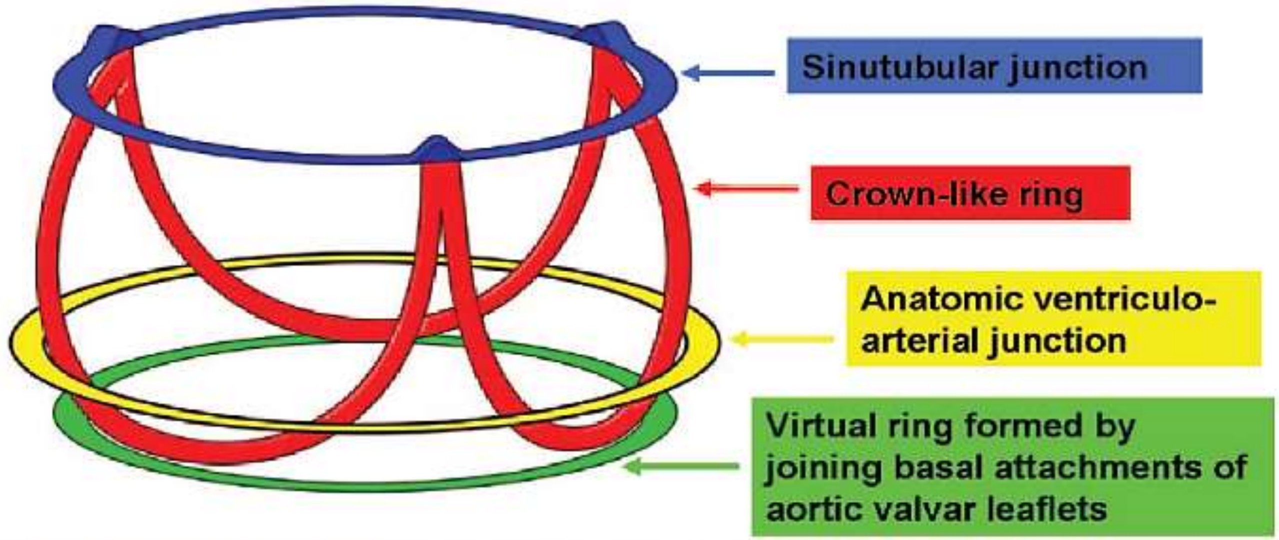
Aortic Root





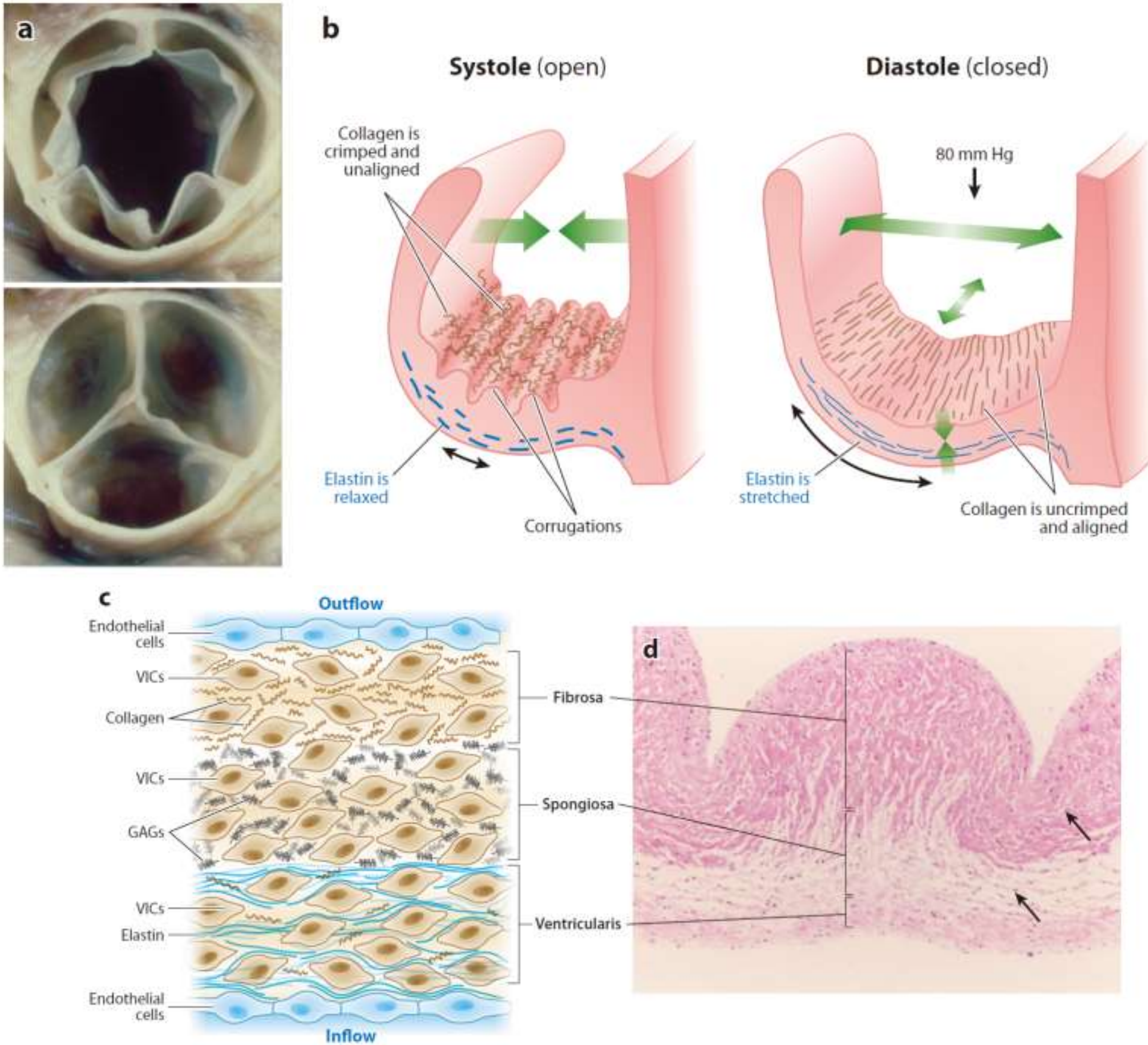
Circ Cardiovasc Intv 2008;1:74

Aortic Root



1) Diameter of ascending aorta
2) Diameter of sinotubular junction
3) Height and width of sinus of Valsalva
4) Height and takeoff of coronary ostium
5) Diameter of LVOT
6) Diameter of basal attachment
7) Thickness of ventricular septum

Circ Cardiovasc Intv 2008;1:74

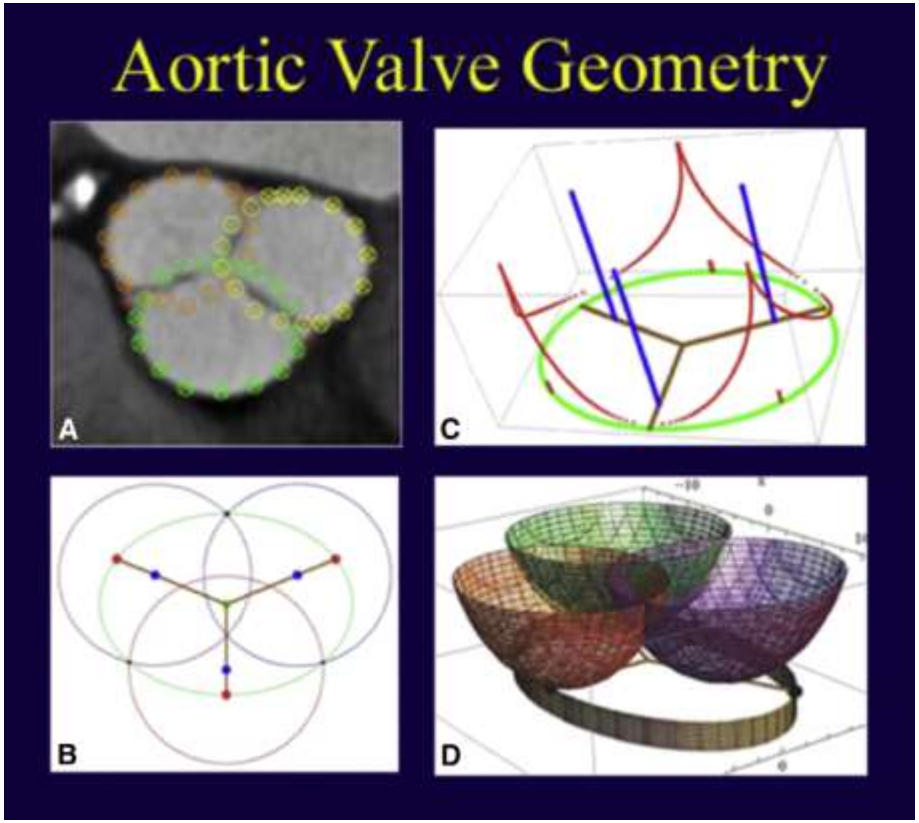


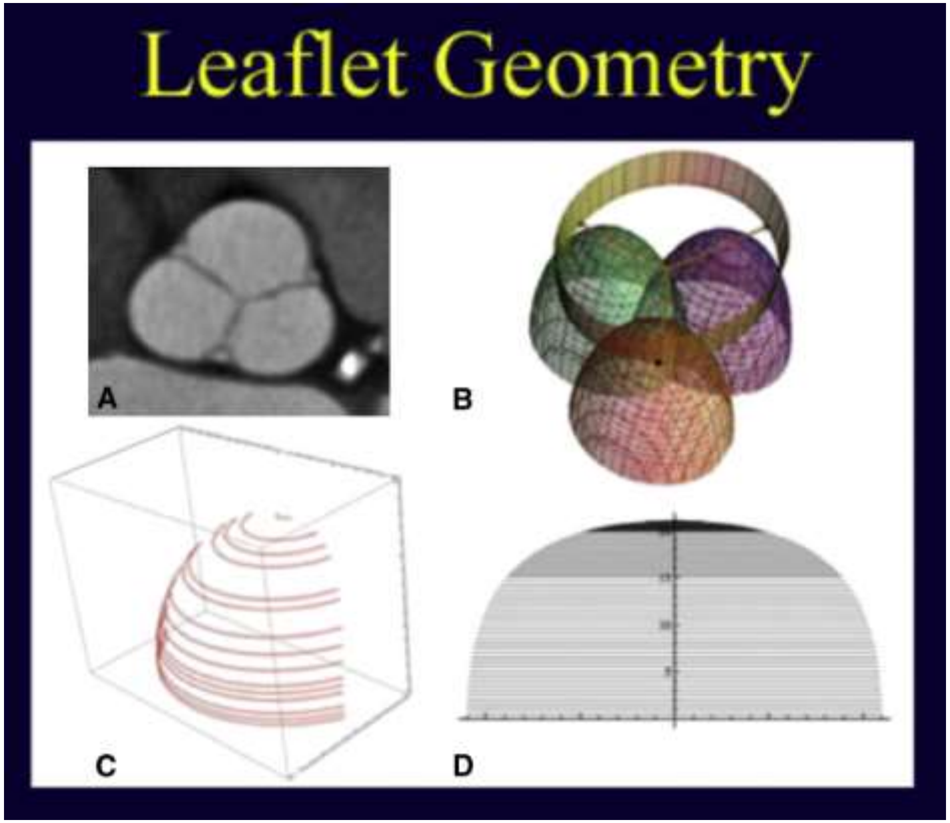
a
b
Systole (open)
Diastole (closed)
Collagen is crimped and unaligned
80 mm Hg
Elastin is relaxed
Corrugations
Elastin is stretched
Collagen is uncrimped and aligned
c
Outflow
Endothelial cells
VICs
Collagen
VICs
GAGs
VICs
Elastin
Endothelial cells
Inflow
Fibrosa
Spongiosa
Ventricularis
d

Da Vinci's Sketch
Over 400 Years ago

A refined hemispheric model of normal human aortic valve and root geometry

J. Scott Rankin, MD, M. Crockett Bone, BS, Peter M. Fries, MD, Diana Aicher, MD, Hans-Joachim Schäfers, MD, Philip S. Crooke, PhD

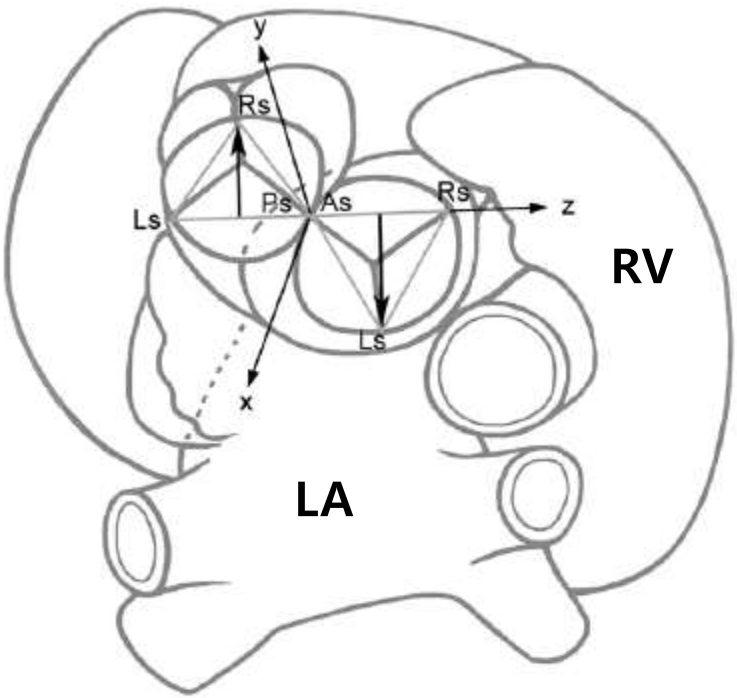


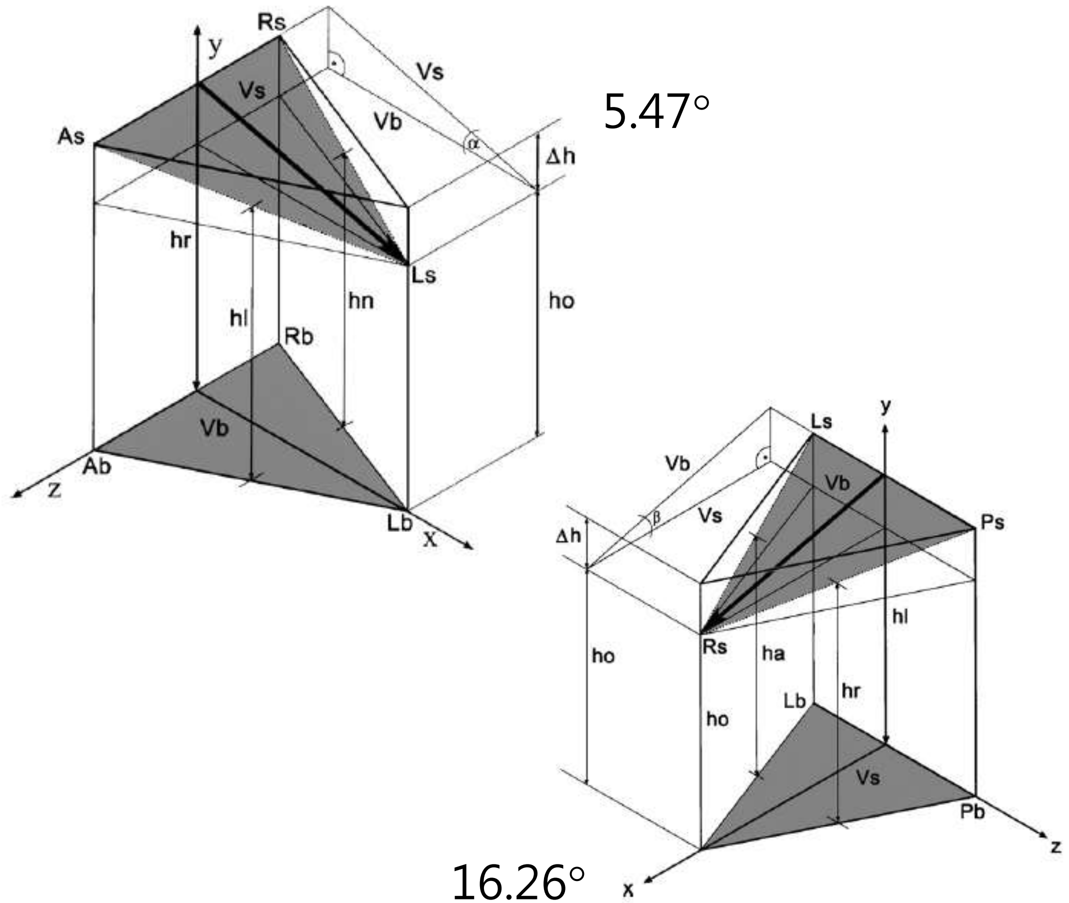


J Thorac Cardiovasc Surg 2013;146:103

Geometric models of the aortic and pulmonary roots: suggestions for the Ross procedure

Denis Berdajs, Gregor Zünd, Ulrich Schurr, Colette Camenisch, Marko I. Turina, Michele Genoni

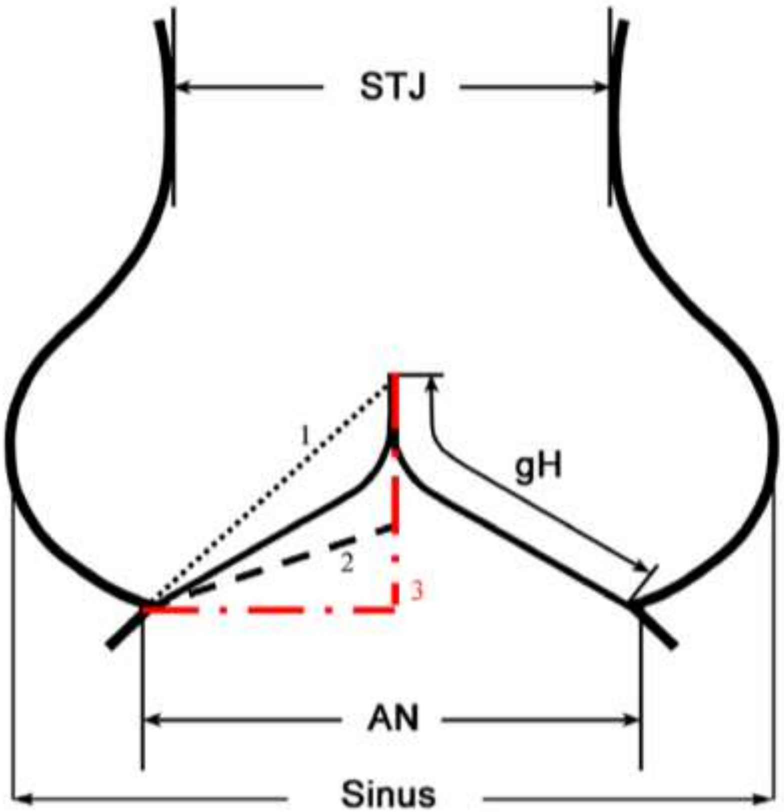


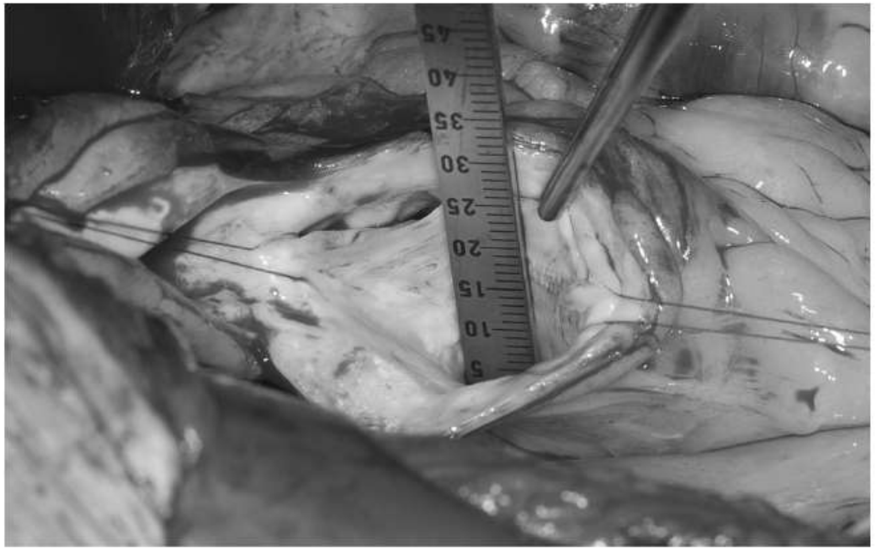


Eur J Cardio-thorac Surg 2007;31:31

Cusp height in aortic valves

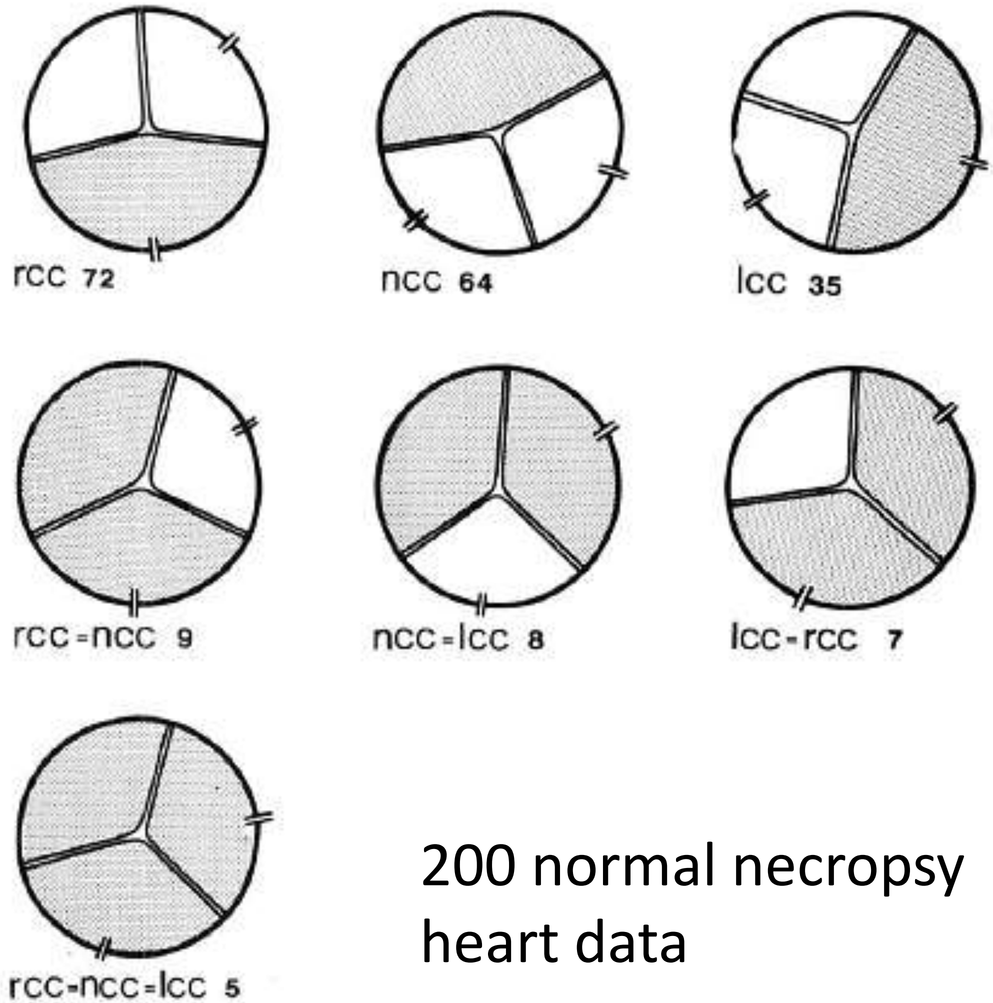
Hans-Joachim Schäfers, MD, Wolfram Schmied, Dipl Psych, Gil Marom, MSc, Diana Aicher, MD





J Thorac Cardiovasc Surg 2013;146:269

Inequality in Aortic Cusp Surface Area

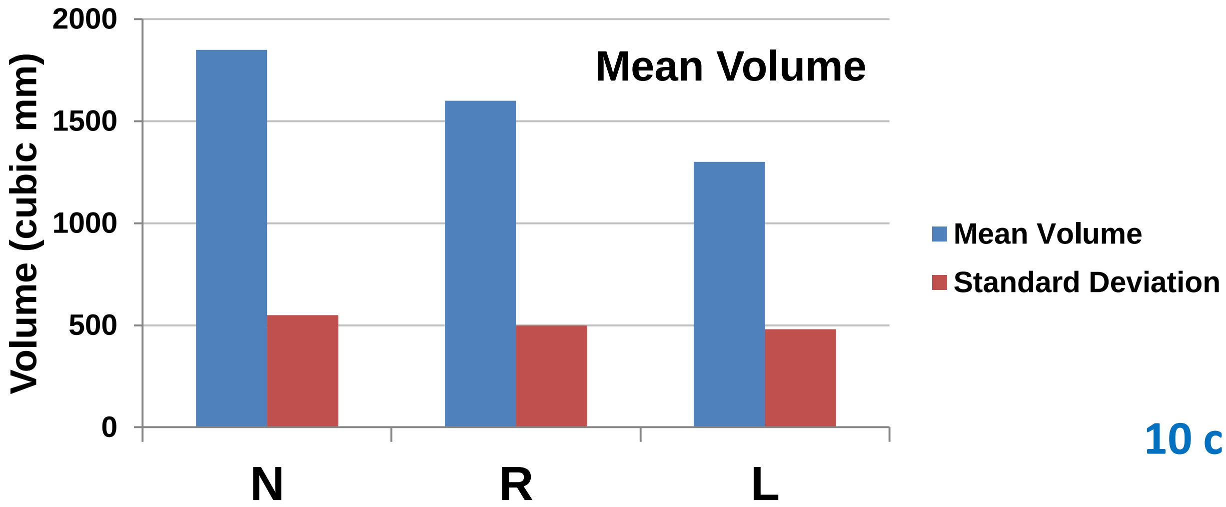


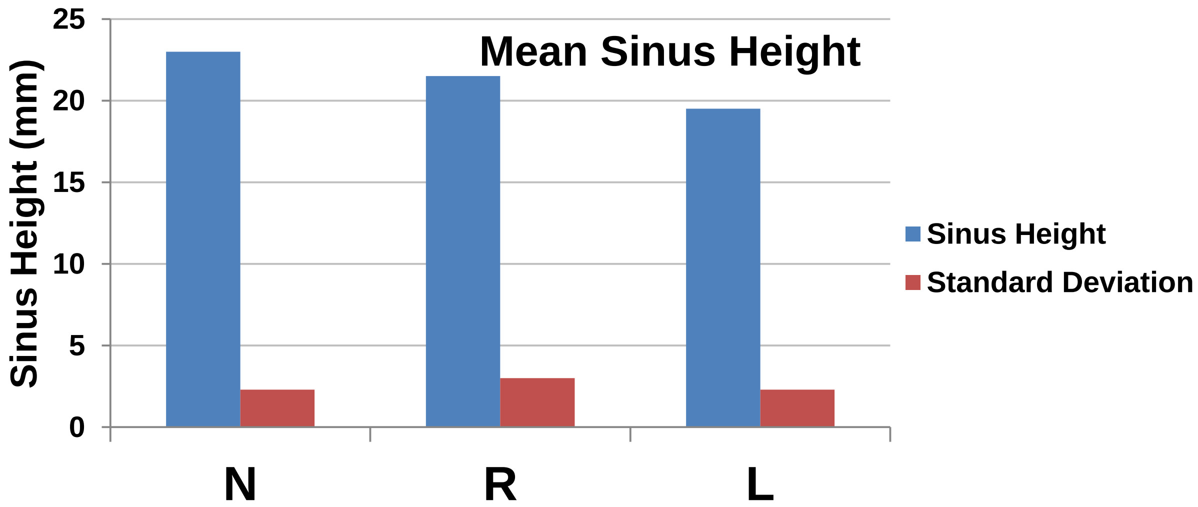
200 normal necropsy heart data

Br Heart J 1977;39:1006

Aortic Root Geometry: Pattern of Differences Between Leaflets and Sinuses of Valsalva

Suk Jung Choo MD, George McRae PhD, James P. Olomon BS, Greg St. George PhD, Wayne Davis MD, Catherine L. Burleson-Bowles MS, David Pang MS, Hong He Luo MD, Daniela Vavra, David T. Cheung PhD, James H. Oury MD, Carlos M. G. Duran MD





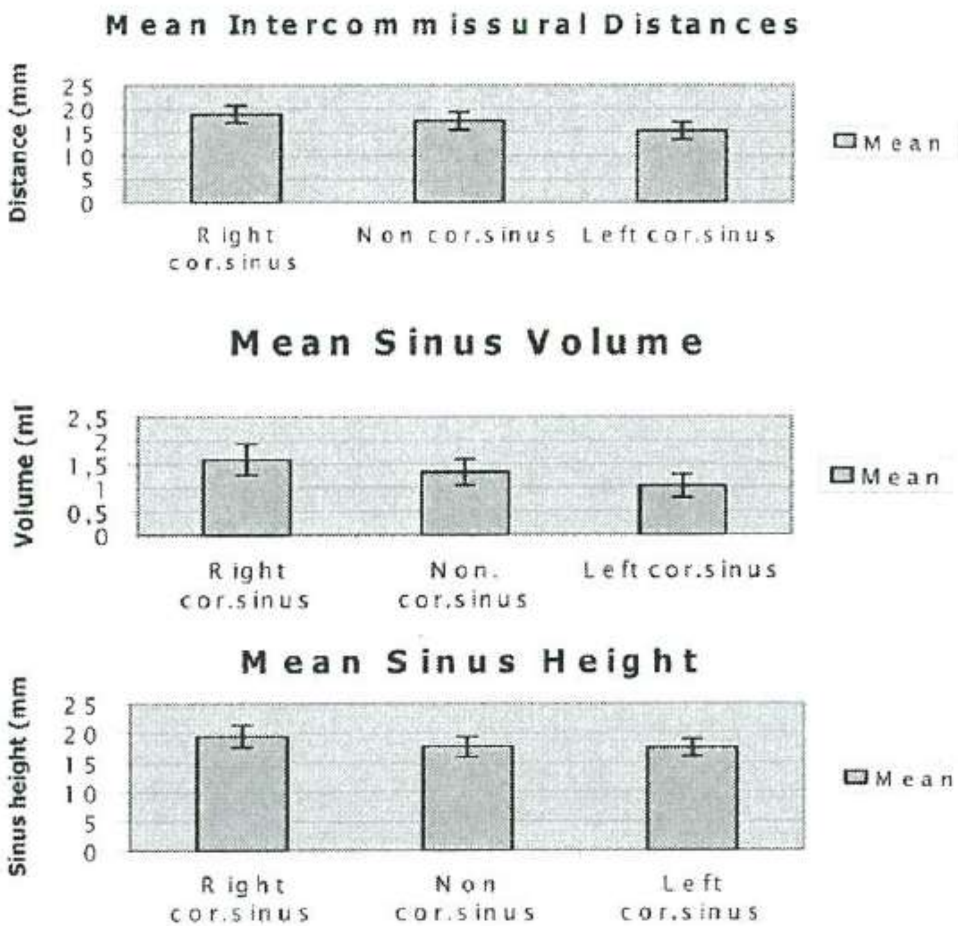
10 cryopreserved aortic root

N>R>L

J Heart Valve Dis 1999;8:407

The anatomy of the aortic root

Denis Berdajs, Patonay Lajos and Marko Turina



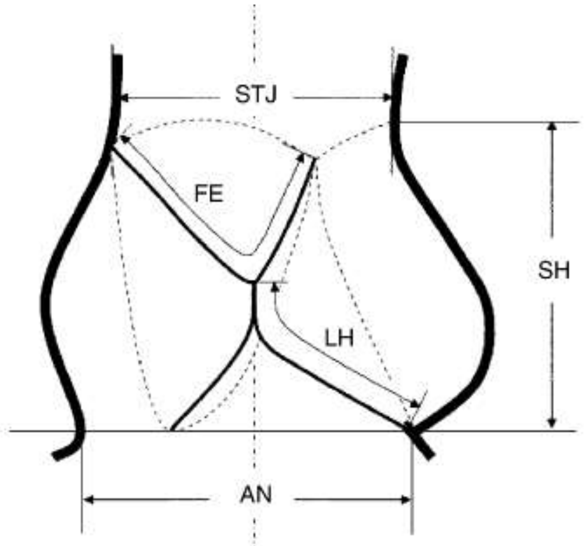
25 normal cadaver hearts

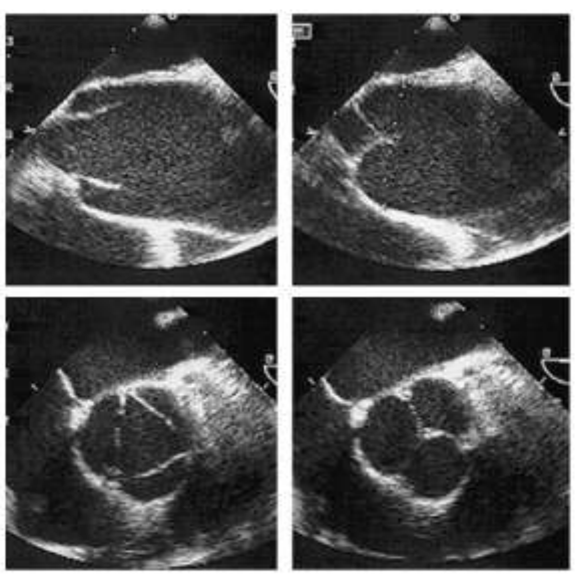
R>N>L

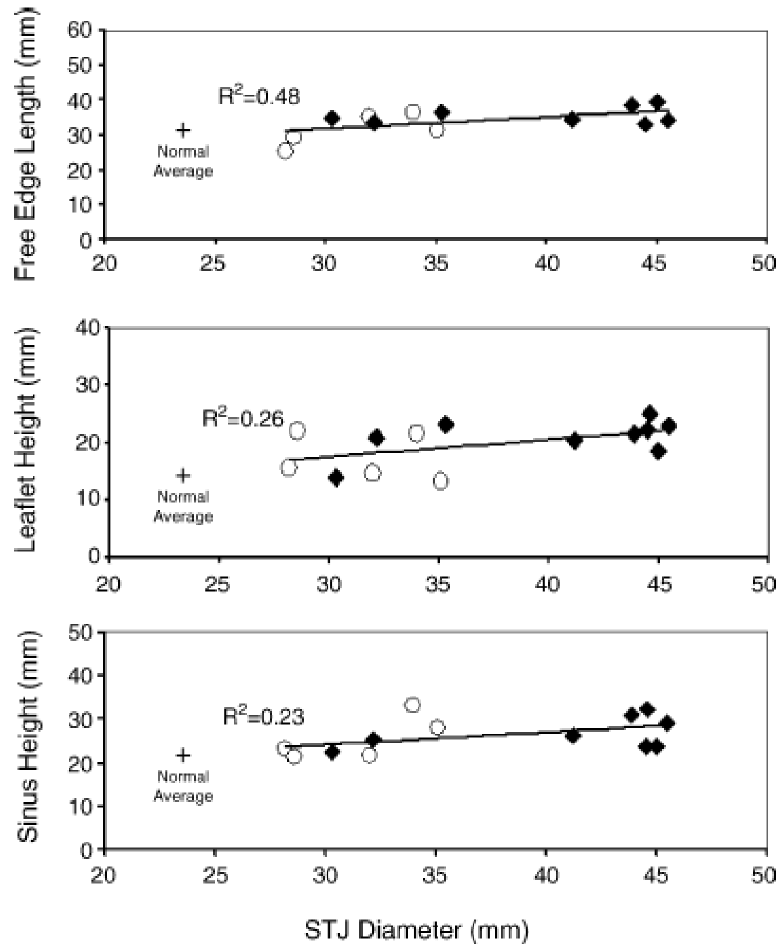
Cardiovasc Surg 2002;10:320

Aortic Root Dilatation may alter the dimensions of the valve leaflets

Mano J. Thubrikar, Michel R. Labrosse, Kenton J. Zehr, Francis Robicsek, Geoffrey G. Gong, Brett L. Fowler

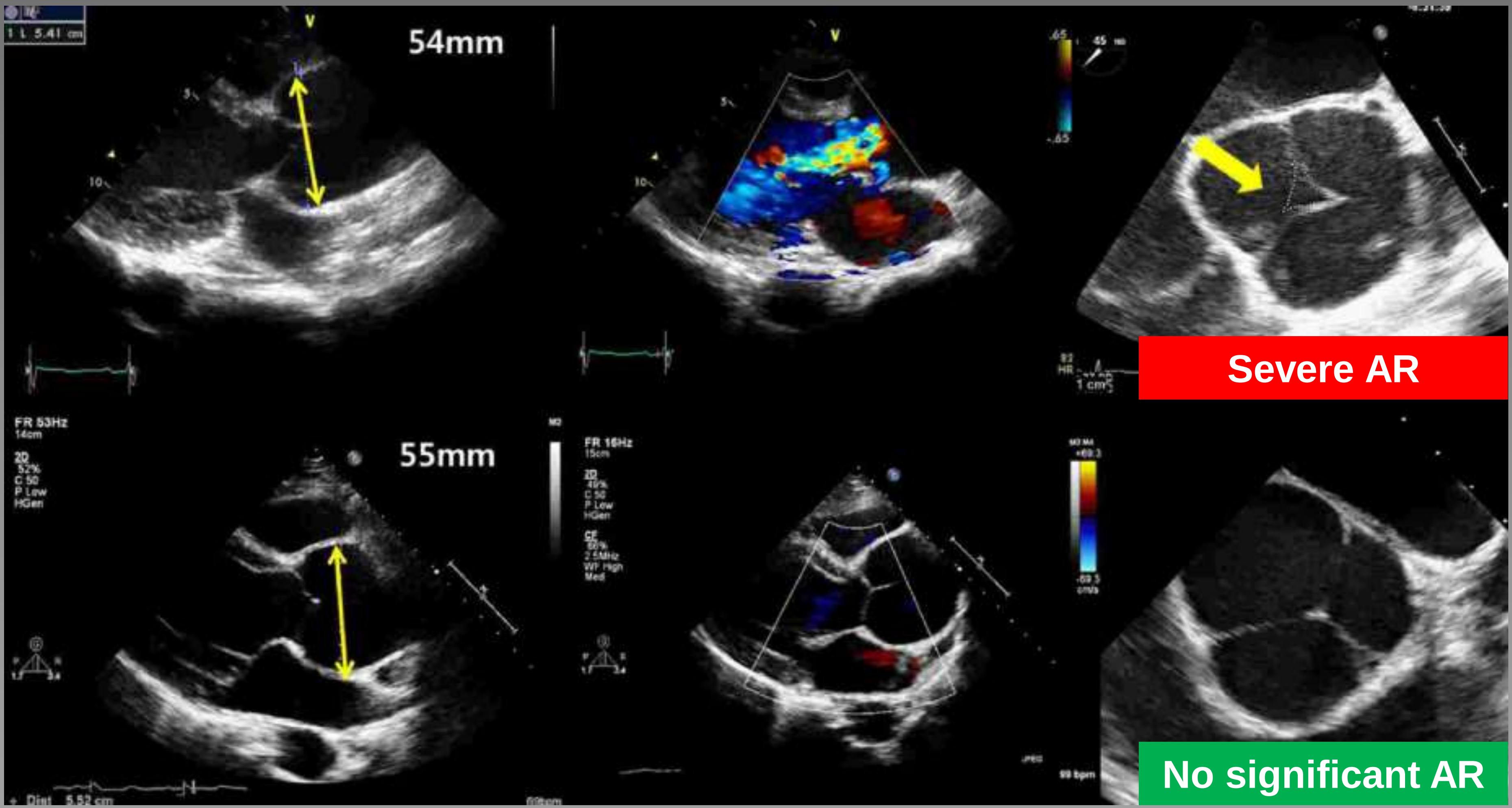






Eur J Cardio-thorac Surg 2005;28:850

Different AR Severity despite Similar Aortic Root Size



Aortic Valve Adaptation to Aortic Root Dilatation:
Insights Into the Mechanism of Functional Aortic Regurgitation From 3-Dimensional Cardiac Computed Tomography

Kim, Dae-Hee MD; Handschumacher, Mark D. BS; Levine, Robert A. MD; Sun, Byung Joo MD; Jang, Jeong Yoon MD; Yang, Dong Hyun MD; Kang, Joon-Won MD; Song, Jong-Min MD; Kang, Duk-Hyun MD; Lim, Tae-Hwan MD; Song, Jae-Kwan MD

1. **One dimensional measurement of aortic root size – NOT GOOD!**

2. **Root Dilatation vs. Cusp Enlargement**

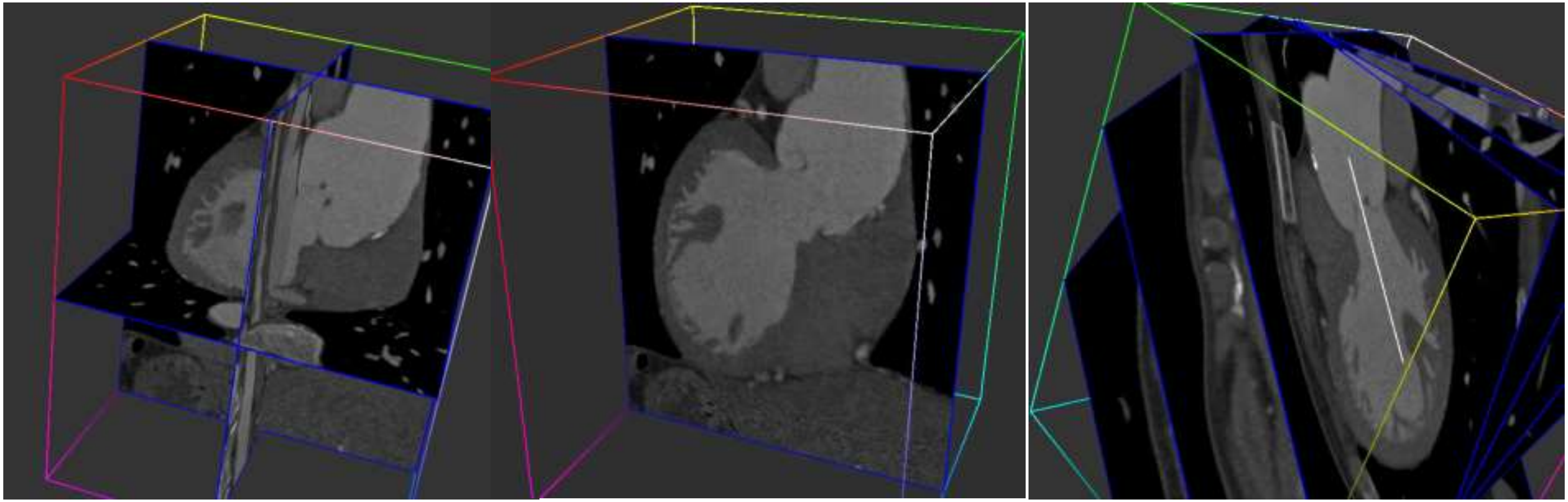
3. **Any role of asymmetry?**

Circ Cardiovasc Imaging 2014;7:828-835

Aortic Valve Adaptation to Aortic Root Dilatation:

Insights Into the Mechanism of Functional Aortic Regurgitation From 3-Dimensional Cardiac Computed Tomography

- Full volume image from axial DICOM CT images
- Omni4D analysis software

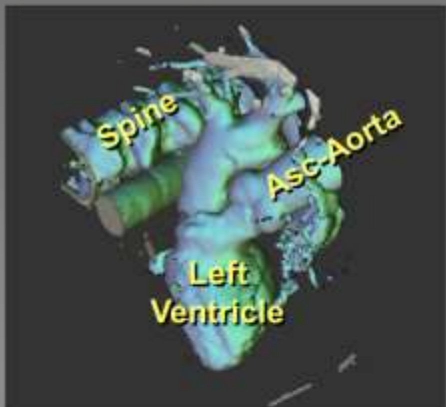


Circ Cardiovasc Imaging 2014;7:828-835

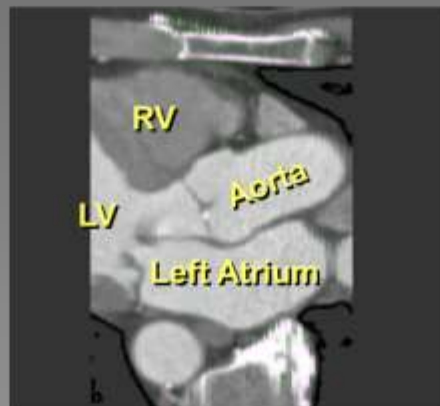
Omni4D

AV cusp area & root geometry measurement

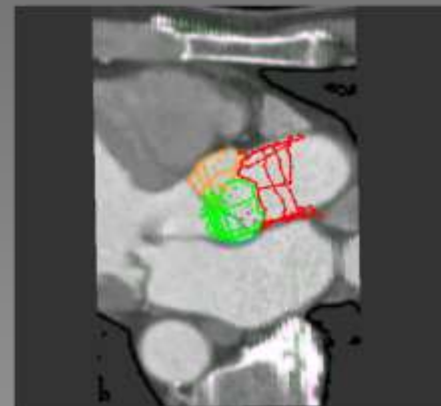
Import 3D image data. Visualize with volume rendering



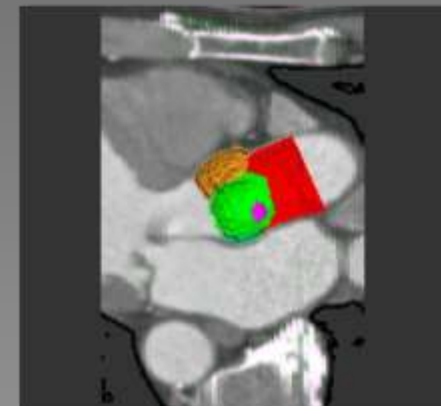
3D volume resected into 2D planes for detailed interpretation



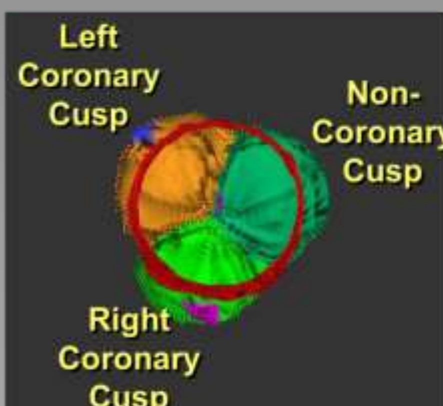
Define features: semi-automatic; automatic; manual



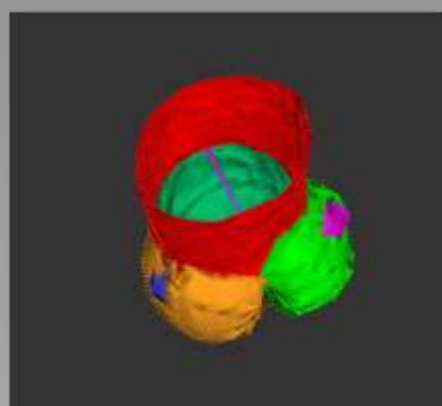
Automatic 3D surface modeling to features.



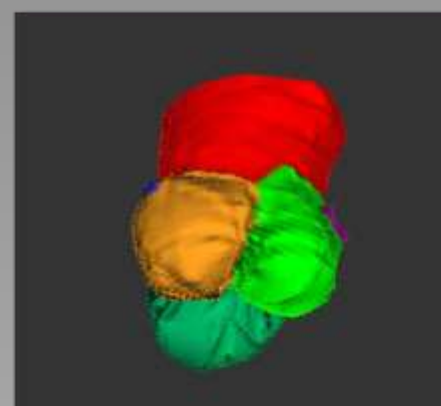
Model-view through axis of ascending aorta to 3 cusps



View of coronary branch points (blue, pink)

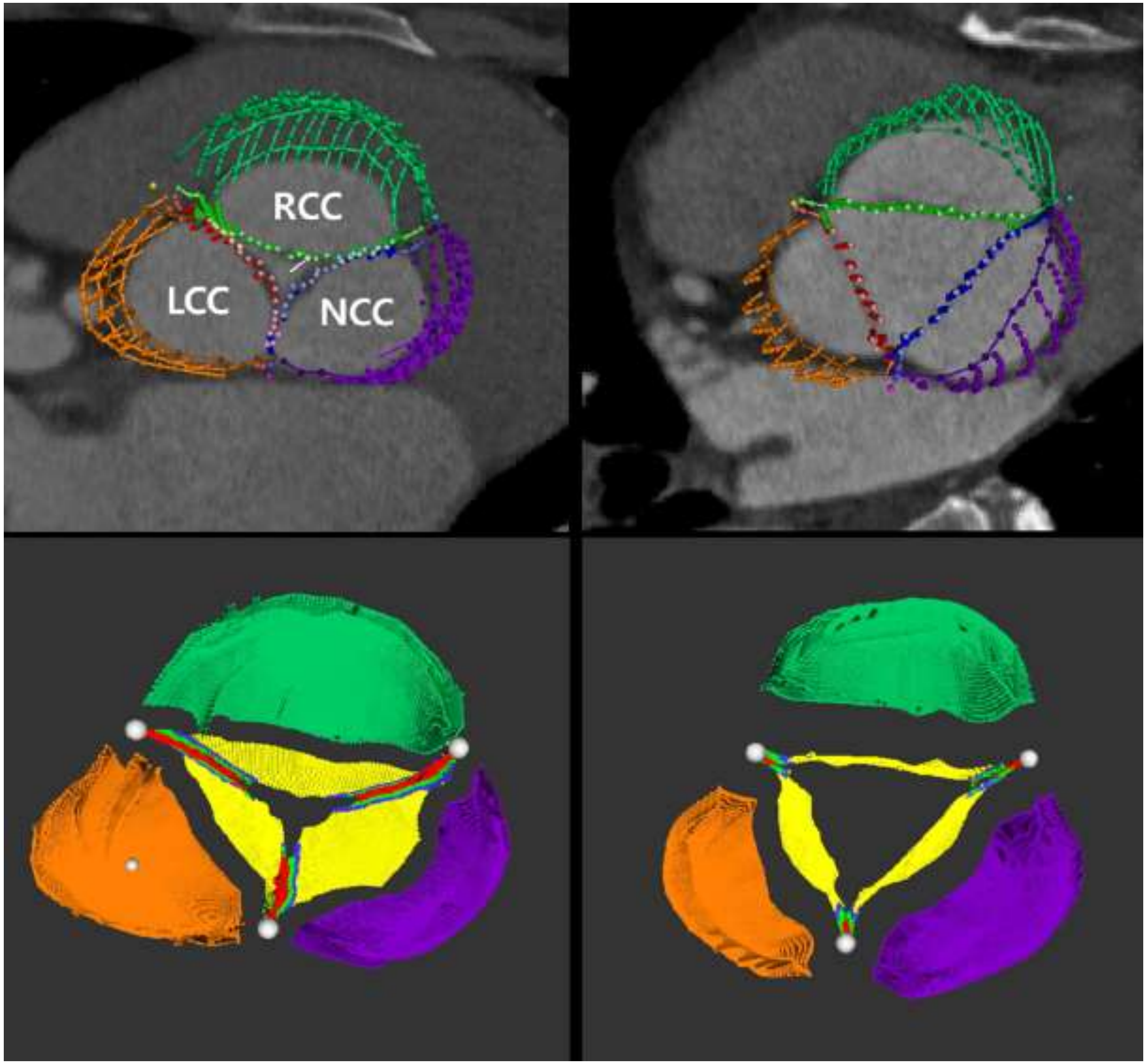


Aortic valve and root viewed from ventricular side

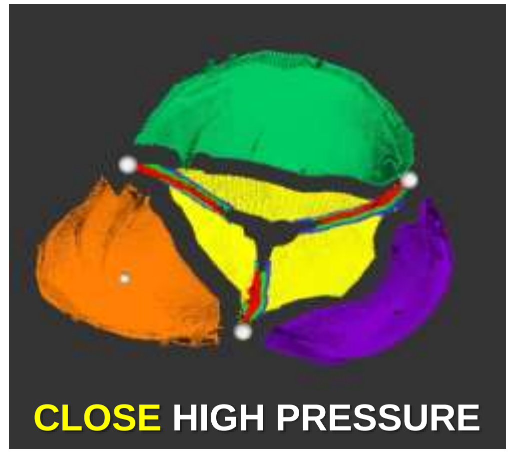


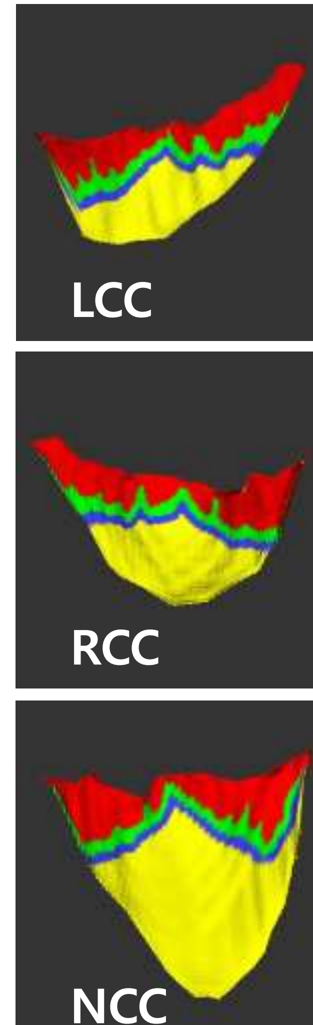
Volumetric rendering with aortic valve model in alignment

Quantification of Aortic Root using CT

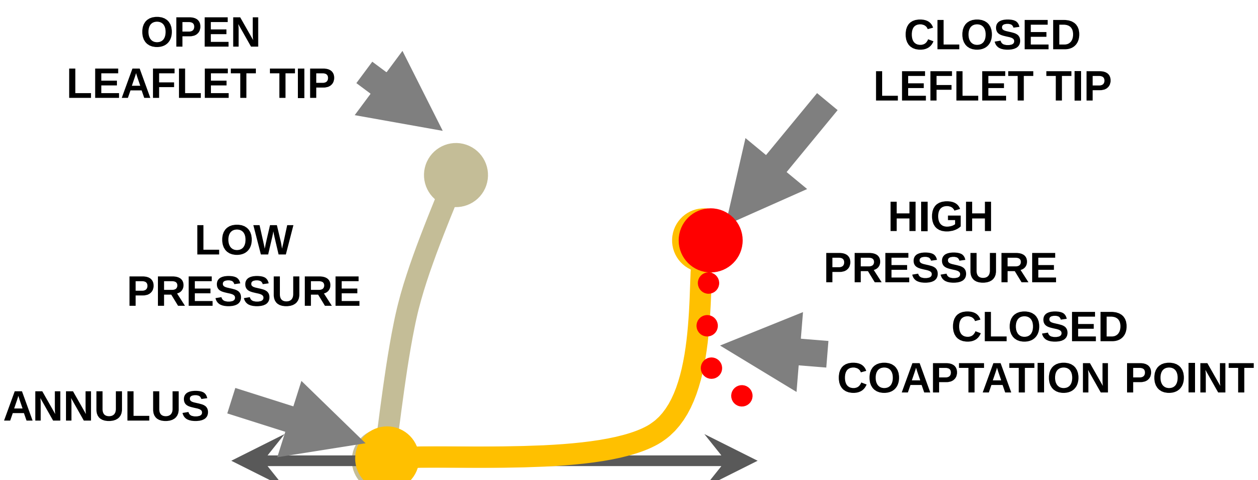


Cusp Surface Area (CSA)



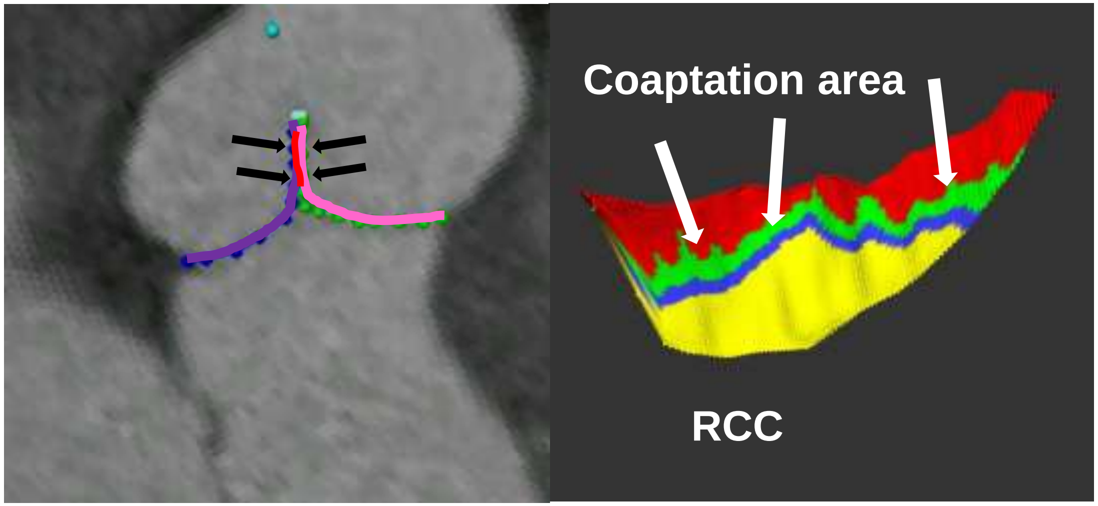


Open to closed CSA ratio: distensibility

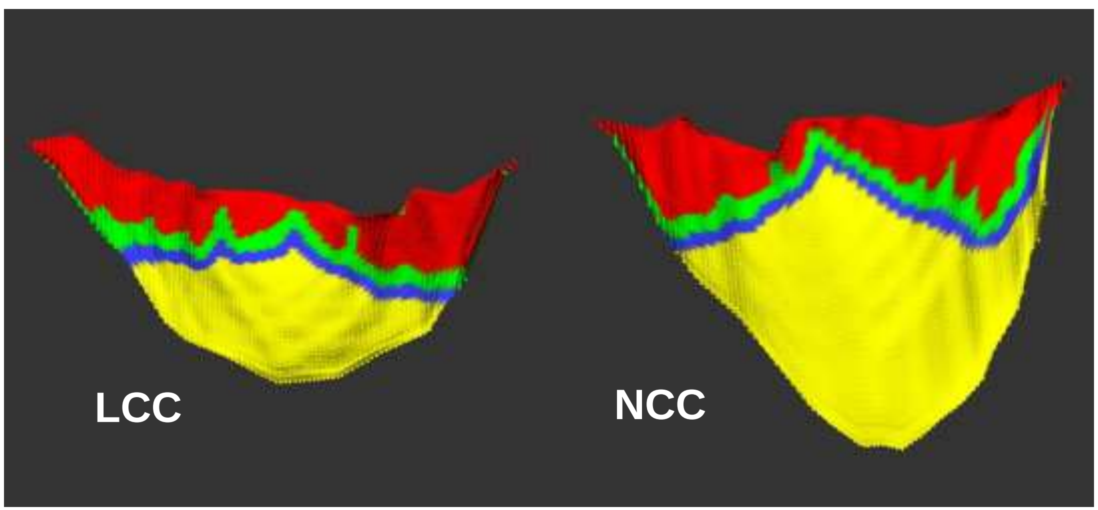


Circ Cardiovasc Imaging 2014;7:828-835

Coaptation Area Fraction



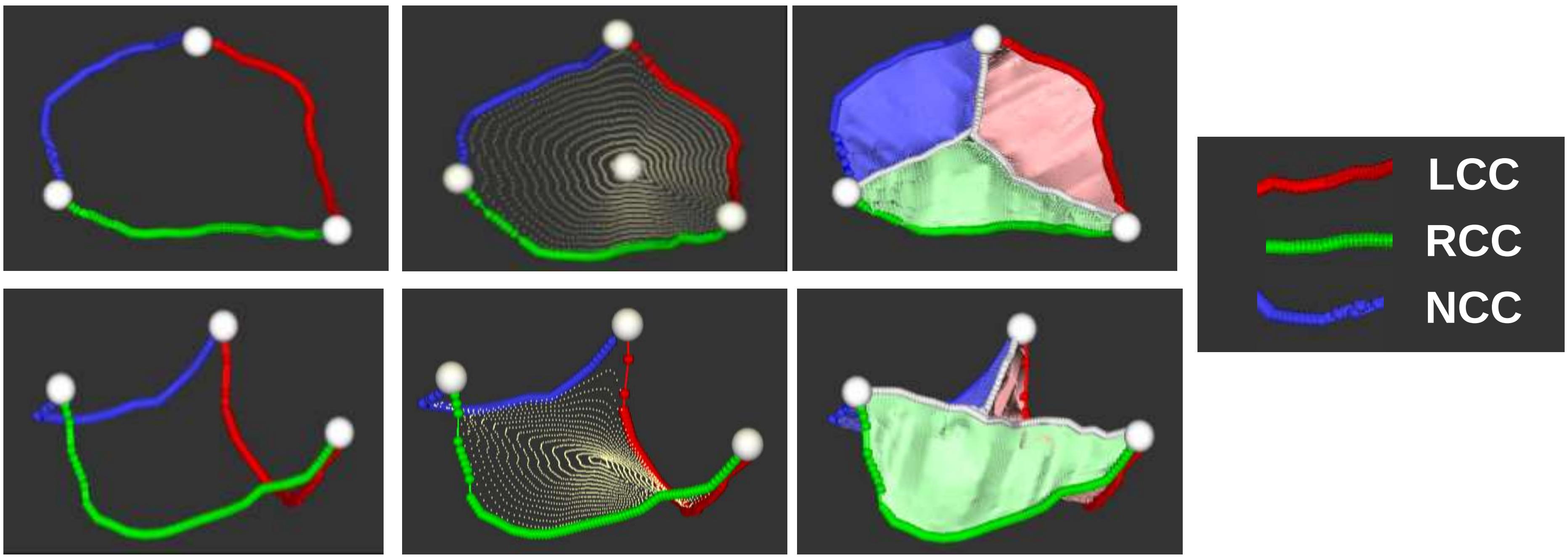
coaptation area
= red area of each cusp



Coaptation area fraction (CAF, %)
= the percentage of the red area over the closed CSA

Circ Cardiovasc Imaging 2014;7:828-835

Minimal 3D Annular Area

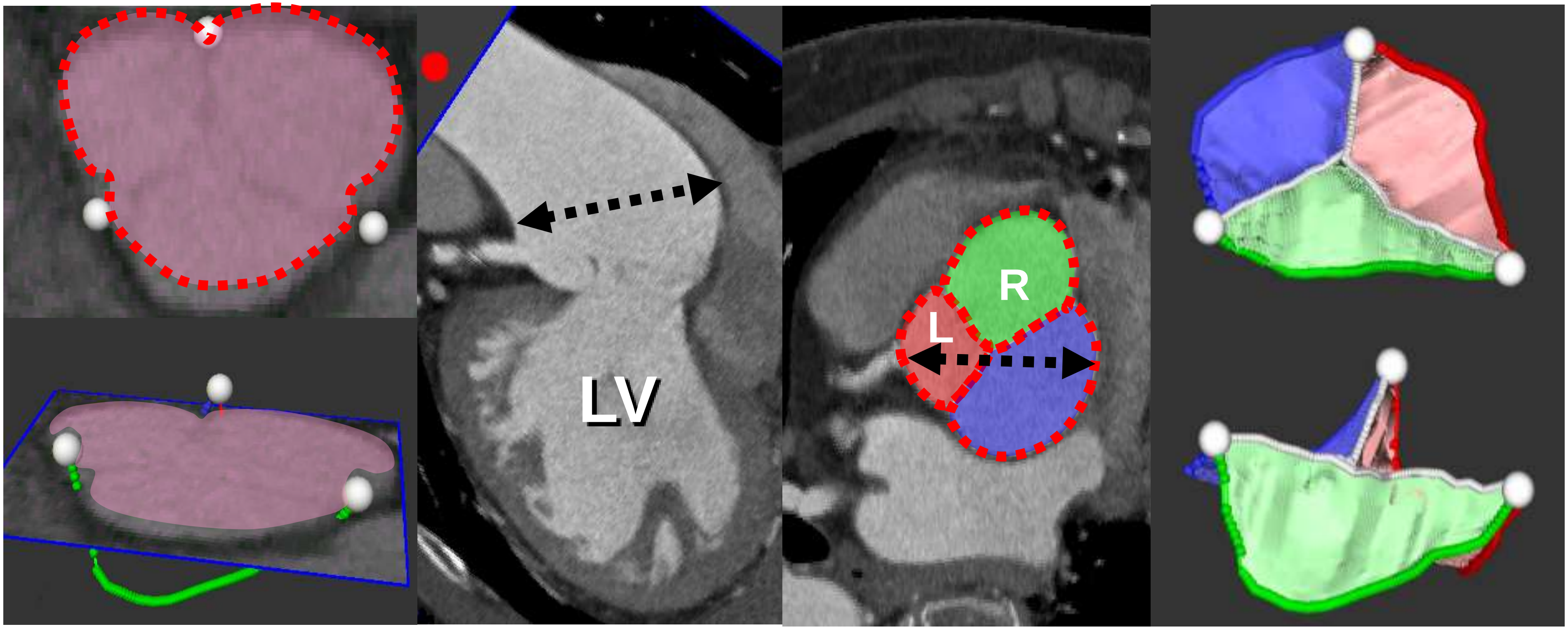


Annulus | **Minimum 3D annular area** | **3D closed cusp surface**

Closed CSA to minimal 3D AA ratio

Circ Cardiovasc Imaging 2014;7:828-835

Mid-sinus Maximal Cross-sectional Area

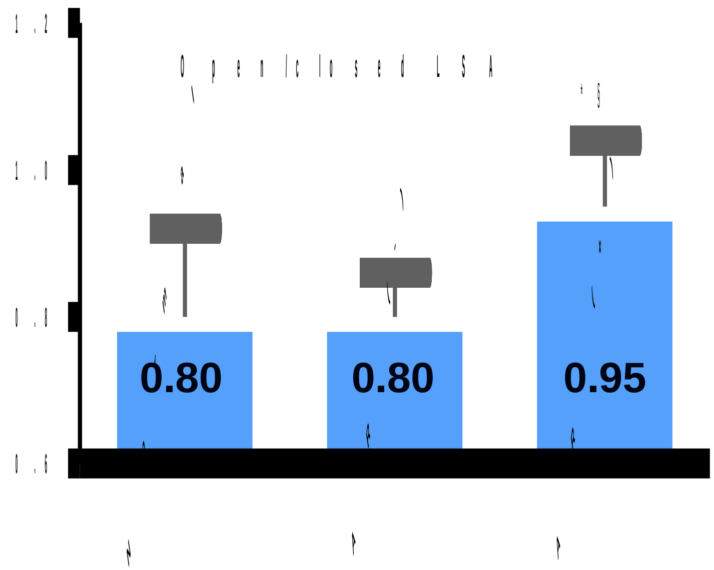


Closed CSA to mid-sinus maximal CSA ratio

Circ Cardiovasc Imaging 2014;7:828-835

Cusp Surface Area

	Group I AR (+) (n=29)	Group II AR (-) (n=28)	Normal controls (n=35)	P-value
Total open CSA, cm^2/m^2	15.2±3.3*§	12.9±2.2*	7.6±1.4	<0.001
LC CSA (open)	4.0±1.2*§	3.3±0.6*	2.2±0.5	<0.001
RC CSA (open)	5.6±1.3*	4.8±1.0*	2.8±0.6	<0.001
NC CSA (open)	5.6±1.2*	4.9±0.9*	2.6±0.6	<0.001
Total closed CSA, cm^2/m^2	16.1±3.6*	16.2±2.7*	9.5±1.3	<0.001



Sinus Volume Asymmetry

	Group I AR (+) (n=29)	Group II AR (-) (n=28)	Normal controls (n=35)	P-value
LC sinus volume, ml/m^2	6.1 ±3.2*	4.9±1.2*	1.5±0.0.4	<0.001
RC sinus volume, ml/m^2	15.3±10.2*§	7.4±2.1*	2.0±0.7	<0.001
NC sinus volume, ml/m^2	13.9±7.8*§	8.1±3.2*	1.8±0.6	<0.001
RC/LC sinus volume ratio	2.60±1.45*§	1.56±0.48	1.32±0.33	<0.001
NC/LC sinus volume ratio	2.63±1.53*§	1.73±0.77*	1.22±0.36	<0.001

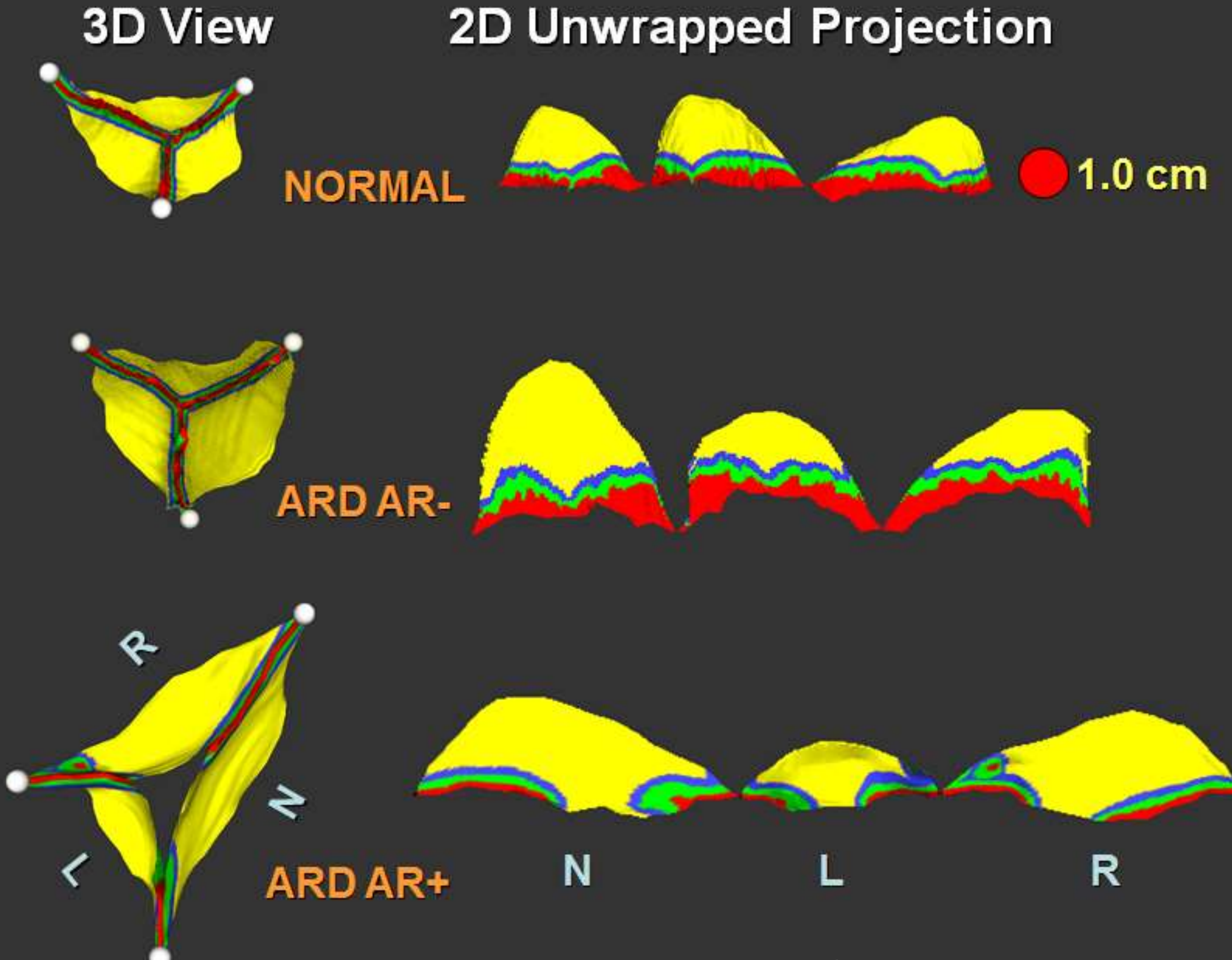
All parameters are indexed to body surface area

§ Bonferroni-corrected p-value<0.05 for difference between Groups I and II,

* Bonferroni- corrected p-value<0.05 for difference from normal controls

Circ Cardiovasc Imaging 2014;7:828-835

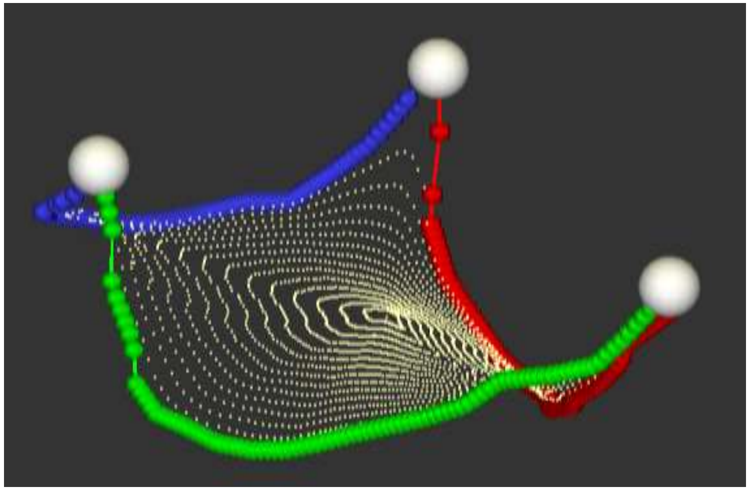
Aortic Valve Leaflet Coaptation

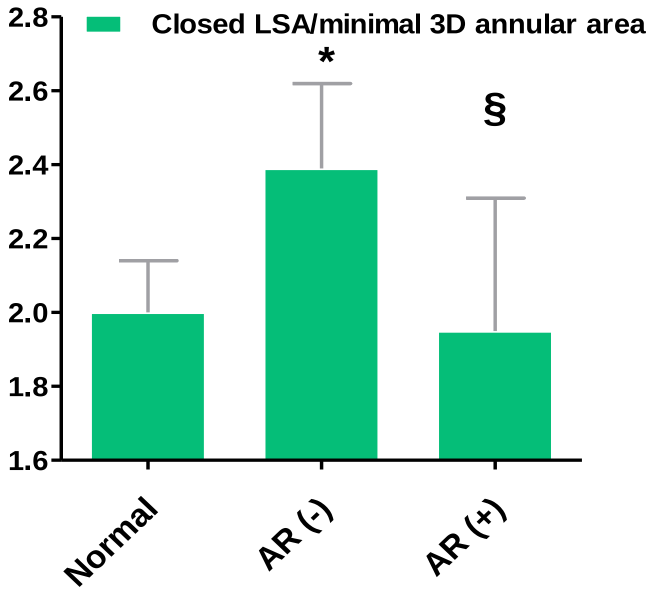


Circ Cardiovasc Imaging 2014;7:828-835

Cusp Surface Area Adaptation (1)

	Group I AR (+) (n=29)	Group II AR (-) (n=28)	Normal controls (n=35)	P-value
Minimal 3D annular area, cm^2/m^2	8.4±2.2*§	6.8±1.0*	4.8±0.7	<0.001
Closed CSA/ minimal 3D AA	1.95±0.36§	2.39±0.23*	2.00±0.14	<0.001

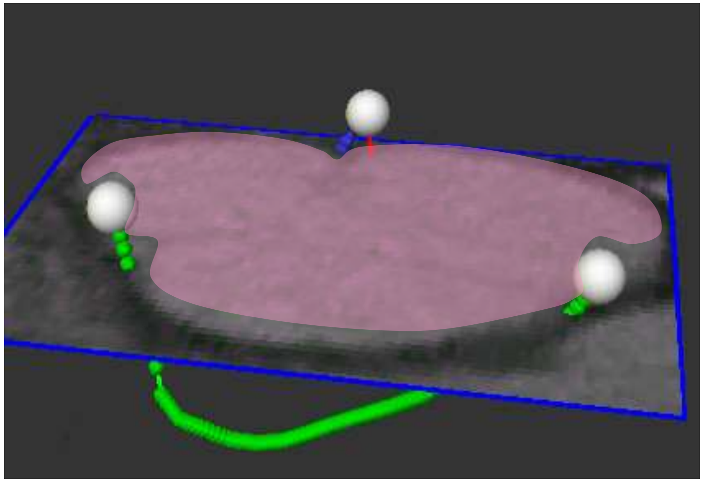


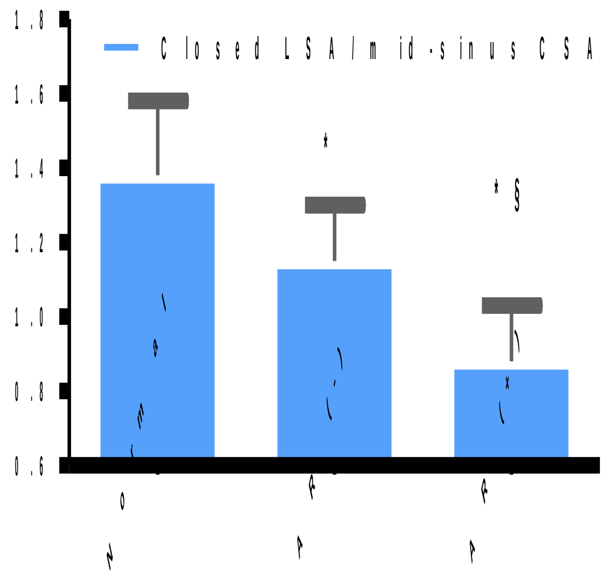


Circ Cardiovasc Imaging 2014;7:828-835

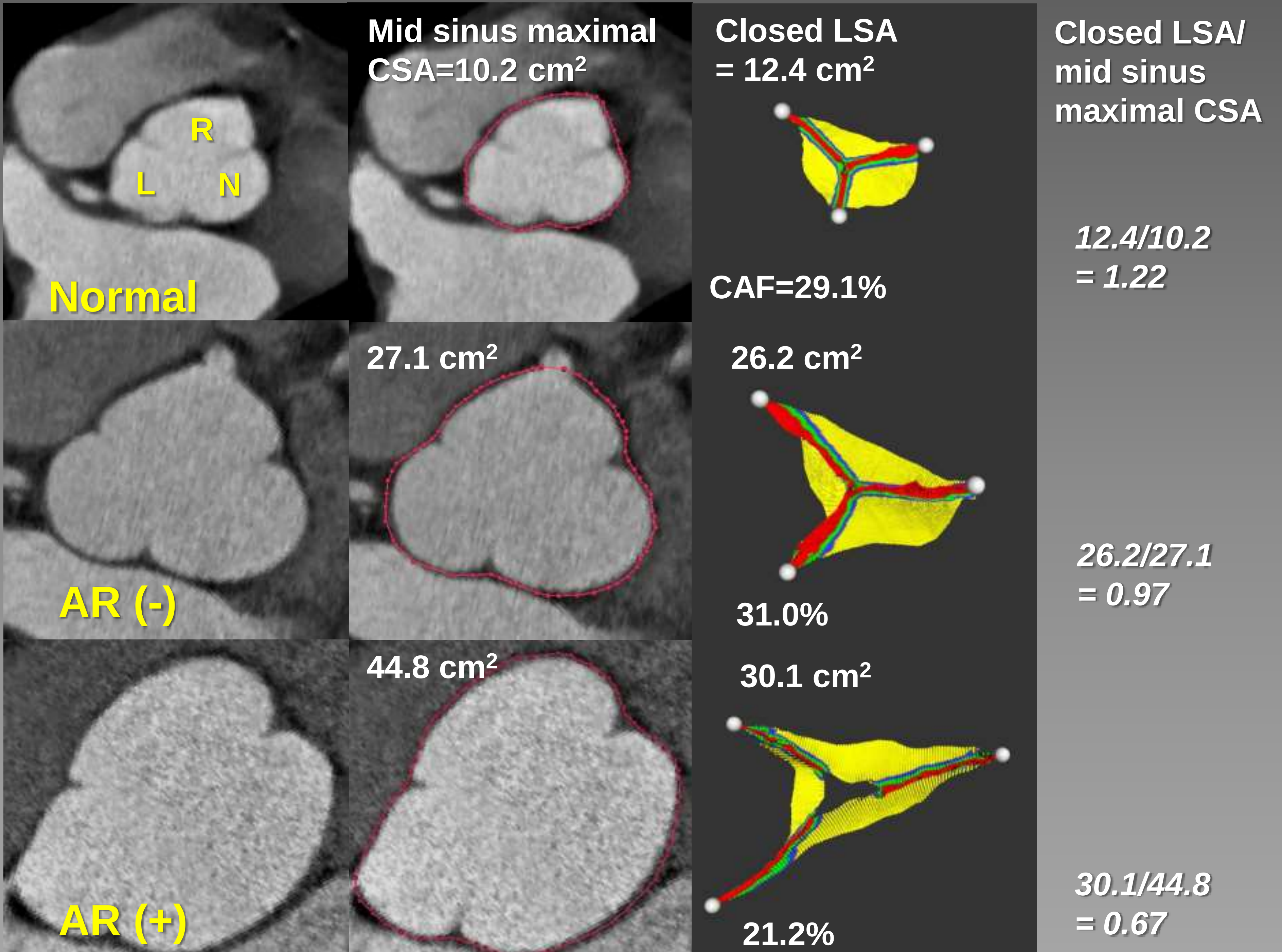
Cusp Surface Area Adaptation (2)

	Group I AR (+) (n=29)	Group II AR (-) (n=28)	Normal controls (n=35)	P-value
Mid-sinus maximal CSA, cm^2/m^2	18.6±4.4§*	14.1±1.7*	7.1±1.2	<0.001
Closed CSA/mid-sinus maximal CSA	0.88±0.15§*	1.15±0.15*	1.38±0.20	<0.001
Coaptation area fraction (%)	23.4±6.1§*	37.4±6.9*	28.1±5.1	<0.001

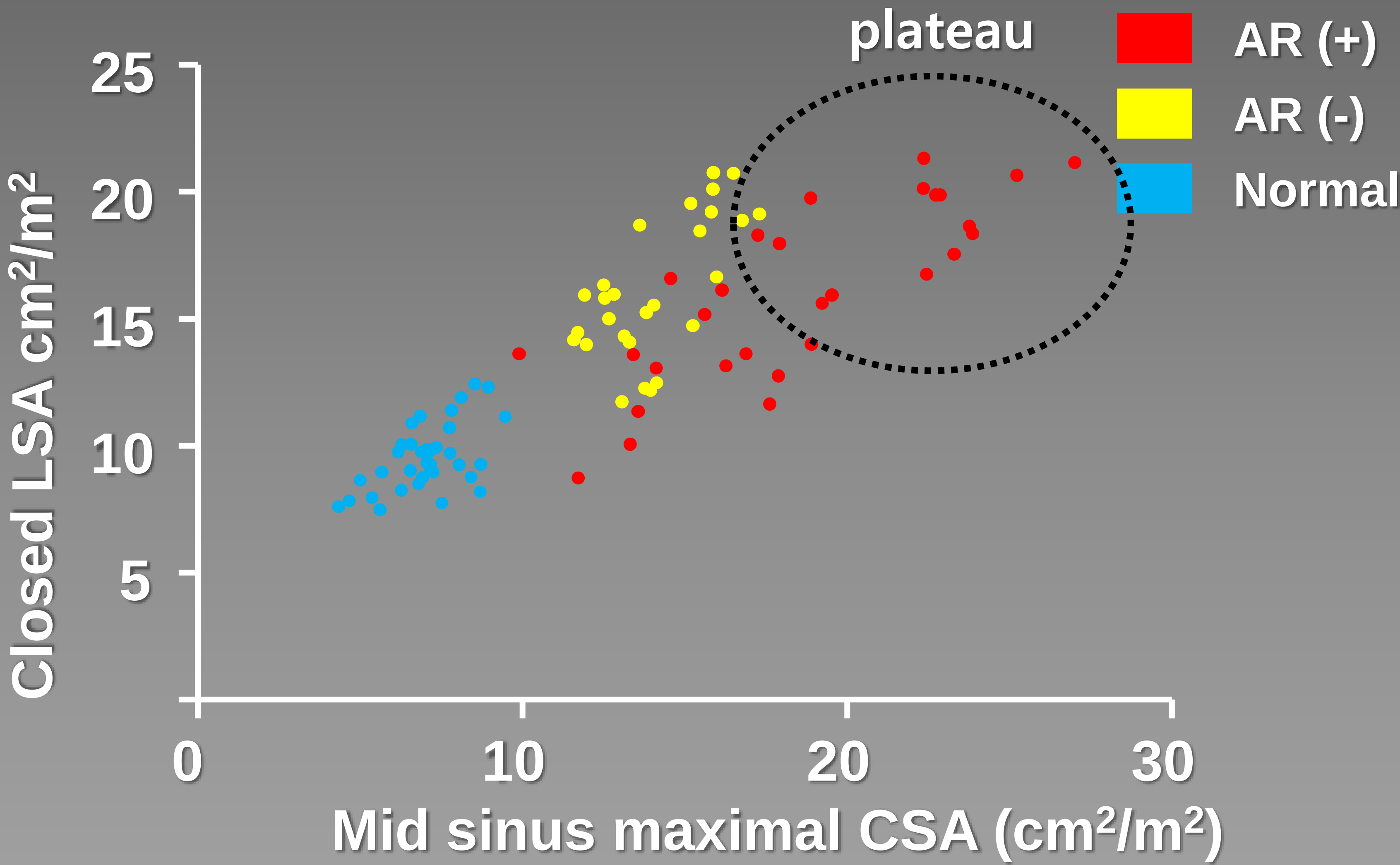




Circ Cardiovasc Imaging 2014;7:828-835



Mid sinus maximal CSA=10.2 cm²
Closed LSA = 12.4 cm²
Closed LSA/ mid sinus maximal CSA
R
L
N
Normal
CAF=29.1%
12.4/10.2 = 1.22
27.1 cm²
26.2 cm²
AR (-)
31.0%
26.2/27.1 = 0.97
44.8 cm²
30.1 cm²
AR (+)
21.2%
30.1/44.8 = 0.67


plateau
AR (+)
AR (-)
Normal
Closed LSA cm²/m²
25
20
15
10
5
0
10
20
30
Mid sinus maximal CSA (cm²/m²)

Determinants of AR development

Presence or absence of AR

Binary logistic regression

	Adjusted OR	95% CI	p-value
Open to closed CSA ratio	1.552	1.166-2.066	0.003
Closed CSA/minimal 3D annular area**	0.395	0.203-0.765	0.006

Determinants of coaptation area fraction

Multiple linear regression

	β	SE	p-value
Mid-sinus maximal cross- sectional area	-0.622	0.114	<0.001
Closed CSA/minimal 3D annular area **	1.956	0.204	<0.001

Circ Cardiovasc Imaging 2014;7:828-835

Summary

Functional AR in ARD patients

1. Cusp adaptation does occur: cusp area increases as the root dilates

2. The larger the root, the more asymmetric the sinuses are

3. Compensatory enlargement plateaus when the aortic root becomes very large: leaflet area is insufficient to cover the annulus – development of AR

Circ Cardiovasc Imaging 2014;7:828-835

Summary

Functional AR in ARD patients

4. Maximally stretched cusps lose their ability to stretch under closing pressures – also impairing coaptation
5. All these changes contribute to reduced CAF and development of AR

Circ Cardiovasc Imaging 2014;7:828-835

Conclusion

Functional AR in ARD patients

- 3D CT evaluation of aortic root geometry was useful to understand the mechanism of AR in patients with aortic root dilation

- Understanding leaflet adaptation mechanisms may ultimately provide therapeutic opportunities to improve such compensation

Circ Cardiovasc Imaging 2014;7:828-835

Asymmetric Aortic Sinus:

any possibility of age-related change?

European Heart Journal - Cardiovascular Imaging Advance Access published July 26, 2016

EUROPEAN SOCIETY OF CARDIOLOGY®

European Heart Journal – Cardiovascular Imaging
doi:10.1093/ehjci/jew146

In vivo assessment of aortic root geometry in normal controls using 3D analysis of computed tomography

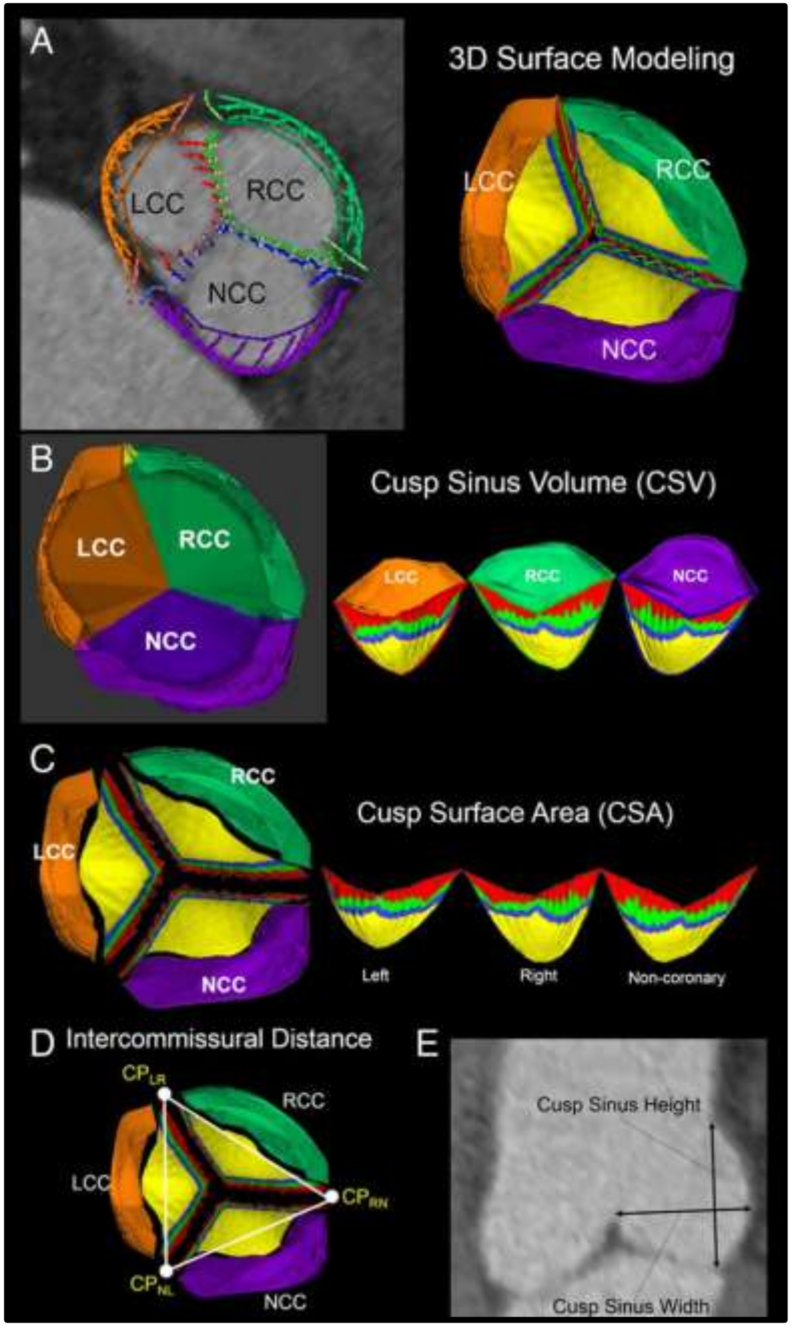
Dong Hyun Yang[1], Dae-Hee Kim[1], Mark D. Handschumacher[2], Robert A. Levine[2], Joon Bum Kim[3], Byung Joo Sun[1], Jeong Yoon Jang[1], Namkug Kim[4], Seunghee Baek[5], Joon-Won Kang[1], Jong-Min Song[1], Duk-Hyun Kang[1], Tae-Hwan Lim[1], and Jae-Kwan Song[1]*[*]

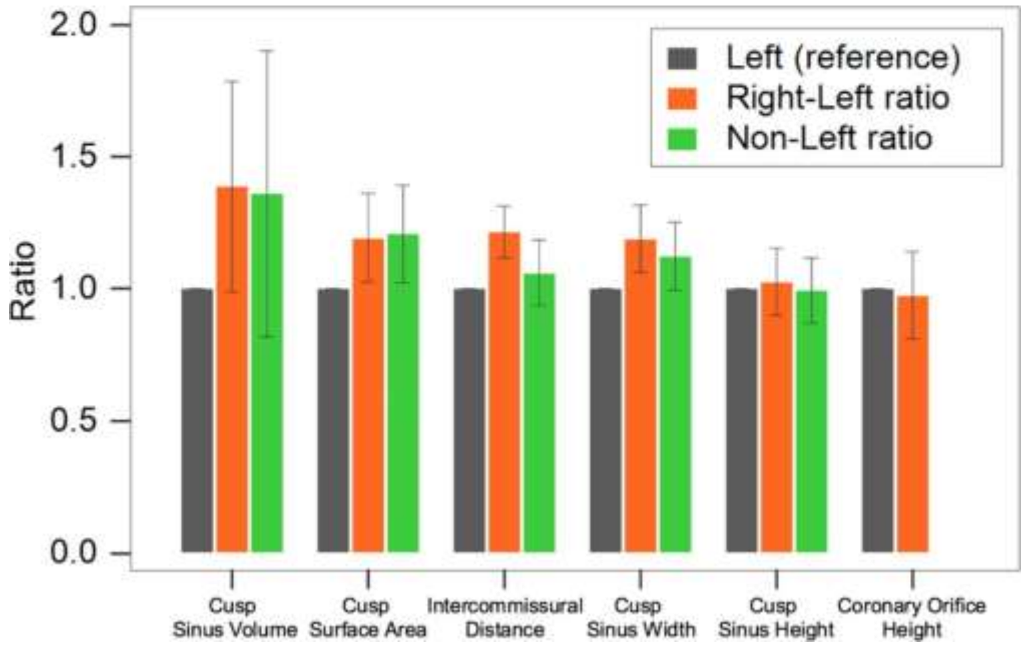
Circ Cardiovasc Imaging 2014;7:828-835

Subjects

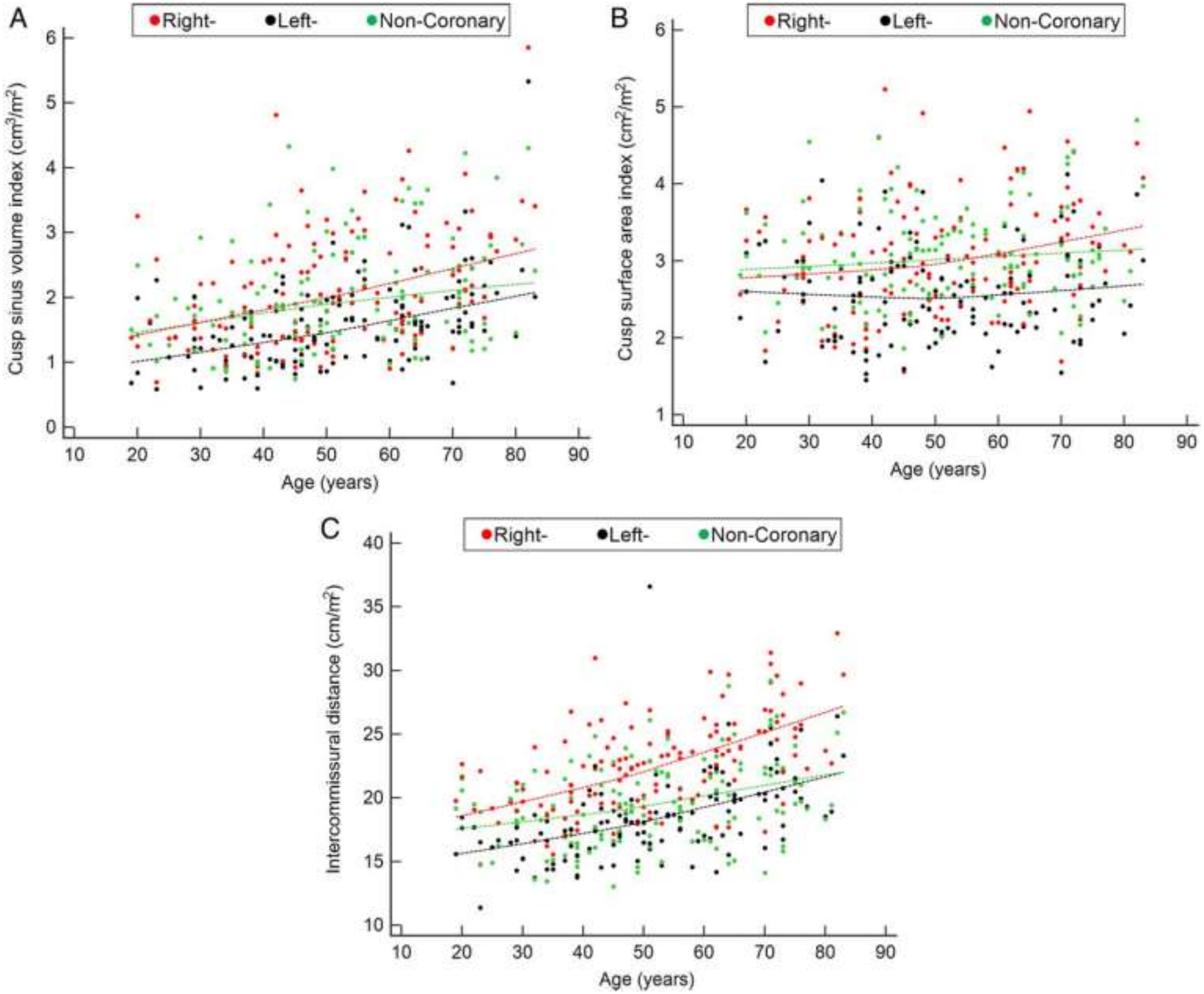
- **130 asymptomatic subjects** who underwent coronary CTA and Echocardiography for general health check-up in Asan Medical Center
- Inclusion criteria
  - No significant coronary disease or valvular disease
  - No DM
  - No Hypertension
- Mean age 51 years **(M:F = 1:1)**
- Randomly selected subjects for evenly distributed **gender and age**

Age (years)	< 30	30 – 39	40 – 49	50 – 59	60 – 69	> 70
No.	15	20	30	21	23	21





Eur Heart J Cardiovasc Img 2016 (ePub)



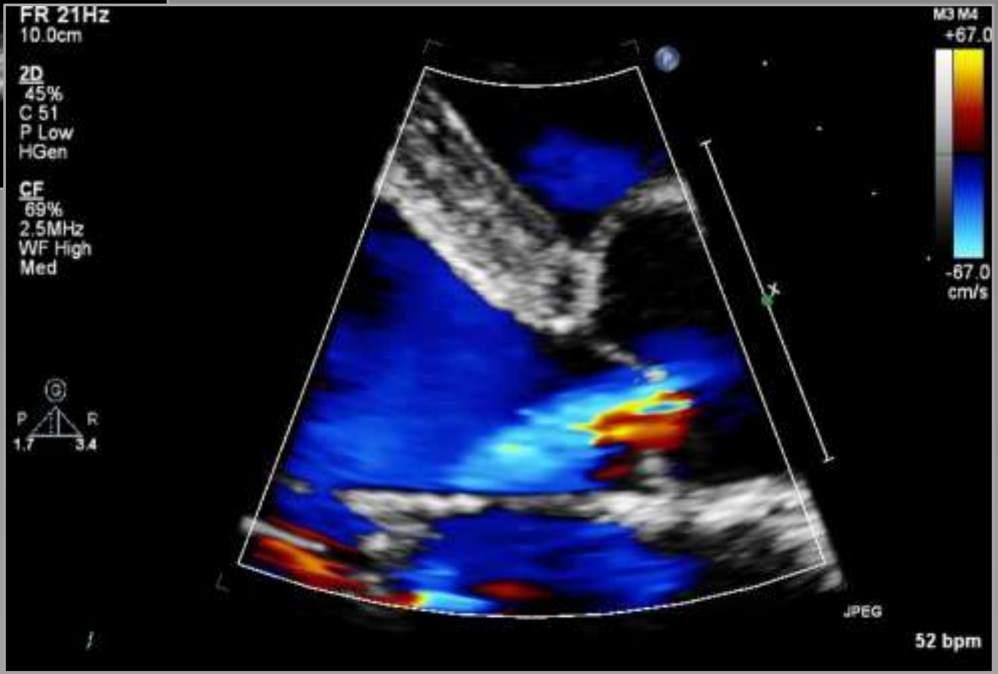
Eur Heart J Cardiovasc Img 2016 (ePub)

Conclusion

- Quantitative analysis of the aortic root reveals normal asymmetry in the aortic sinus and cusp surface area (CSA).
- The size of left coronary sinus was smaller than the other two sinuses.
- The sinus volume showed increasing tendency by increasing age. However the CSA did not showed age-related change.

F/54


FR 93Hz
14cm
2D
43%
C 51
P Low
HGen
M3


FR 21Hz
10.0cm
2D
45%
C 51
P Low
HGen
CF
69%
2.5MHz
WF High
Med
M3 M4
+67.0
-67.0
cm/s
JPEG
52 bpm


FR 50Hz
12cm
2D
62%
C 50
P Off
Gen
130
M4
P
R
JPEG
PAT T: 37.0C
TEE T: 39.0C
56 bpm


FR 88Hz
11cm
2D
54%
C 50
P Off
Gen
38
M4
P
R
JPEG
PAT T: 37.0C
TEE T: 39.3C
55 bpm


FR 88Hz
11cm
2D
54%
C 50
P Off
Gen
130
M4
P
R
JPEG
PAT T: 37.0C
TEE T: 39.1C
56 bpm


FR 20Hz
11cm
2D
57%
C 50
P Off
Gen
CF
59%
4.4MHz
WF High
Med
38
M4 M4
+57.8
-57.8
cm/s
P
R
JPEG
PAT T: 37.0C
TEE T: 39.5C
55 bpm

Asymmetry vs. Cusp Adaptation

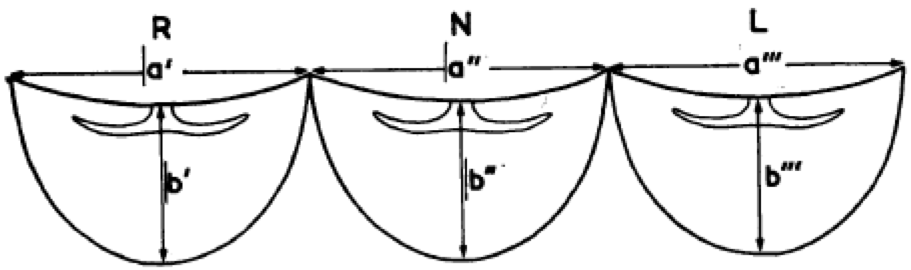
Surgical and Pathological Anatomy of the Aortic Valve and Root

Anton E. Becker

Minor congenital variations of cusp size in tricuspid aortic valves
Possible link with isolated aortic stenosis

F. E. M. G. VOLLEBERGH AND A. E. BECKER

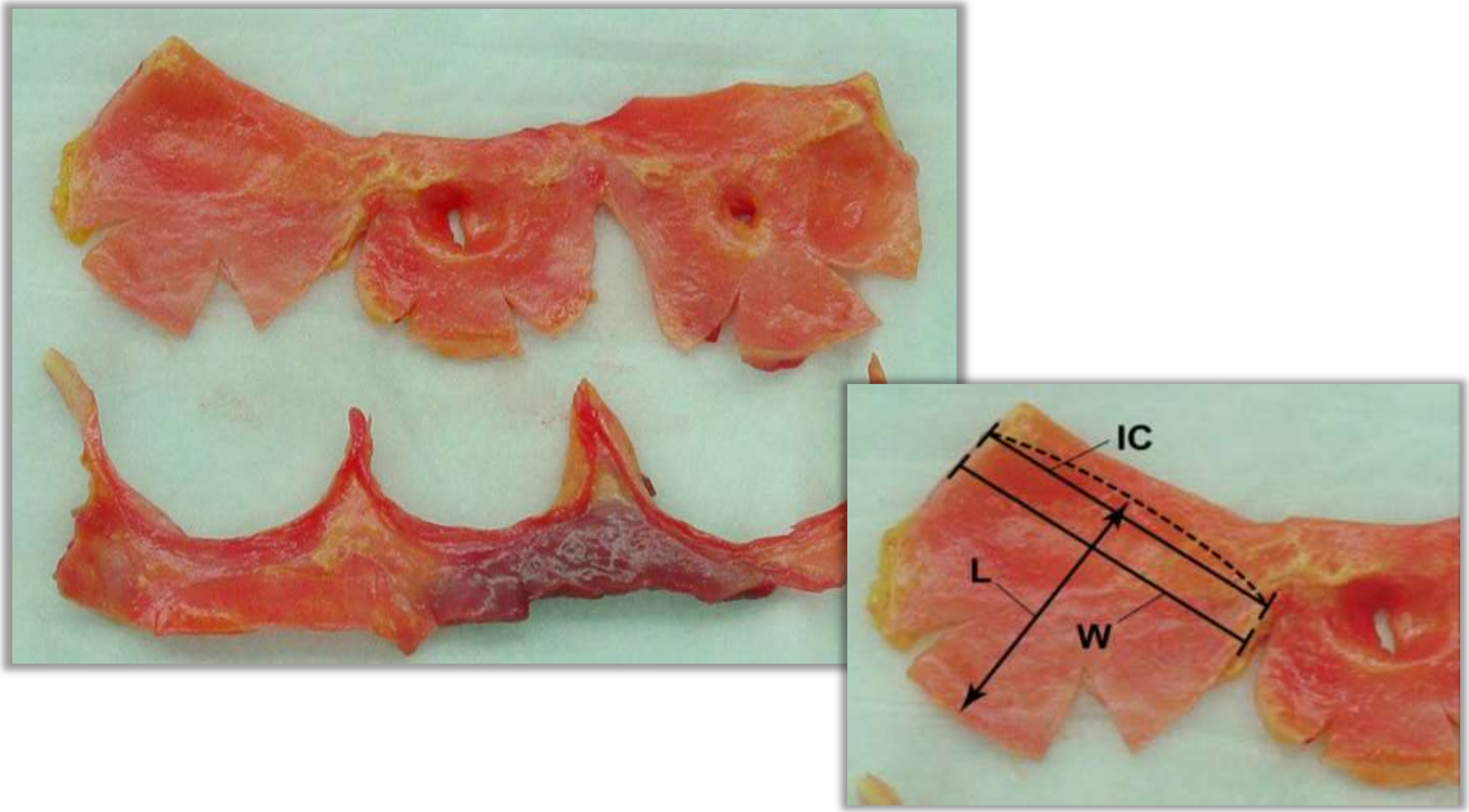
From the Department of Pathology, University of Amsterdam, Wilhelmina Gasthuis, Amsterdam, The Netherlands



Width, mm
R/N/L 25.9/25.5/25.0

Br Heart J 1977;39:1006

Previous Study



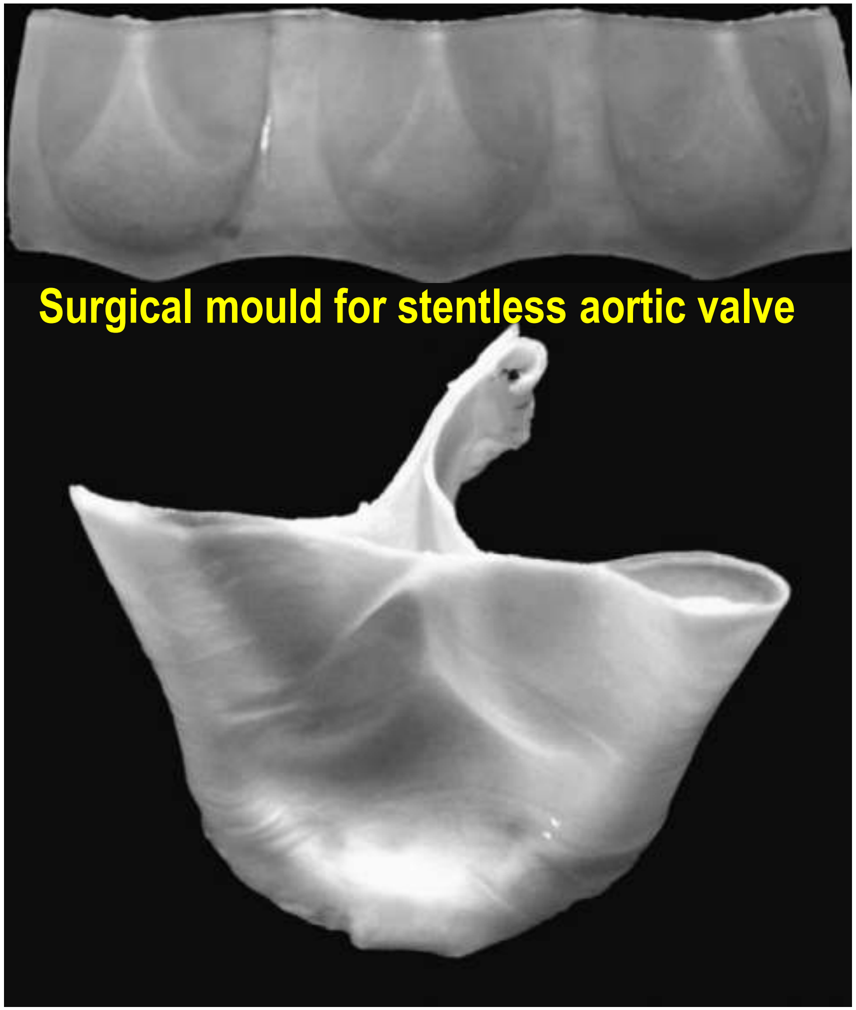
http://aats.org/multimedia/files/CME/2010/AorticSymposium2010_POD/11_Kollar.ppt

Previous Study

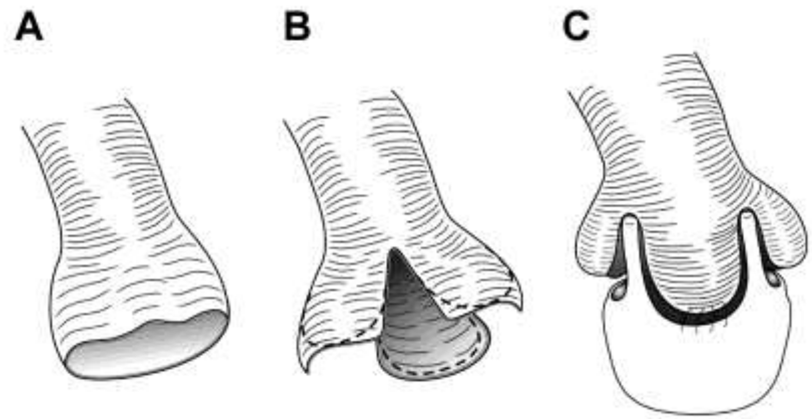
	Left Sinus (n=30)	Right Sinus (n=30)	Noncoronary Sinus (n=30)
Intercomissural distance (mm)	21.7±3.7	23.5±4.0	23.4±3.5
Sinus width (mm)	22.7±3.5	24.2±4.0	24.4±3.9
Sinus length (mm)	20.0±3.0	21.2±3.9	21.4±4.1
Sinus surface area (calculated mm^2)	362.2±102.4	413.4±137.6	420±146.7
Length/width (ratio)	0.89±0.10	0.88±0.09	0.87±0.10

http://aats.org/multimedia/files/CME/2010/AorticSymposium2010_POD/11_Kollar.ppt

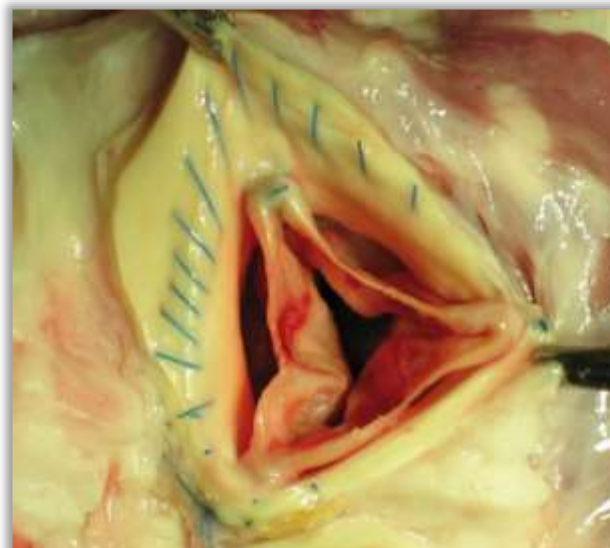
Potential Clinical Implications



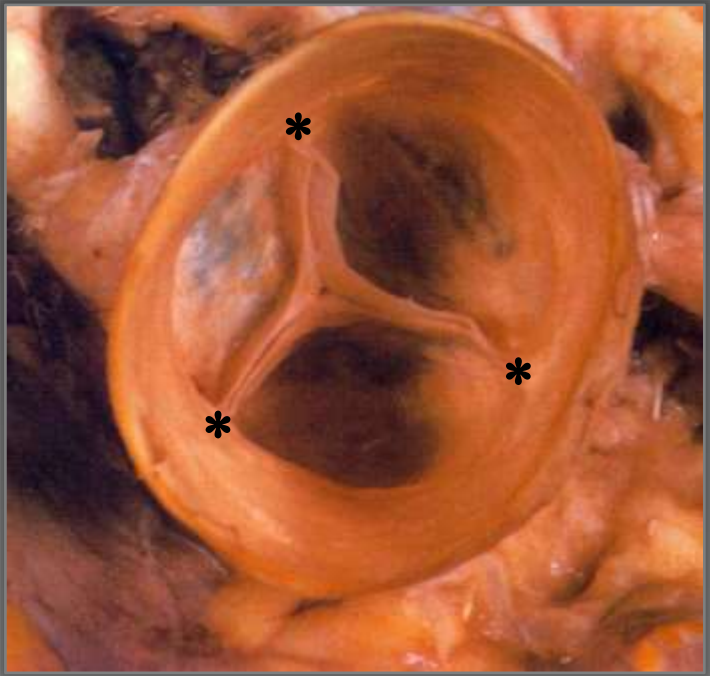
Surgical mould for stentless aortic valve

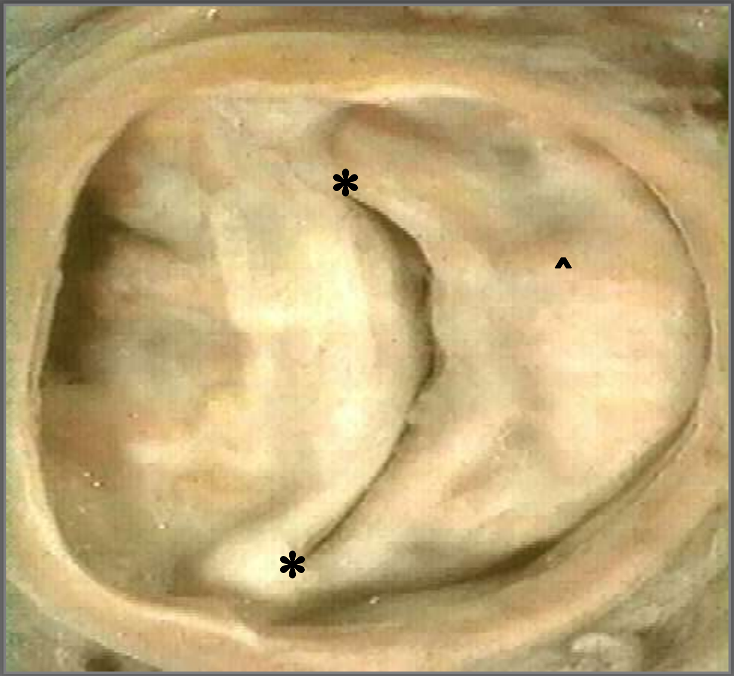


‘Cone’ graft for aortic root remodeling



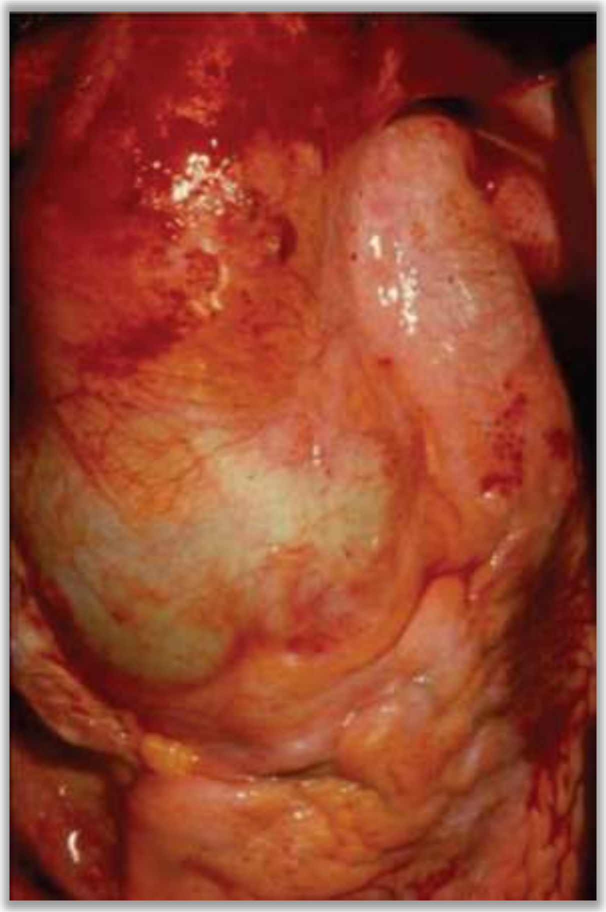
Goetz WA et al. Eur J of Cardiothoracic Surgery 2008 548-553

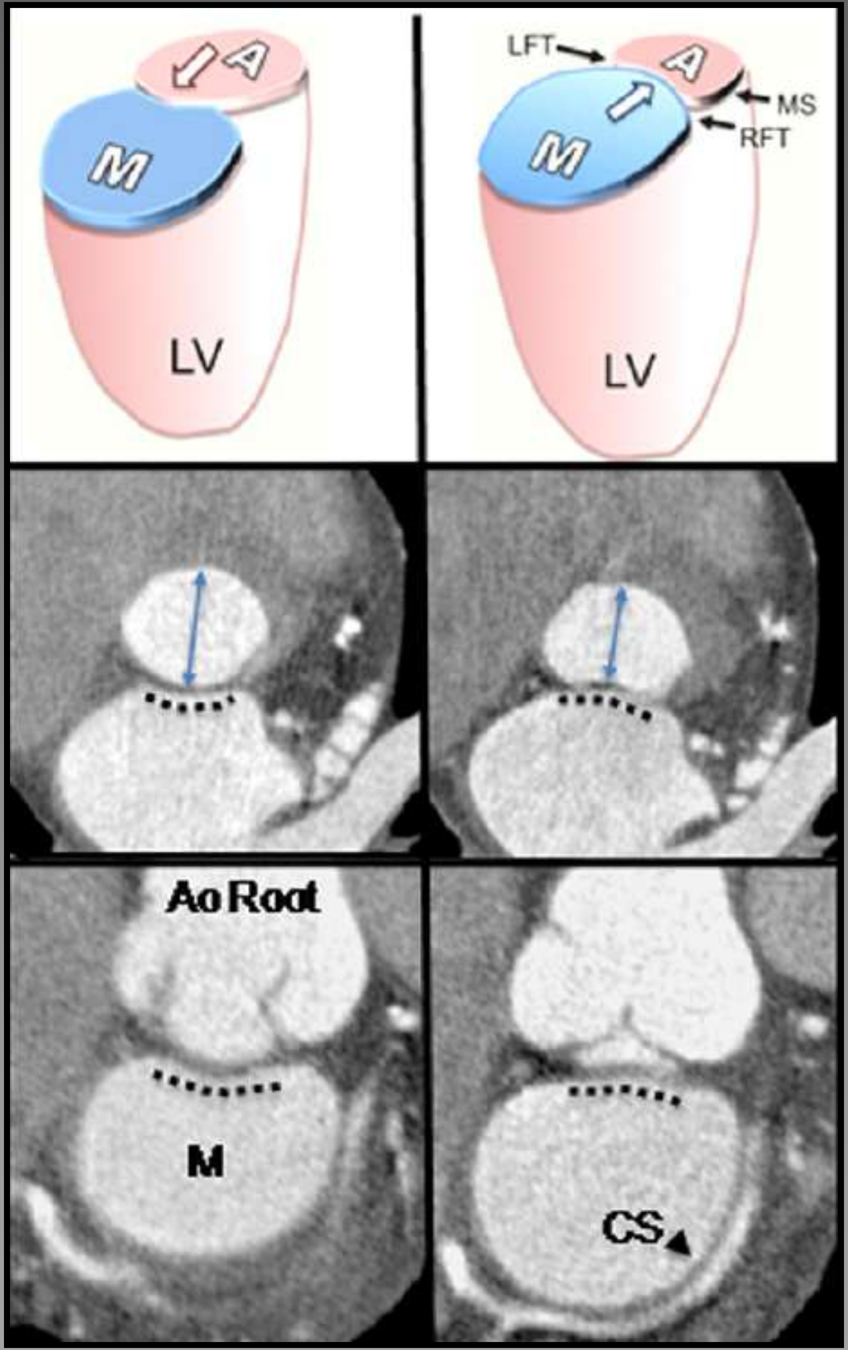




How I Do Aortic Valve Sparing Operations to Treat Aortic Root Aneurysm

Tirone E. David, M.D.





J Am Coll Cardiol 2012;59:119

Aortic Root Remodeling and Risk of Heart Failure in the Framingham Heart Study

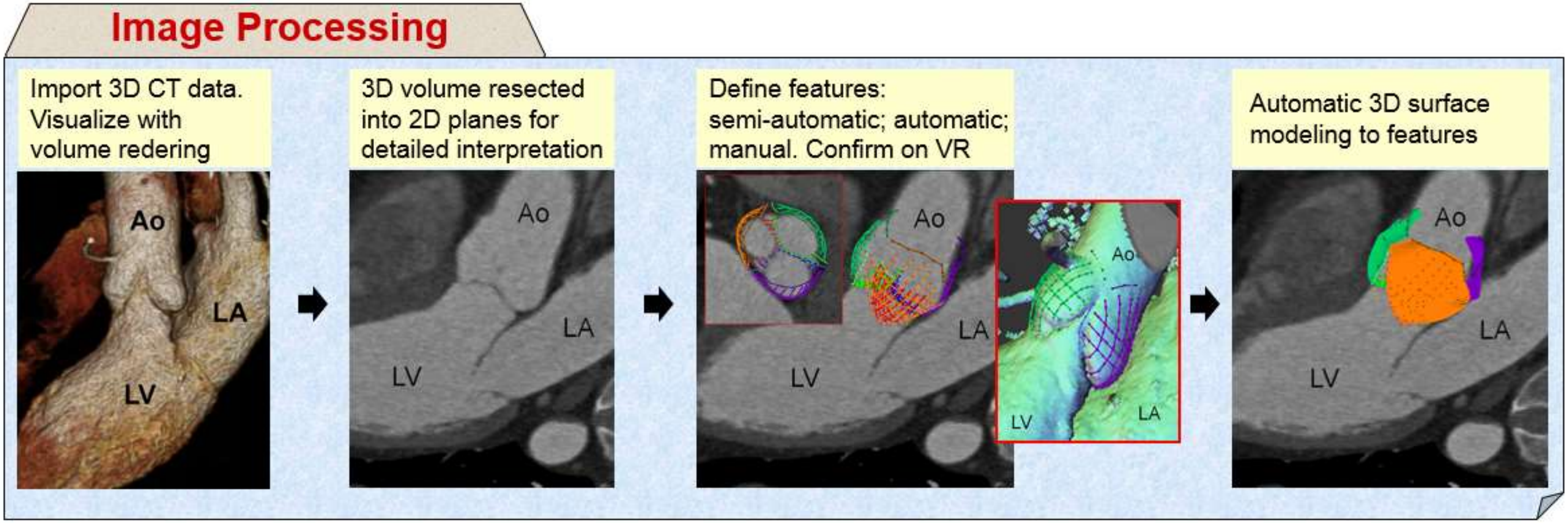
Carolyn S. P. Lam, MBBS,[*†] Philimon Gona, PhD,[*‡] Martin G. Larson, ScD,[*§] Jayashri Aragam, MD,[||] Douglas S. Lee, MD, PhD,[¶] Gary F. Mitchell, MD,[#] Daniel Levy, MD,[***] Susan Cheng, MD,[*††] Emelia J. Benjamin, MD, ScM,[*†] Ramachandran S. Vasan, MD[*]

Framingham, Worcester, Boston, West Roxbury, and Norwood, Massachusetts; Toronto, Ontario, Canada; and Bethesda, Maryland

J Am Coll Cardiol HF 2013;7:19

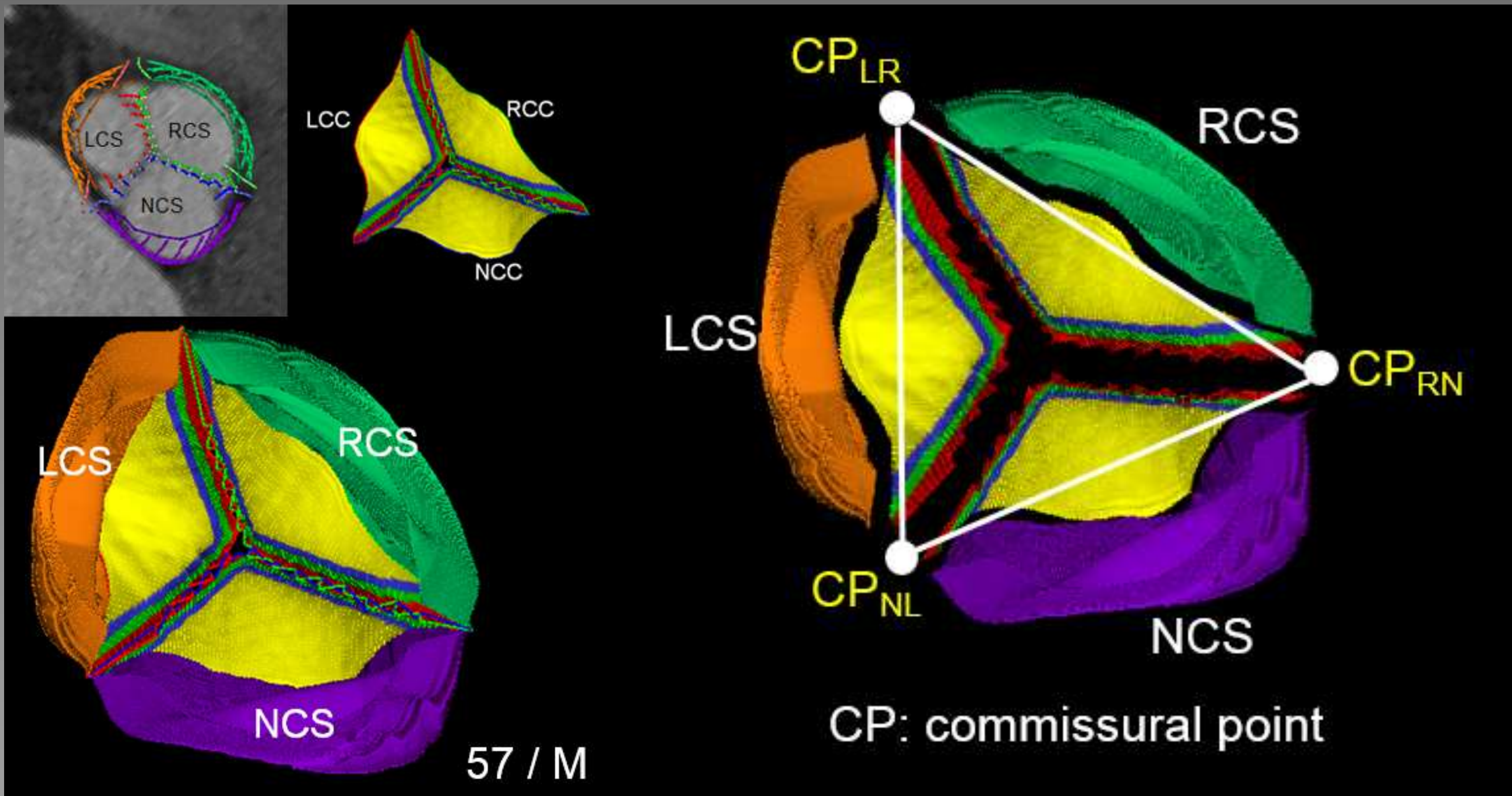
CT Imaging and Analysis

- Dual-source CT (Siemens; first or second generation)
- 1-mm thin-slice data (R-R interval 70 – 80%)
- Customized software (Omni 4D)

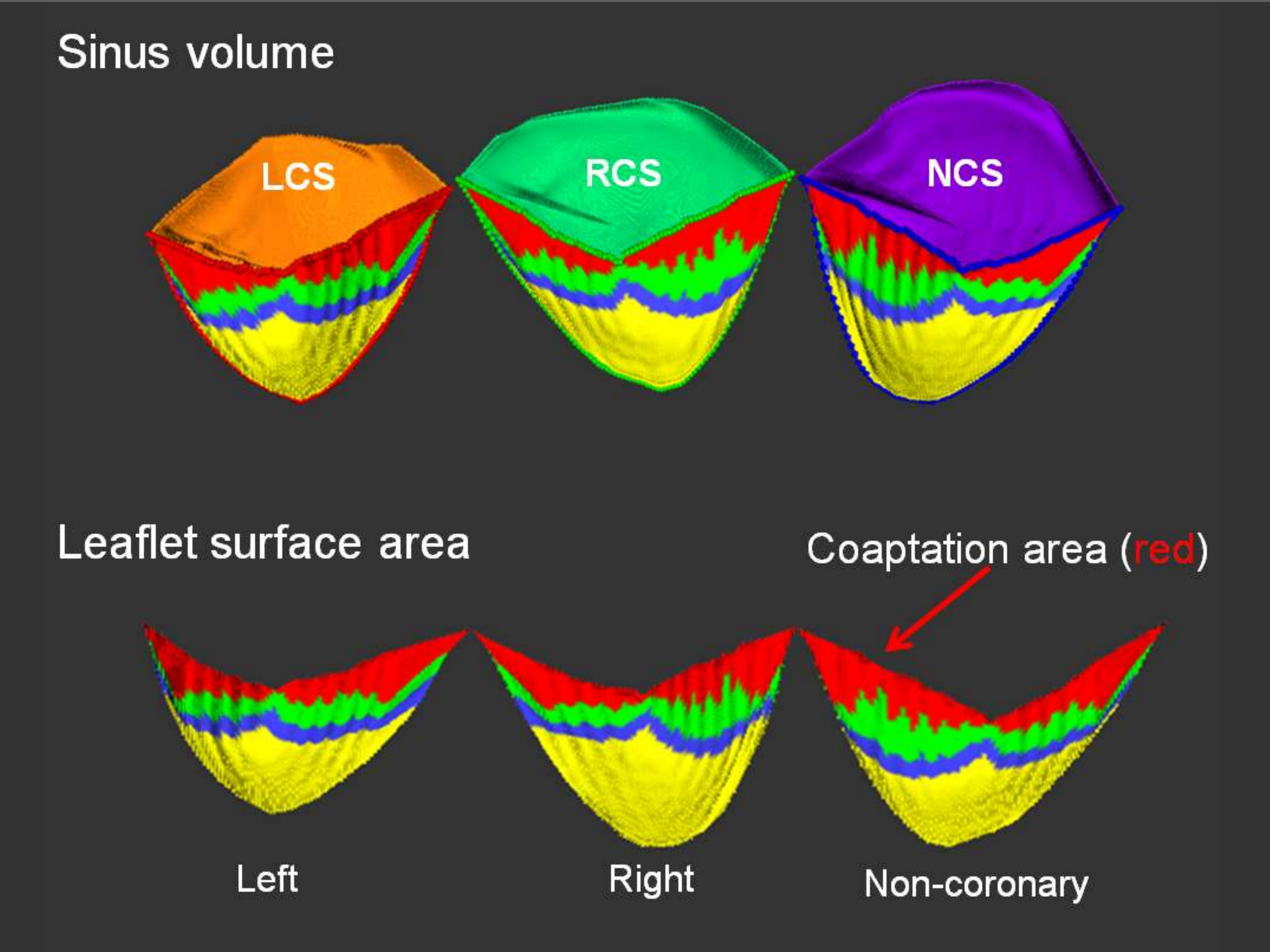


Quantitative Parameters

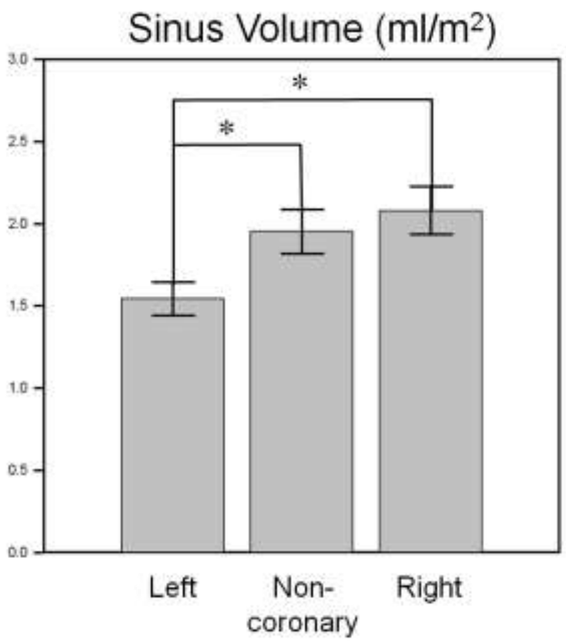
- Sinus volume
- Cusp surface area (CSA)
- Cusp surface coaptation area
  - Surface proximity algorithm (< 1.0 mm)
- Inter-commissural distances

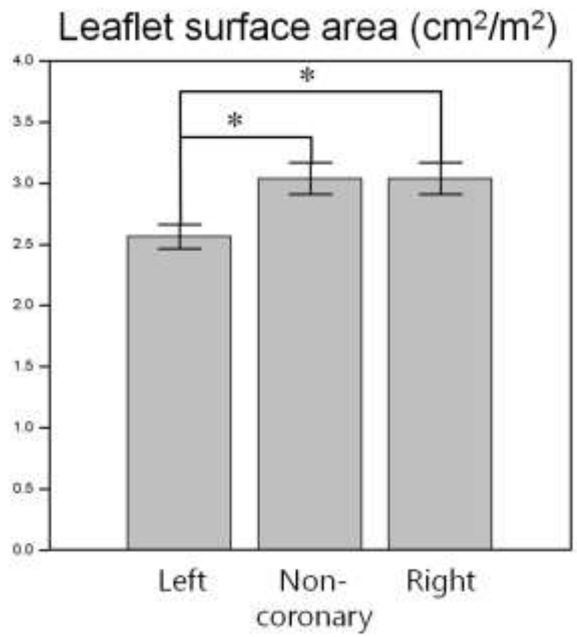


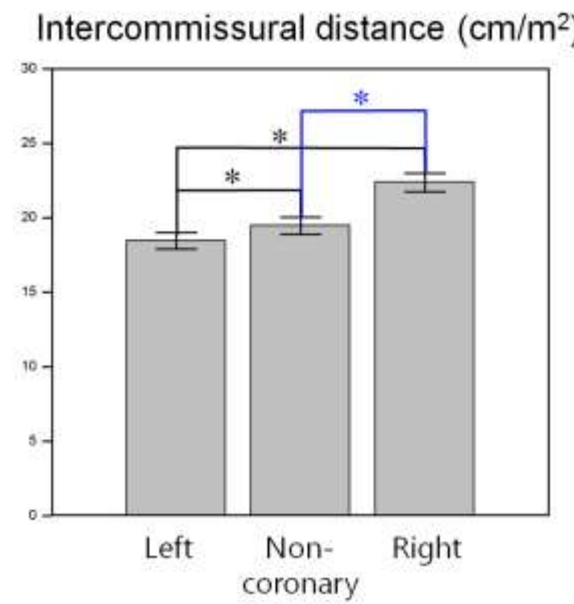
LCS
RCS
NCS
LCC
RCC
NCC
LCS
RCS
NCS
57 / M
CP_LR
RCS
LCS
CP_RN
CP_NL
NCS
CP: commissural point


Sinus volume
LCS
RCS
NCS
Leaflet surface area
Coaptation area (red)
Left
Right
Non-coronary

Results: Asymmetry of the Aortic Root

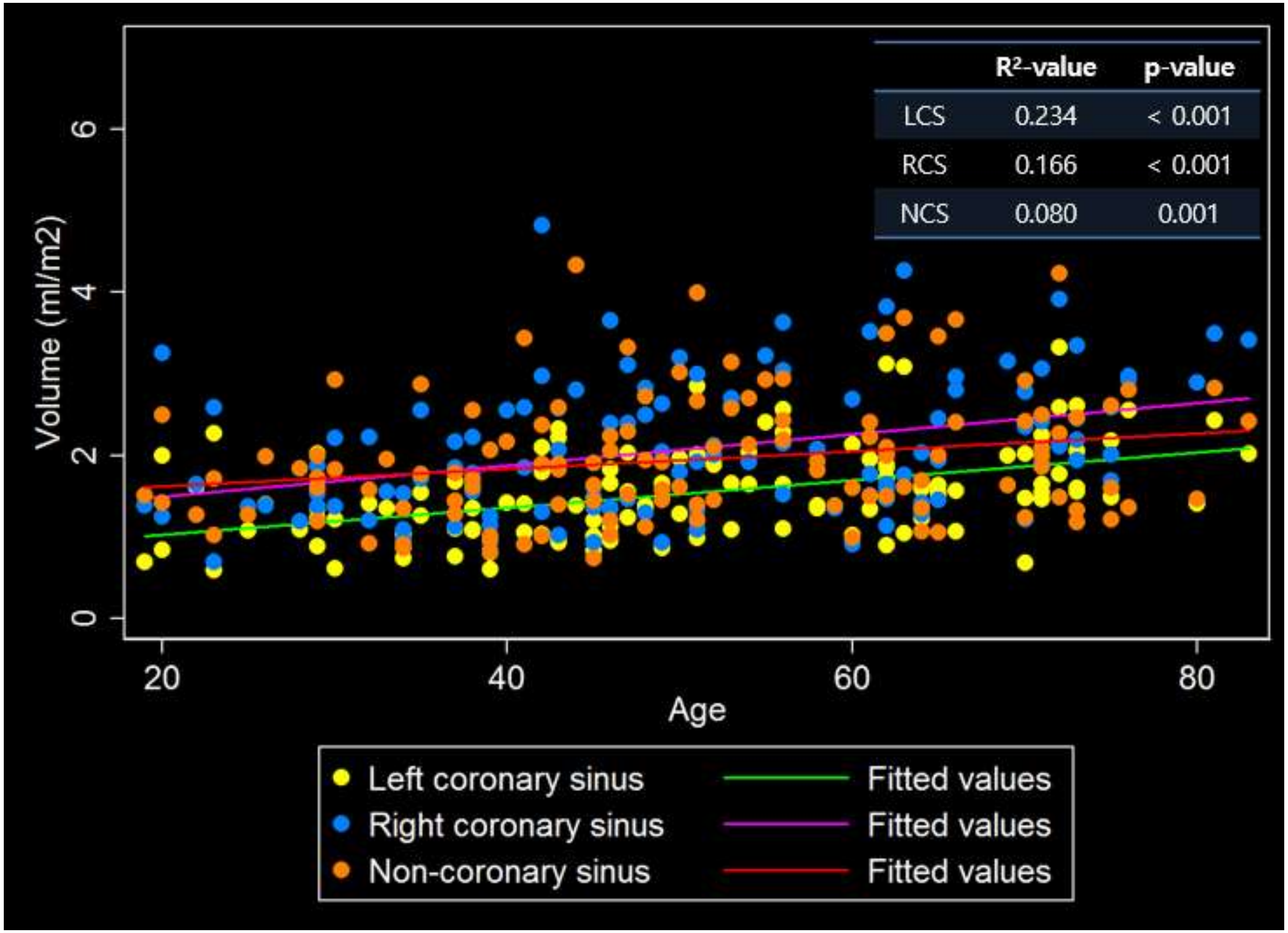




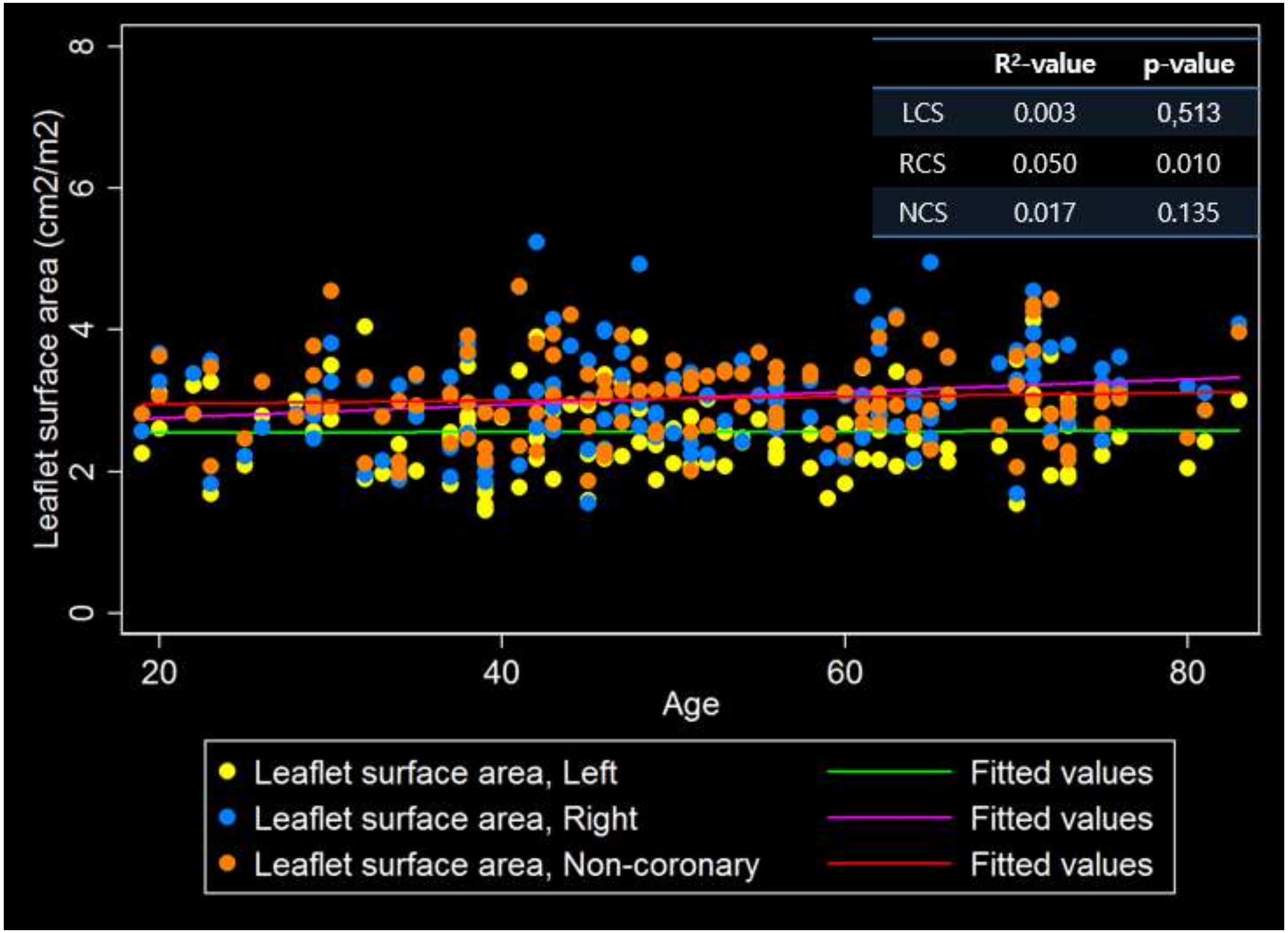


	Left	Non-coronary	Right
Sinus volume (ml/m2)	1.58 ± 0.65	2.00 ± 0.81	2.12 ± 0.88
Leaflet surface area (cm2/m2)	2.57 ± 0.56	3.06 ± 0.60	3.06 ± 0.73
Inter-commissural distance (cm/m2)	18.5 ± 3.2	19.6 ± 3.3	22.5 ± 3.7

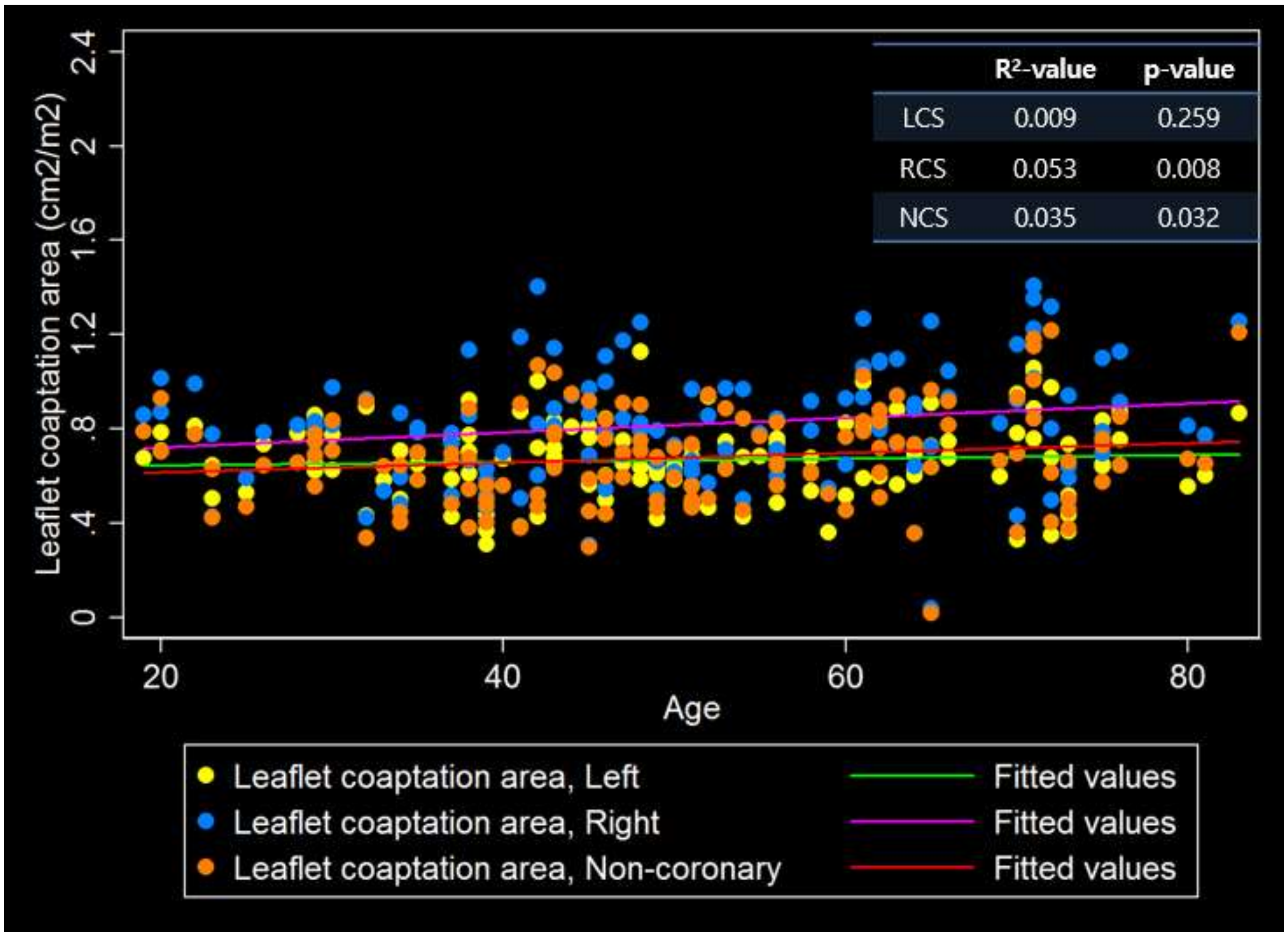
Sinus Volume Change by Age



Cusp Surface Area Change by Age



Cusp Coaptation Area Change by Age



I-C Distance Change by Age