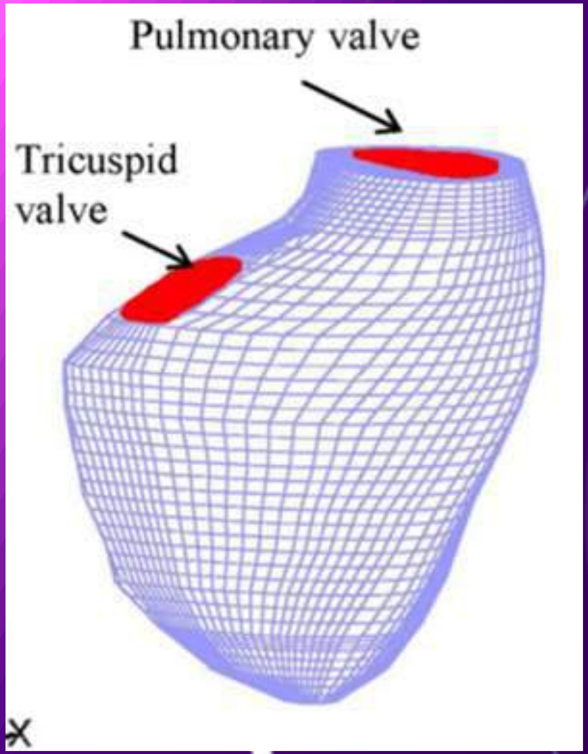
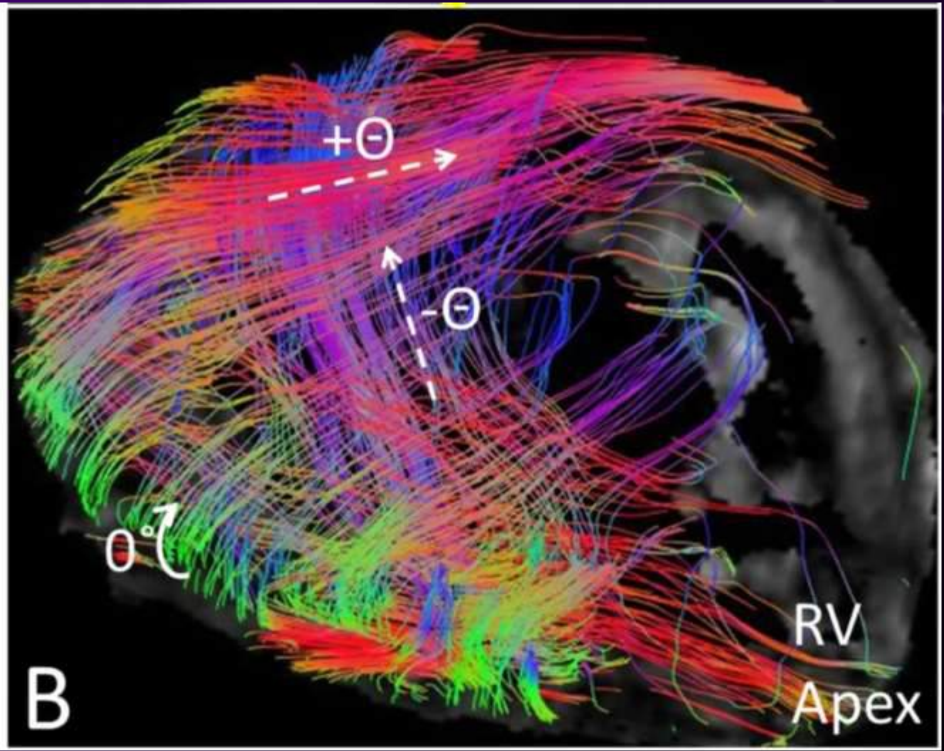
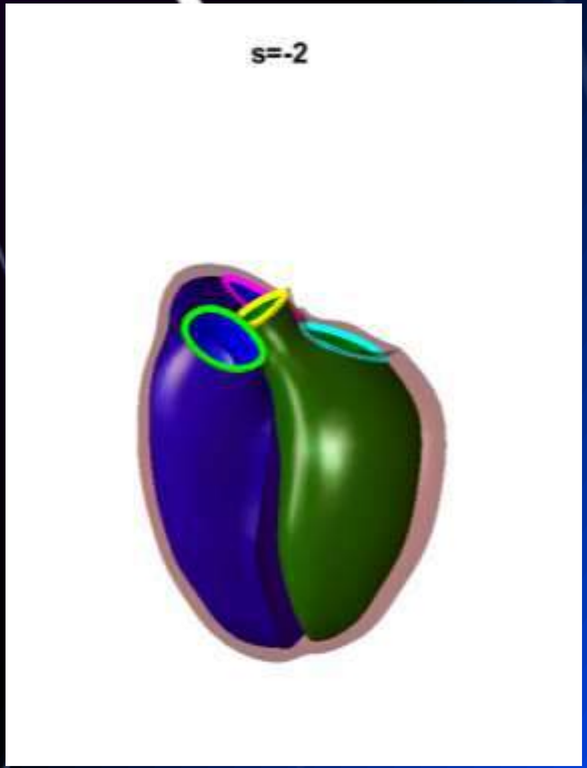
MODELING THE RV







Mark A Fogel, MD FACC, FAHA, MSCMR, FNASCI, FAAP

Professor of Pediatrics (Cardiology) and Radiology

Director of Cardiac MR

Penn Medicine
University of Pennsylvania School of Medicine

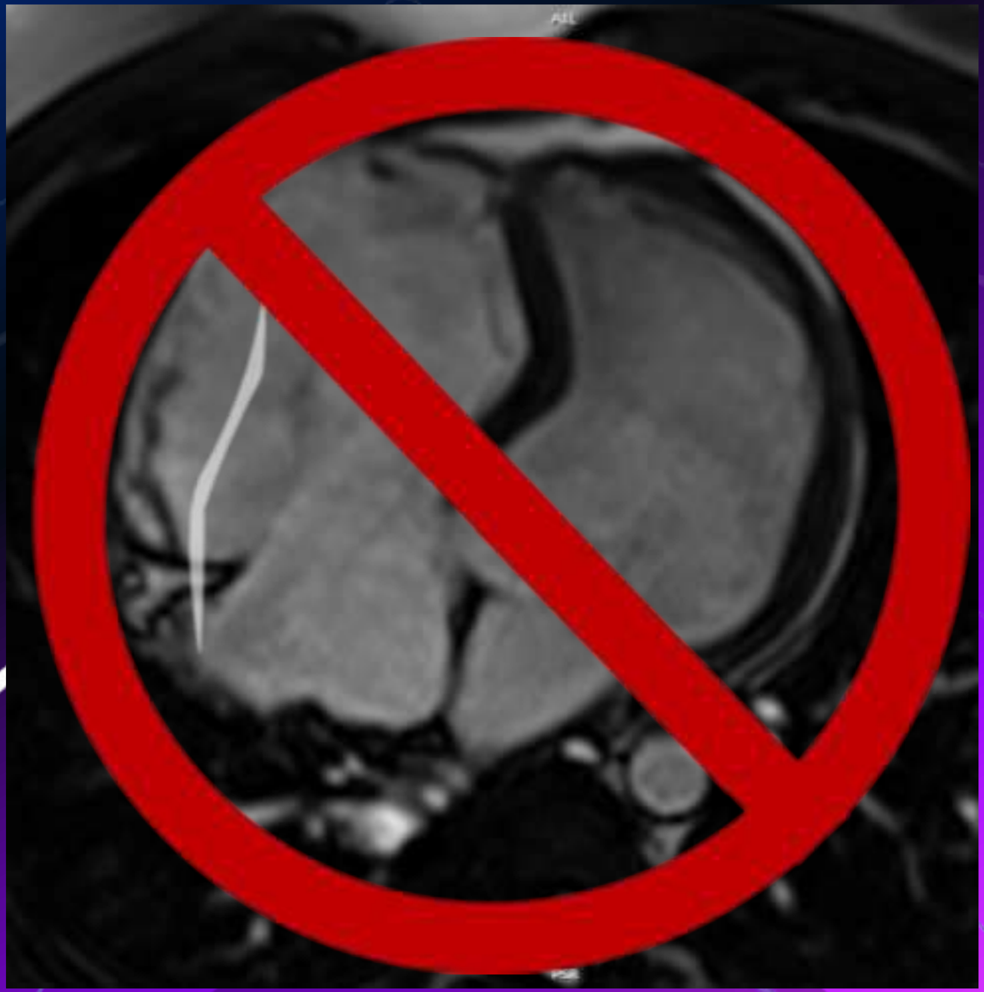
The Children's Hospital of Philadelphia®

DISCLOSURES

- NIH RO1
- Additional Ventures Grant
- CMP Pharma – grant of drug
- Rocket Pharma – Core Lab

AGENDA

- What is modeling?
- Why bother modeling?
- What is modeling dependent on?
- Types of modeling with examples
- In depth and understand SSM



DEFINING MODELING

The use of computational or mathematical techniques to simulate and analyze the heart and cardiovascular system

Structure

Function

Behavior

Organized

Respond to changing environment

WHY BOTHER WITH MODELING?

Study complex processes in a controlled environment

Understand how changes (eg HR or BP) affect the various components of the system

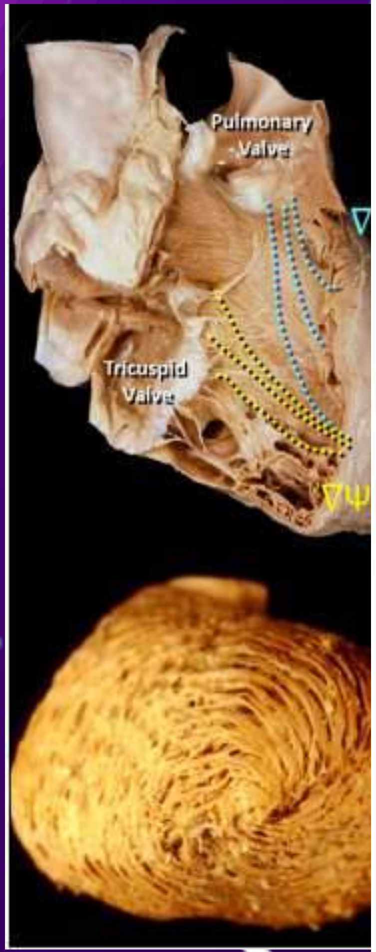
Gain insights into underlying mechanisms of the healthy and diseased heart

Test different treatment strategies without patient risk

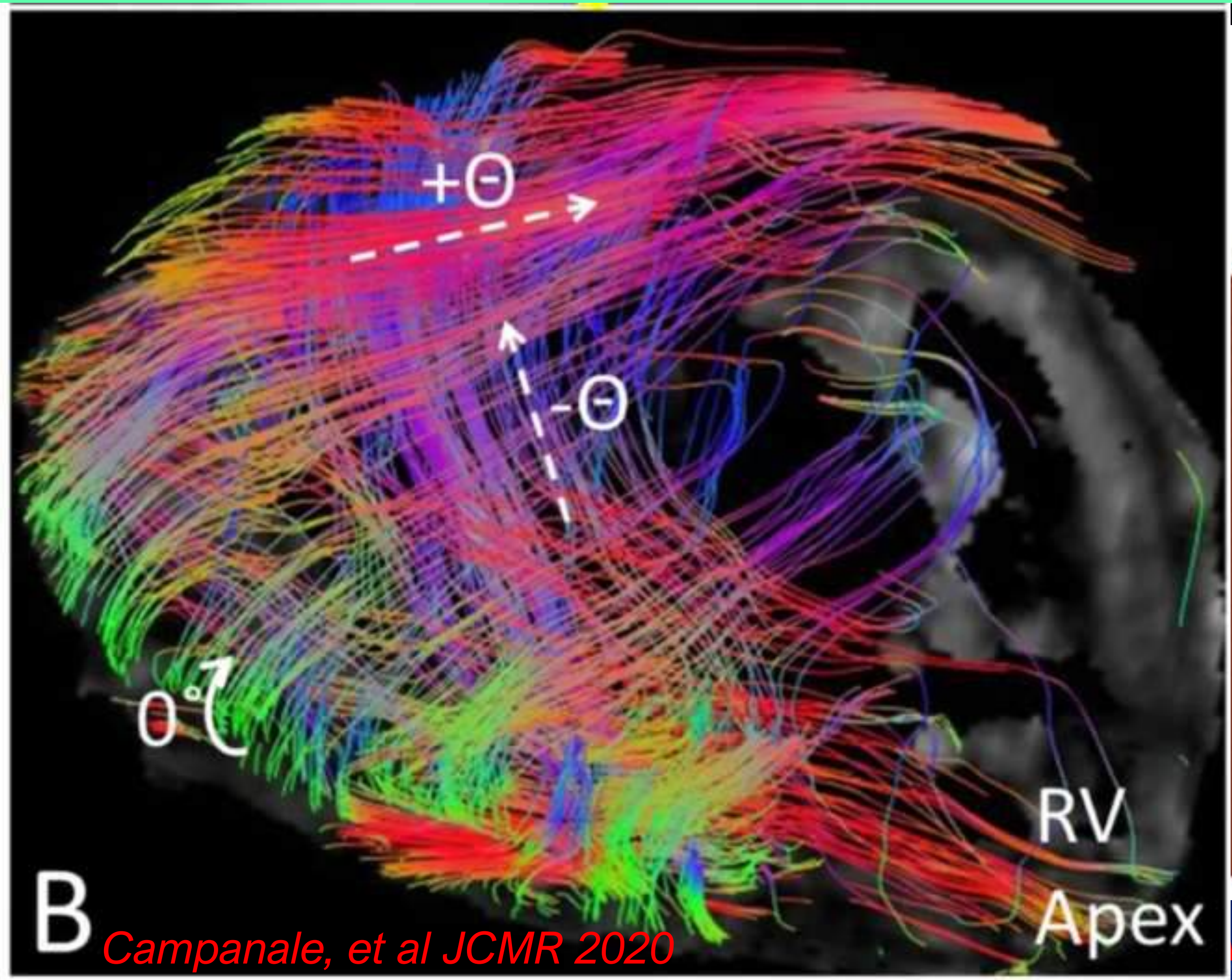
Device design

MODELING DEPENDENT UPON

RV and LV fiber orientation



Doste R, et al

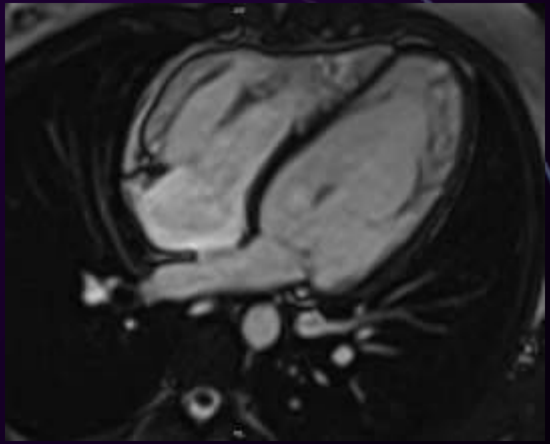


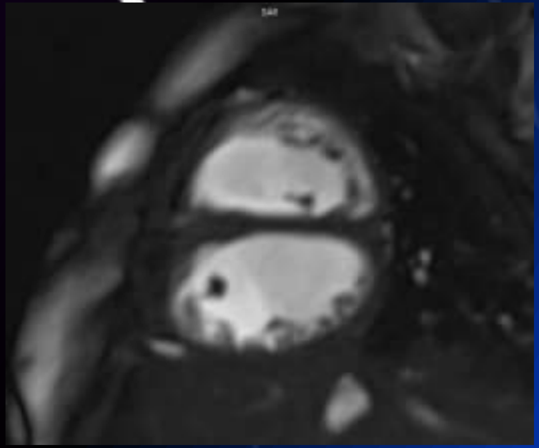
Campanale, et al JCMR 2020

views. 2019;24:511-520

MODELING DEPENDENT UPON

Shape





MODELING DEPENDENT UPON

Shape

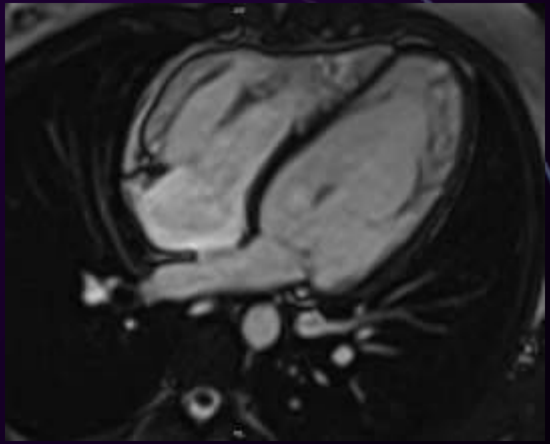
Size

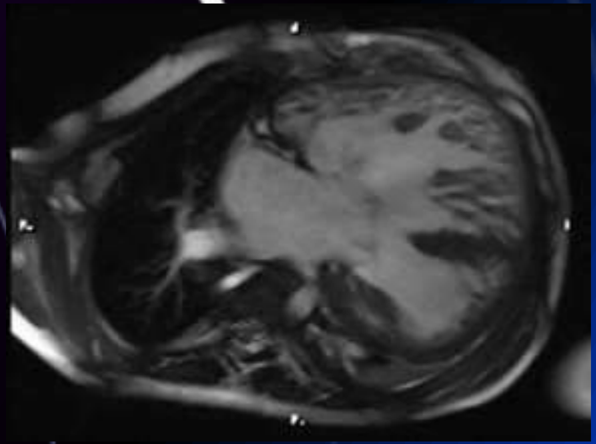
Mechanical properties

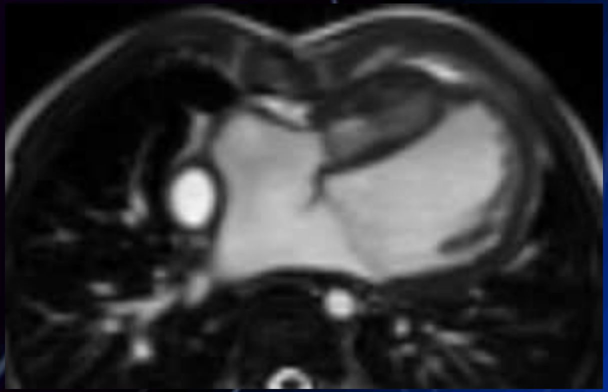
- Compliance
- V-V interaction
- Wall motion

Boundary Conditions

- RV inflow
- RV outflow
- Extrinsic







MODELING DEPENDENT UPON

Shape

Size

Mechanical properties

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Boundary Conditions

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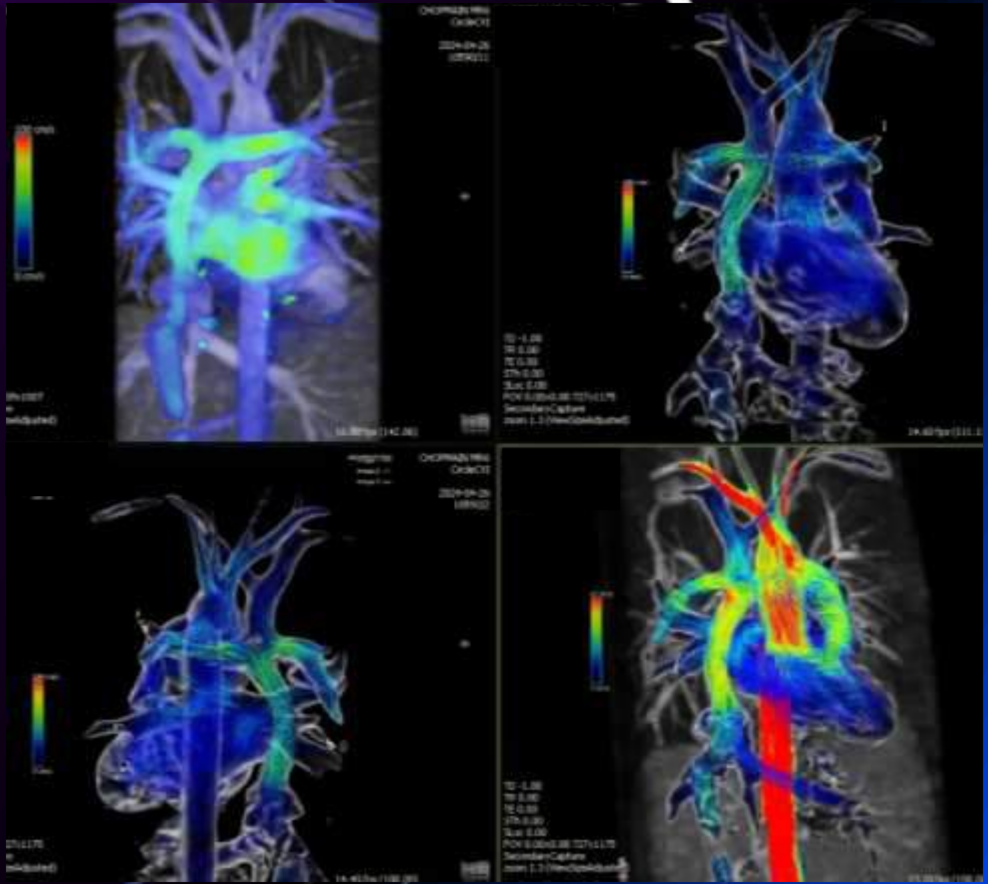


Intraventricular Flows

MODELING DEPENDENT UPON

Left Ventricular Pressure Effects on Right Ventricular Pressure and Volume Outflow

Catheterization and Cardiovascular Diagnosis 19:269–278 (1990)

Ralph J. Damiano, Jr., MD, James L. Cox, MD, James E. Lowe, MD, and William P. Santamore, PhD

Contribution of each wall to biventricular function

Cardiovascular Research 1993:27:792-800

Kun S Li and William P Santamore

- Targeted ischemia of each wall of each ventricle
- Electrically isolating each wall
- Gluteralderhyde of walls
- Ripping the RV free wall off

(and it still generated pressure)

V-V interaction

Significant left ventricular contribution to right ventricular systolic function

Am. J. Physiol. 261 (Heart Circ. Physiol. 30): H1514– H1524, 1991

RALPH J. DAMIANO, JR., PAUL LA FOLLETTE, JR., JAMES L. COX, JAMES E. LOWE, AND WILLIAM P. SANTAMORE

Up to 63% of RV ejection, depending on how you measure, is due to the LV!

A Study in Ventricular–Ventricular Interaction

Single Right Ventricles Compared With Systemic Right Ventricles in a Dual-Chamber Circulation

Mark A. Fogel, Paul M. Weinberg, Kenneth E. Fellows, and Eric A. Hoffman

Circulation

Volume 92, Issue 2, 15 July 1995; Pages 219-230

Imaging Right-Left Ventricular Interactions

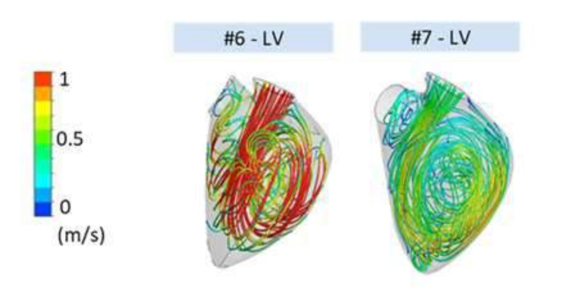
Mark K. Friedberg, MD

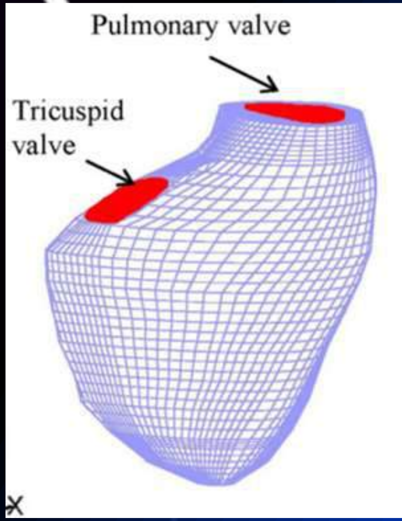
(J Am Coll Cardiol Img 2018;11:755-71)

TYPES OF RV MODELING

Intraventricular flow with CFD

Finite Element Analysis (FE)





TYPES OF RV MODELING

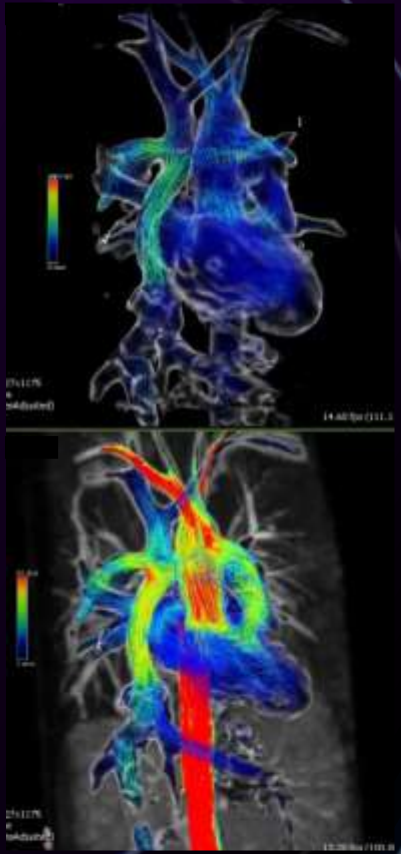
Intraventricular flow with CFD

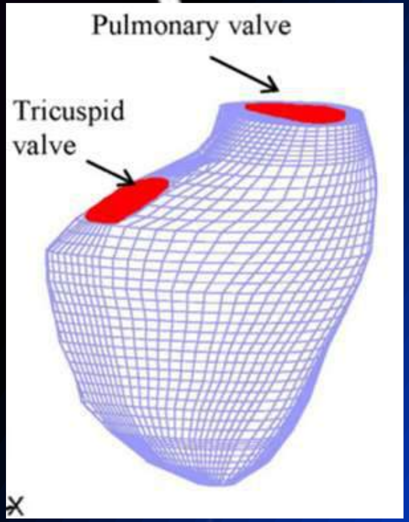
Finite Element Analysis (FE)

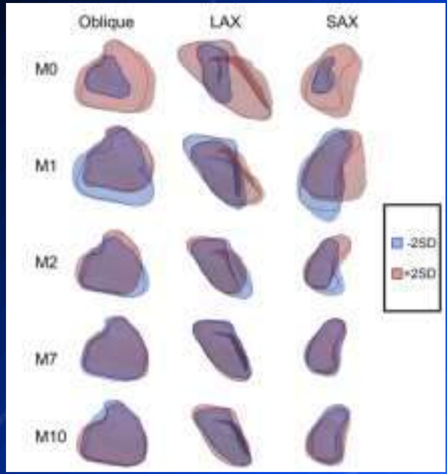
Fluid Structure Interaction (FSI)

Statistical Shape Modeling (SSM)

Electrophysiologic and electro-mechanical modeling







RV INTRAVENTRICULAR FLOW

Intraventricular Flow Simulations in Singular Right Ventricles Reveal Deteriorated Washout and Low Vortex Formation

Cardiovascular Engineering and Technology, Vol. 13, No. 3, June 2022 (*© 2021*) pp. 495–503

Anna Grünwald,[1] Jana Korte,[1] Nadja Wilmanns,[3] Christian Winkler,[2] Katharina Linden,[2] Ulrike Herberg,[2] Sascha Groß-Hardt,[1] Ulrich Steinseifer,[1] and Michael Neidlin[1]

[1]Department of Cardiovascular Engineering, Institute of Applied Medical Engineering, Medical Faculty, RWTH Aachen University, Aachen, Germany; [2]Department of Pediatric Cardiology, University Hospital of Bonn, Bonn, Germany; and [3]Institute of General Mechanics, RWTH Aachen University, Aachen, Germany

Applied CFD to echocardiographic data to simulate flows in 5 single RV vs 2 normal LVs

RV INTRAVENTRICULAR FLOW

Intraventricular Flow Simulations in Singular Right Ventricles Reveal Deteriorated Washout and Low Vortex Formation

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[1]Department of Cardiovascular Engineering, Institute of Applied Medical Engineering, Medical Faculty, RWTH Aachen University, Aachen, Germany; [2]Department of Pediatric Cardiology, University Hospital of Bonn, Bonn, Germany; and [3]Institute of General Mechanics, RWTH Aachen University, Aachen, Germany

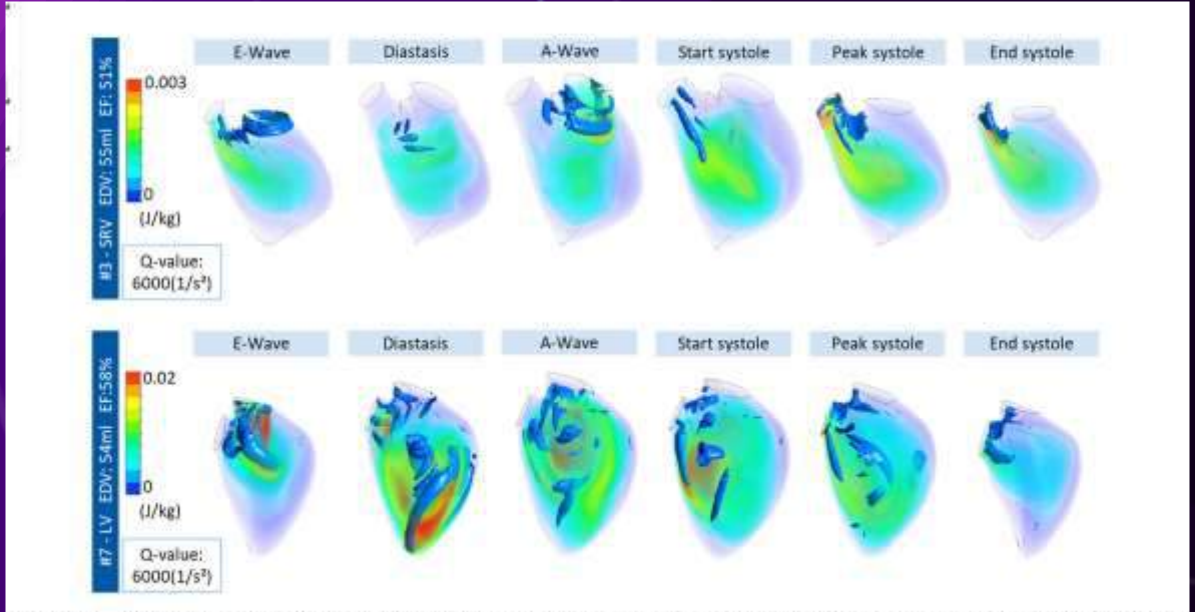


FIGURE 1. Representative turbulent kinetic energy (J/kg) and vortex structure formation with *Q*-value (1/s) for subject #3 (SRV) and subject #7 (LV). TKE represented by different scales, subject #3 max 0.003 J/kg, subject #8 max 0.02 J/kg.

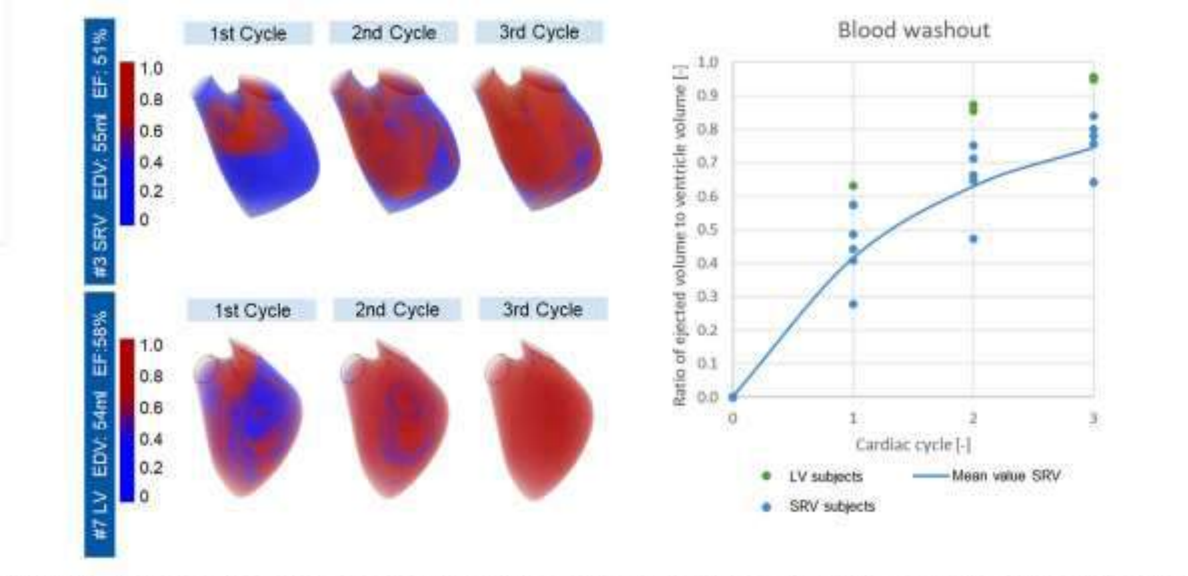


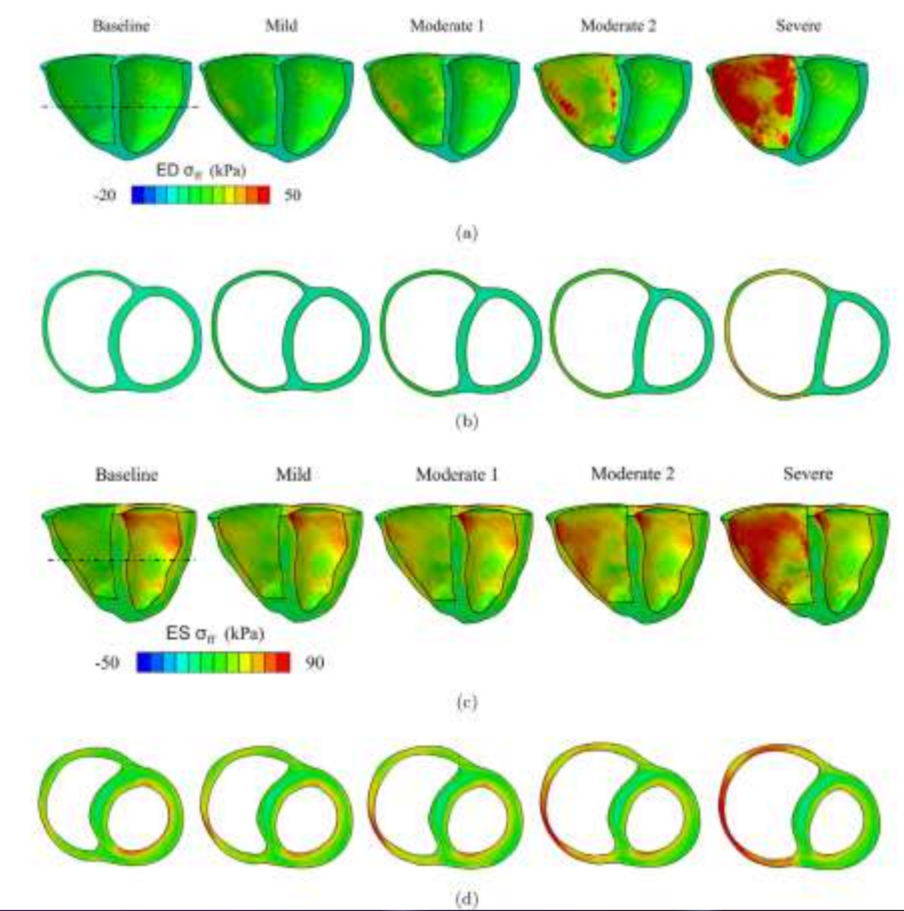
FIGURE 3. Left: Washout simulation for subject #3 (SRV) and subject #7 (LV). Time point of diastase for three cardiac cycles. Blue old blood, red new blood. Right: Volume percentage distribution of ejected volume to the total ventricle volume for SRV subjects (blue) and LV subjects (green).

RV FINITE ELEMENT ANALYSIS (FE)

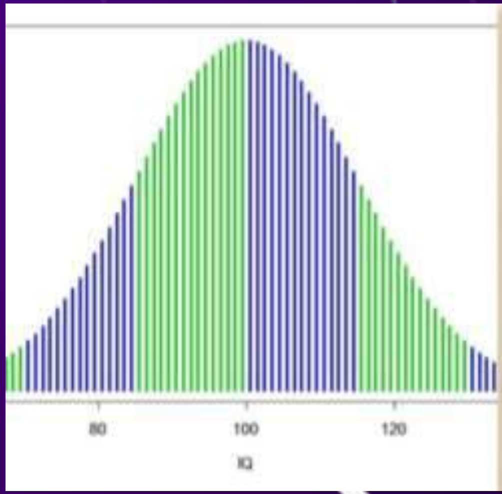
Effect of pulmonary regurgitation on cardiac functions based on a human bi-ventricle model

Xueqing Yin[a], Yingjie Wang[a,*]

Computer Methods and Programs in Biomedicine 238 (2023) 107600



STATISTICAL SHAPE MODELING (SSM)



STATISTICAL SHAPE MODELING (SSM)

MODE 2

Height

40/180=22%

$$\frac{22\%}{22\%+57\%}=28\%$$

$$\frac{57\%}{22\%+57\%}=72\%$$

MODE 1

Weight

40/70=57%

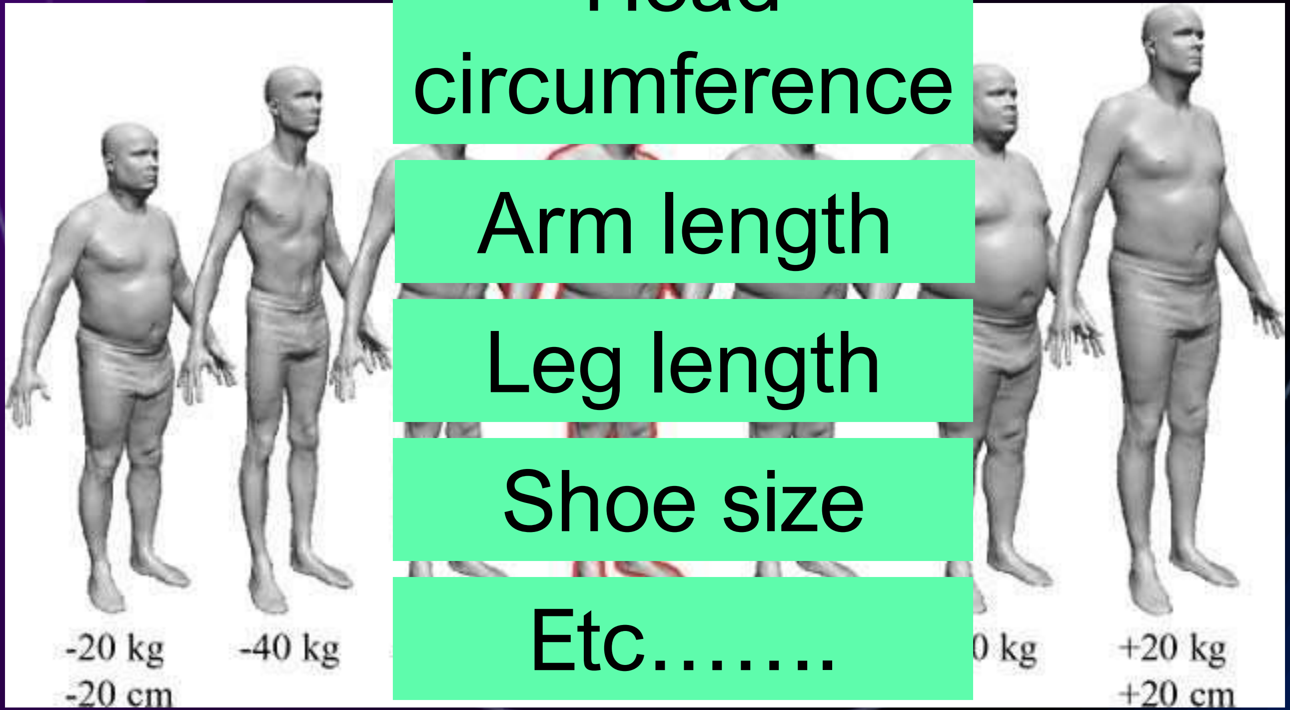
Head circumference

Arm length

Leg length

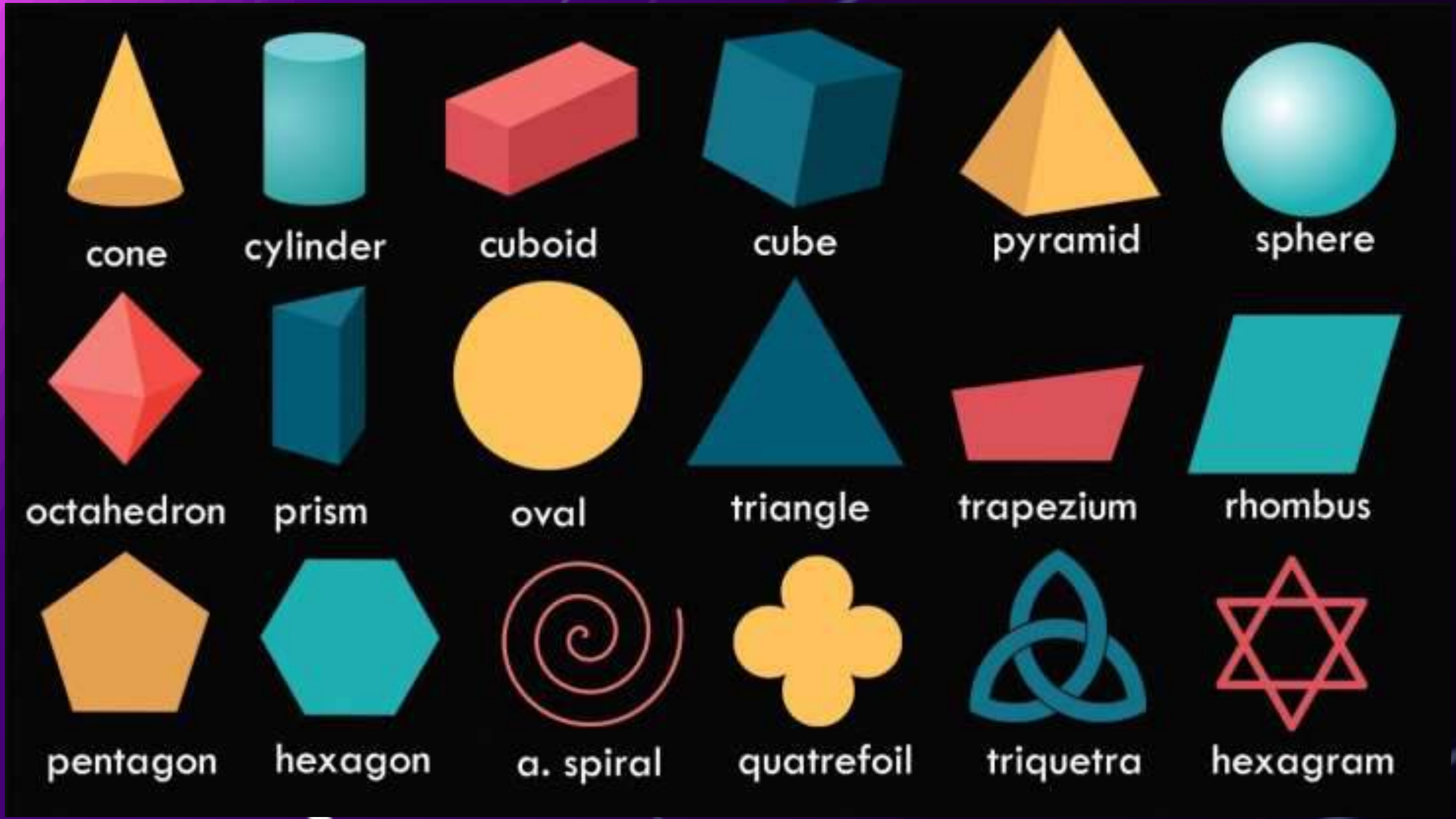
Shoe size

Etc…….



Principle Component Analysis (PCA)

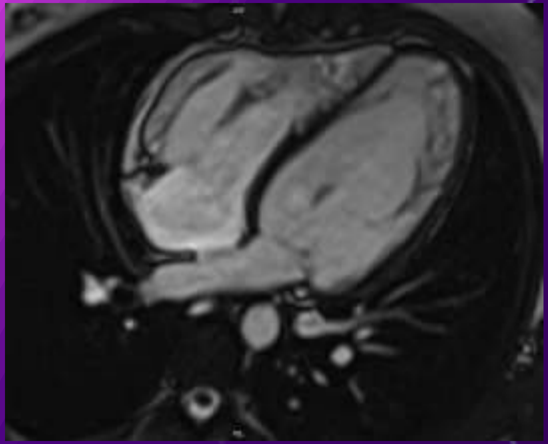
STATISTICAL SHAPE MODELING (SSM)

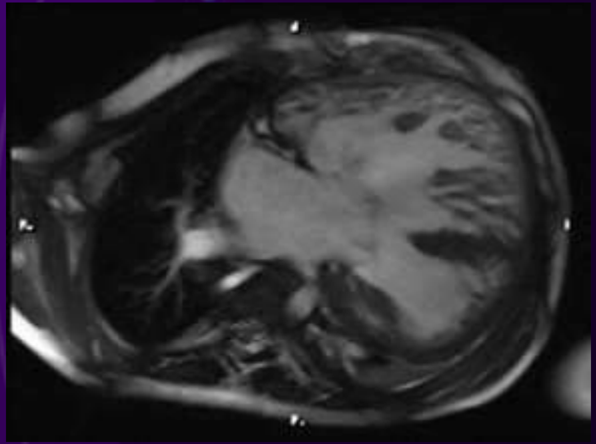


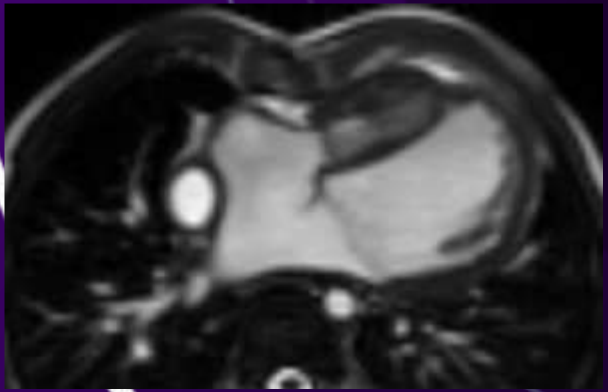
- Number of sides
- Diameter
- Color
- Area
- Circumference
- Etc……

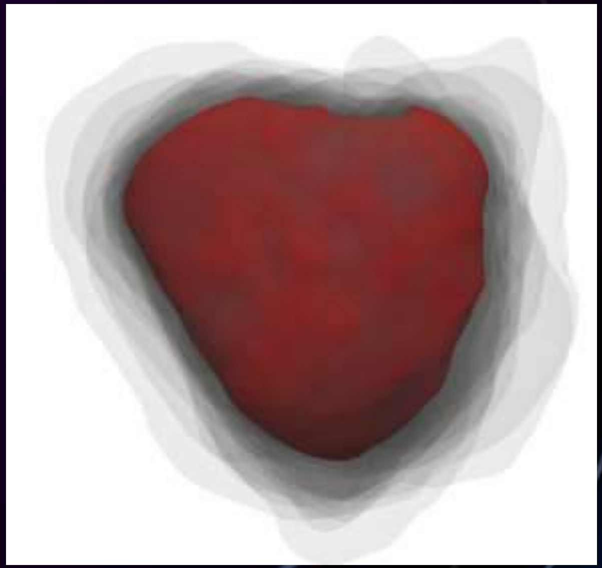
MODELING DEPENDENT UPON

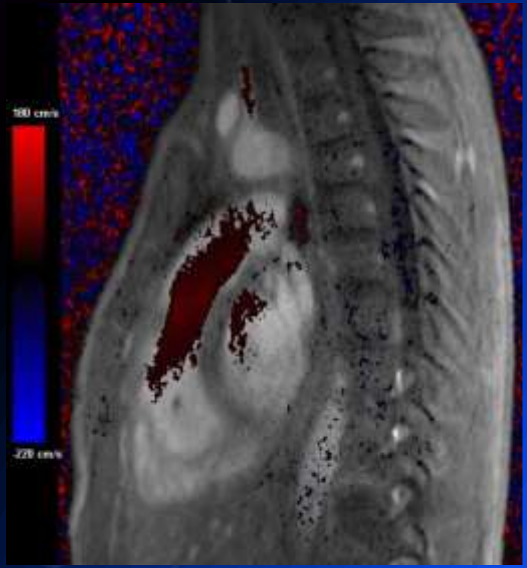
Shape of the RV











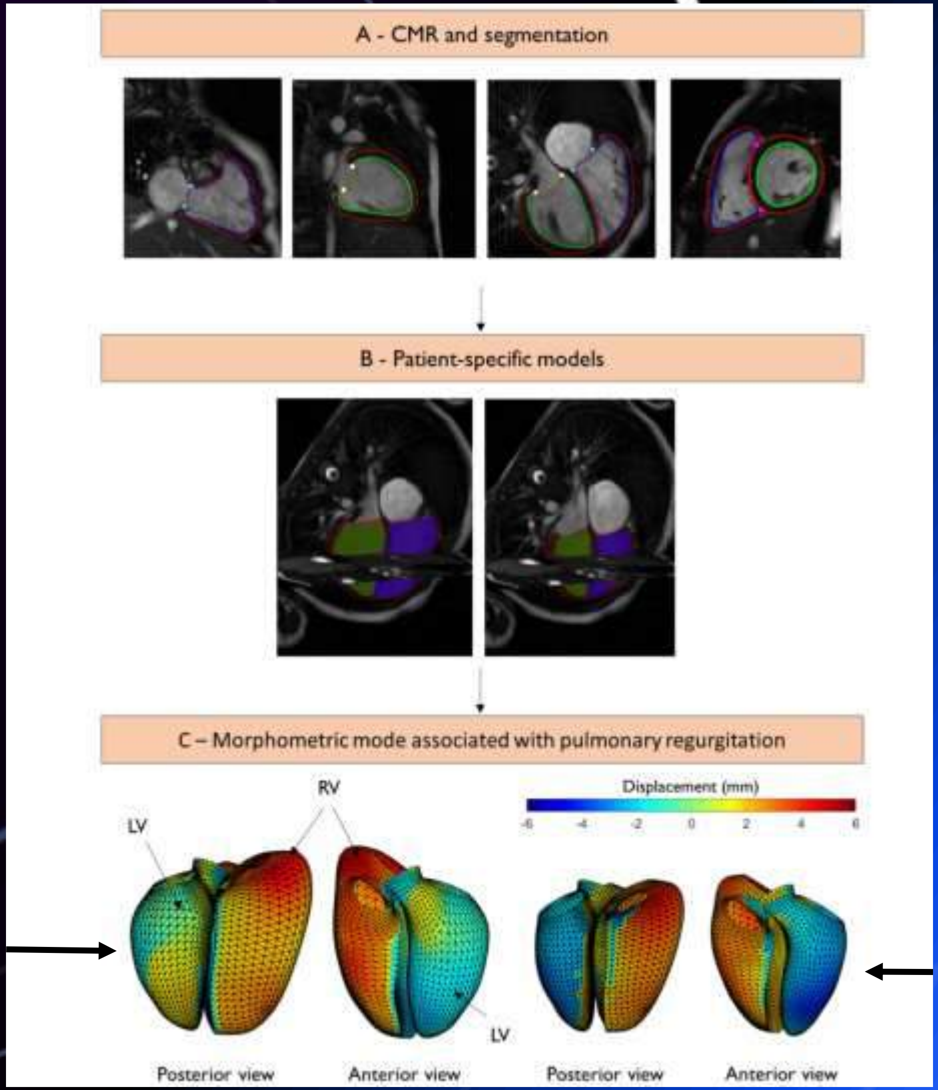
SSM OF THE RV

Right-left ventricular shape variations in tetralogy of Fallot: associations with pulmonary regurgitation

Charlène A. Mauger[1,2†], Sachin Govil[3†], Radomir Chabiniok[4,5,6,7], Kathleen Gilbert[2], Sanjeet Hegde[3,8], Tarique Hussain[4], Andrew D. McCulloch[3], Christopher J. Occleshaw[9], Jeffrey Omens[3], James C. Perry[3,8], Kuberan Pushparajah[10], Avan Suinesiaputra[11], Liang Zhong[12,13] and Alistair A. Young[1,10*]

J Cardiovasc Magn Reson (2021) 23:105

- N = 88 TOF patients
- Mean age = 16 yrs
- RV and LV volumes
- Pulmonary regugitation



ED

ES

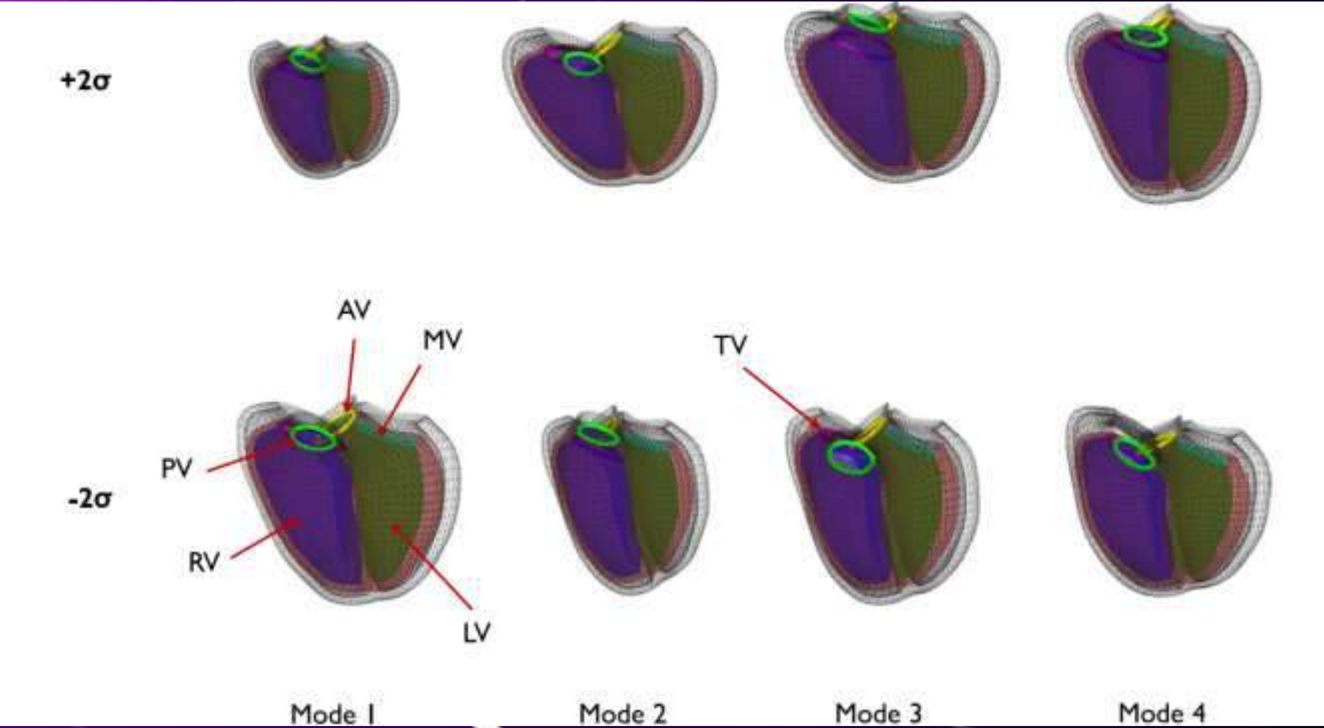
SSM OF THE RV

Right-left ventricular shape variations in tetralogy of Fallot: associations with pulmonary regurgitation

Charlène A. Mauger[1,2†], Sachin Govil[3†], Radomir Chabiniok[4,5,6,7], Kathleen Gilbert[2], Sanjeet Hegde[3,8], Tarique Hussain[4], Andrew D. McCulloch[3], Christopher J. Occleshaw[9], Jeffrey Omens[3], James C. Perry[3,8], Kuberan Pushparajah[10], Avan Suinesiaputra[11], Liang Zhong[12,13] and Alistair A. Young[1,10*]

J Cardiovasc Magn Reson (2021) 23:105

Four PCA modes accounted for 59% of overall variation



Mode

- 1 = overall RV size
- 2 = Septal-free wall dimension
- 3 = basal vs apical bulging (basal away from septum)
- 4 = Systolic septal bulging towards LV

SSM OF THE RV

Right-left ventricular shape variations in tetralogy of Fallot: associations with pulmonary regurgitation

Charlène A. Mauger[1,2†], Sachin Govil[3†], Radomir Chabiniok[4,5,6,7], Kathleen Gilbert[2], Sanjeet Hegde[3,8], Tarique Hussain[4], Andrew D. McCulloch[3], Christopher J. Occleshaw[9], Jeffrey Omens[3], James C. Perry[3,8], Kuberan Pushparajah[10], Avan Suinesiaputra[11], Liang Zhong[12,13] and Alistair A. Young[1,10*]

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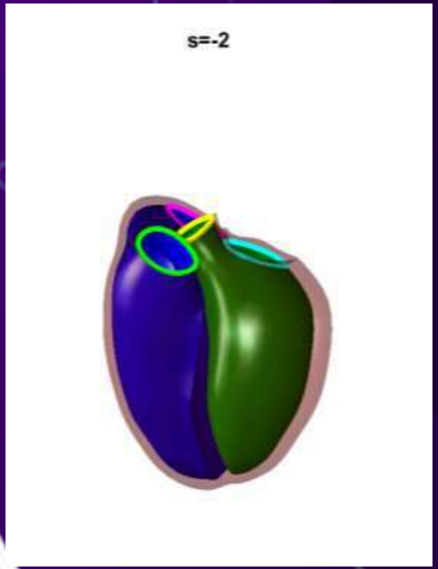
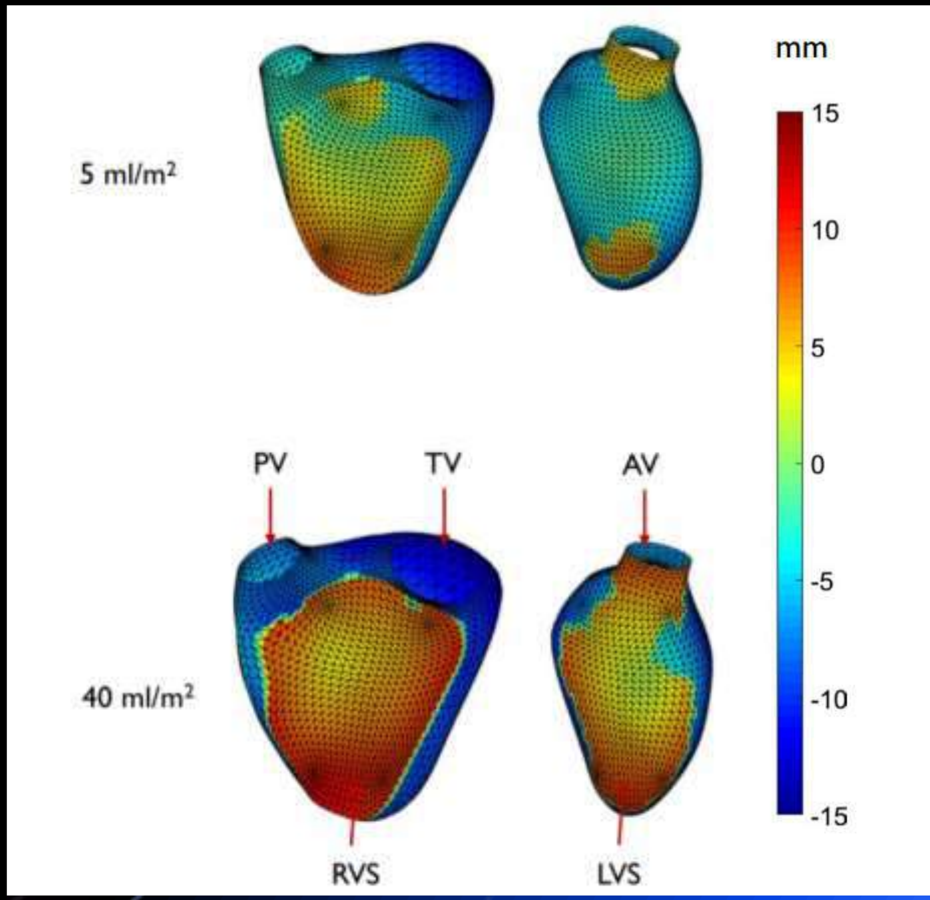




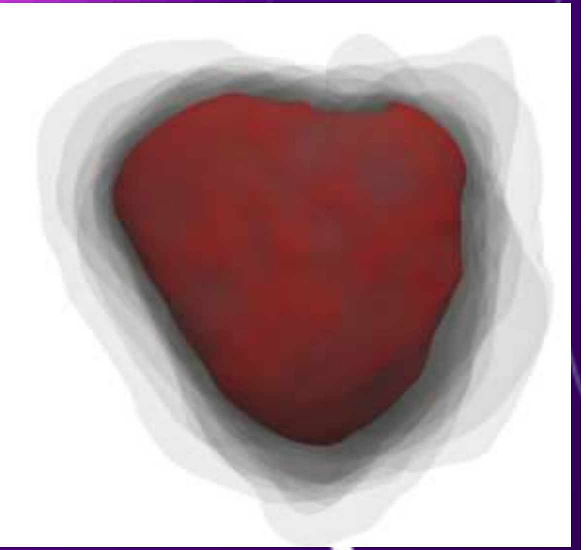
Using SSM, increasing PR: a) RV dilation, b) decreased LV septal-lateral dimension (LV fattening), c) paradoxical septal motion & d) RV basal bulging

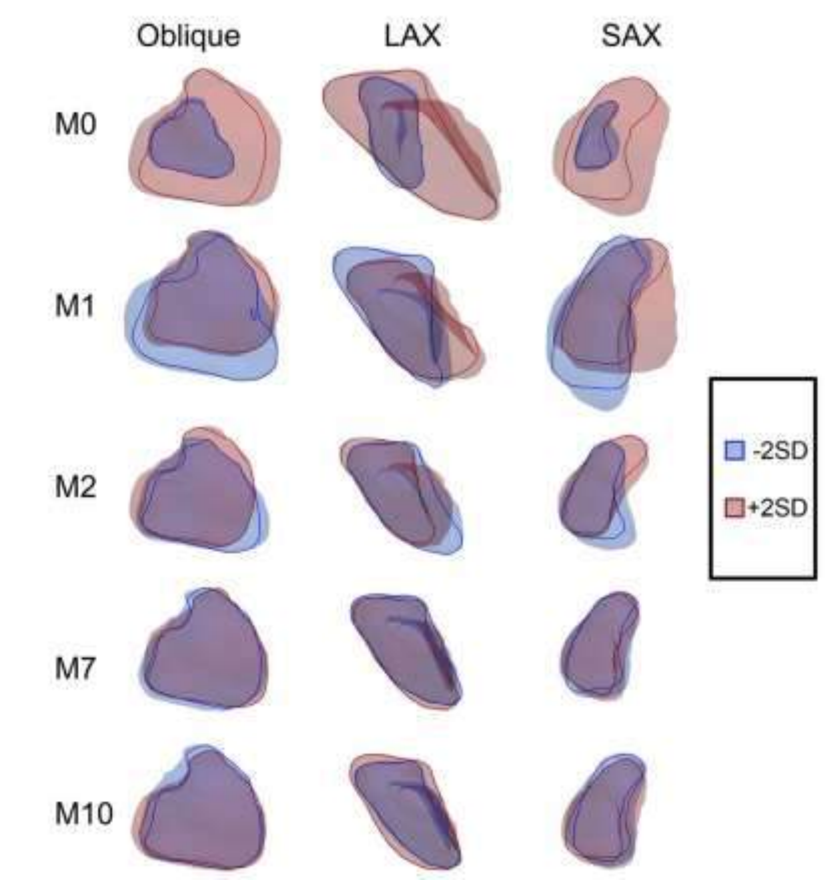
SSM OF THE RV

Statistical shape modeling reveals the link between right ventricular shape, hemodynamic force, and myocardial function in patients with repaired tetralogy of Fallot

Am J Physiol Heart Circ Physiol 323: H449–H460, 2022.

Sarah Kollar,[1] Elias Balaras,[2] Laura J. Olivieri,[3] Yue-Hin Loke,[1*] and Francesco Capuano[4*]





Mode

- 0 = overall RV size
- 1 = Apical bulge & RVOT diameter
- 2 = Longitudinal shortening, ∢ of RV inflow-outflow, globular RV
- 7 = ∢ of RV inflow-outflow, RV apical bulge
- 10 = Apical bulge, length from base to apex, circumference of the RV inflow portion and RVOT size

SSM OF THE RV

Statistical shape modeling reveals the link between right ventricular shape, hemodynamic force, and myocardial function in patients with repaired tetralogy of Fallot

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Mode
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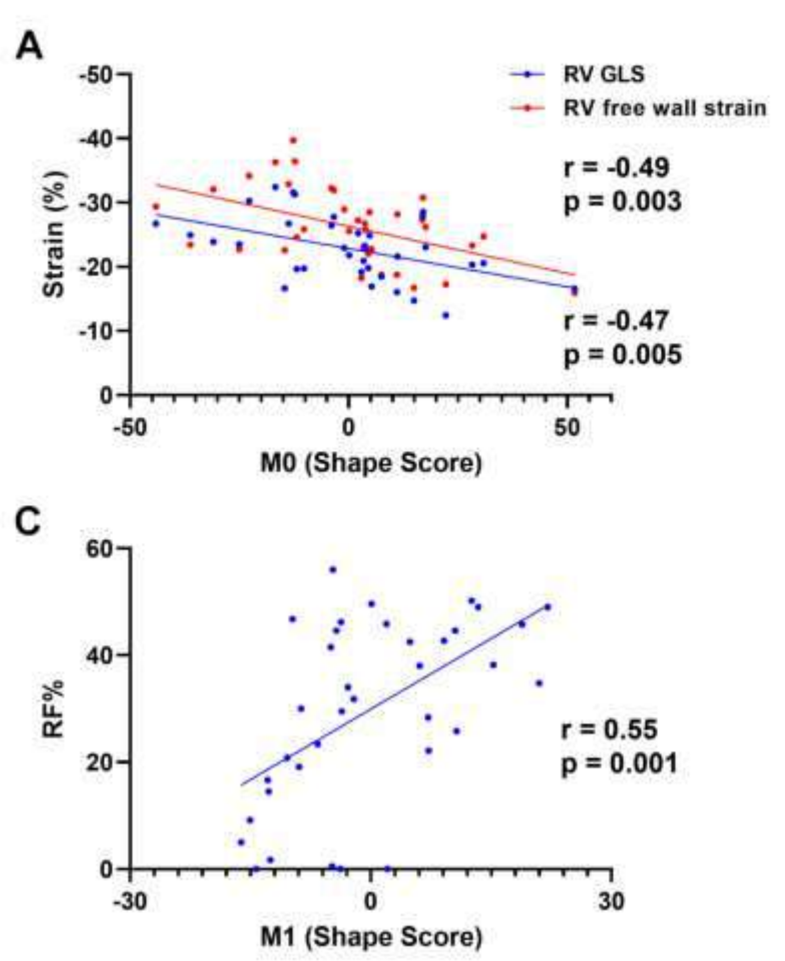
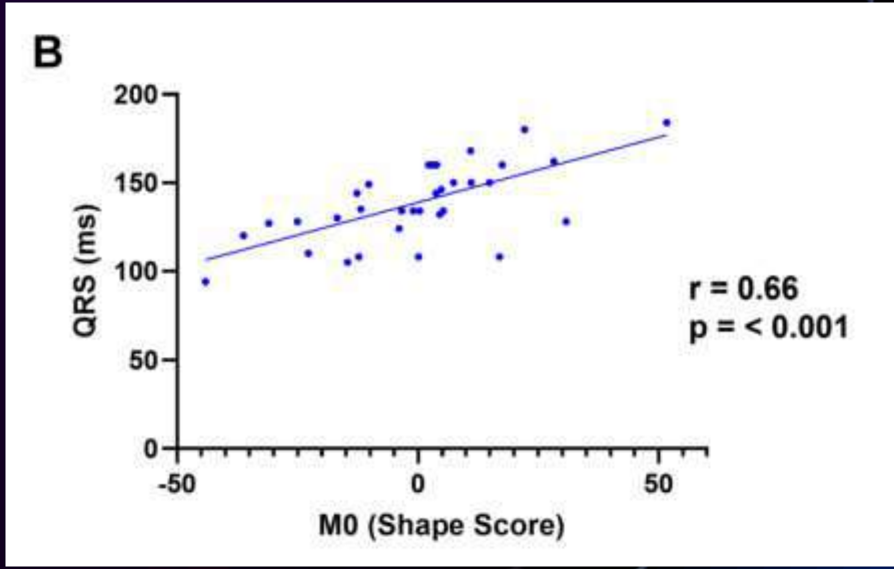




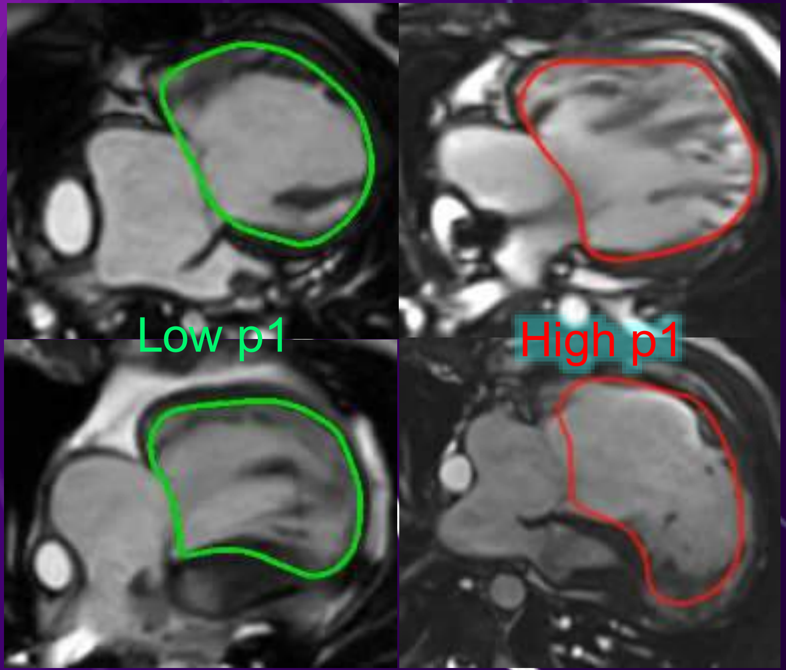
SSM OF THE RV

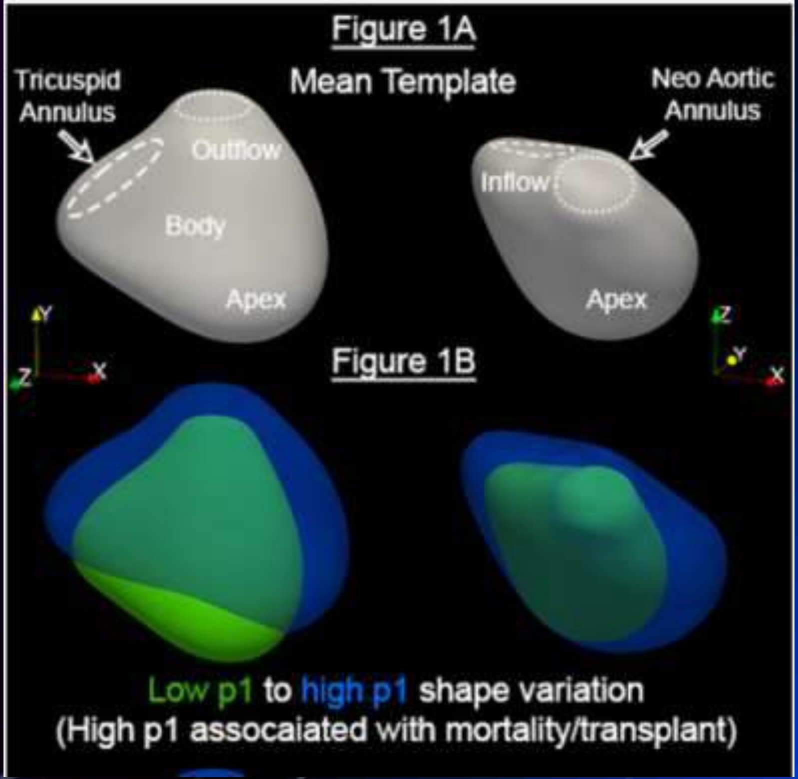
ABSTRACT | Originally Published 11 November 2024 | Check for updates

Abstract 4114497: Shape Variations in Right Ventricular 3D Geometry are associated with adverse outcomes in Hypoplastic Left Heart Syndrome Patients: A Fontan Outcomes Registry using CMR Examination (FORCE) Study

Yue-Hin Loke, MD, Ryan O'Hara, BS, Jacqueline Contento, BSE, Nicole Marella, MD, Lekha Anantuni, MD, Susana Gaviria, MD, Sarah Kollar, DO
, ... SHOW ALL ..., and Francesco Capuano, PhD AUTHOR INFO & AFFILIATIONS

N=388 HLHS Fontan Patients





Multivariable Analysis	Odds Ratio (Death or heart transplantation)	(95% CI) 2.5 % 97.5 %	p-value
Shape Mode p1*	2.67	1.44, 10.67	<0.01
RV Mass$_i$ (gm/m^2)	1.025	1.005, 1.041	0.01

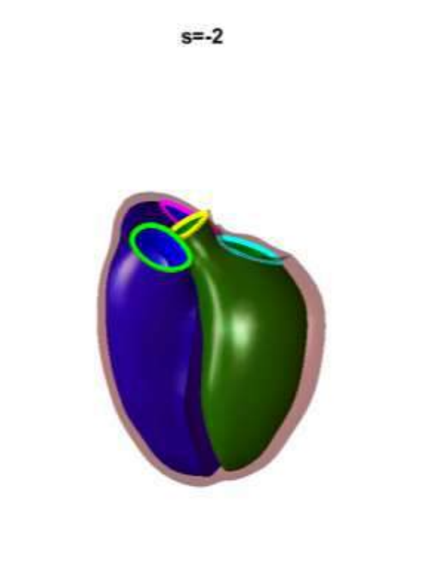
SUMMARY

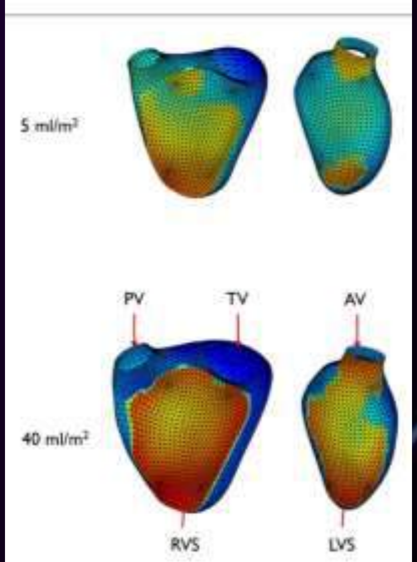
Modeling – math and computational methods for structure, fxn, behavior

- Understanding mechanics
- Test different Tx strategies
- Design device

Various types of modeling

Up to 63% of RV ejection is due to the LV!





SSM

- Variations from the "average"
- Insights into pathophysiology
- ? Predictor of events

Fellow/junior attending:
Modeling in Ebstein's is wide open

THANK YOU

THANK YOU AND CREDITS

CHOP CMR Team

Cardiac Anesthesia

Adreas Lopke, Susan Nicolson

CMR Nursing

Denise Virden, Traci Sullivan

CHOP Administration

Joe Rossano, Kasa Darge, Larry Barnes
Ana Spraycar, Jim Zheng, Trish Mecca

CT Surgery

Jonathan Chen, Stephanie Fuller, Bill Gaynor
Kats Maeda, Mo Nuri, Constantine Mavroudis

Cardiac Cath

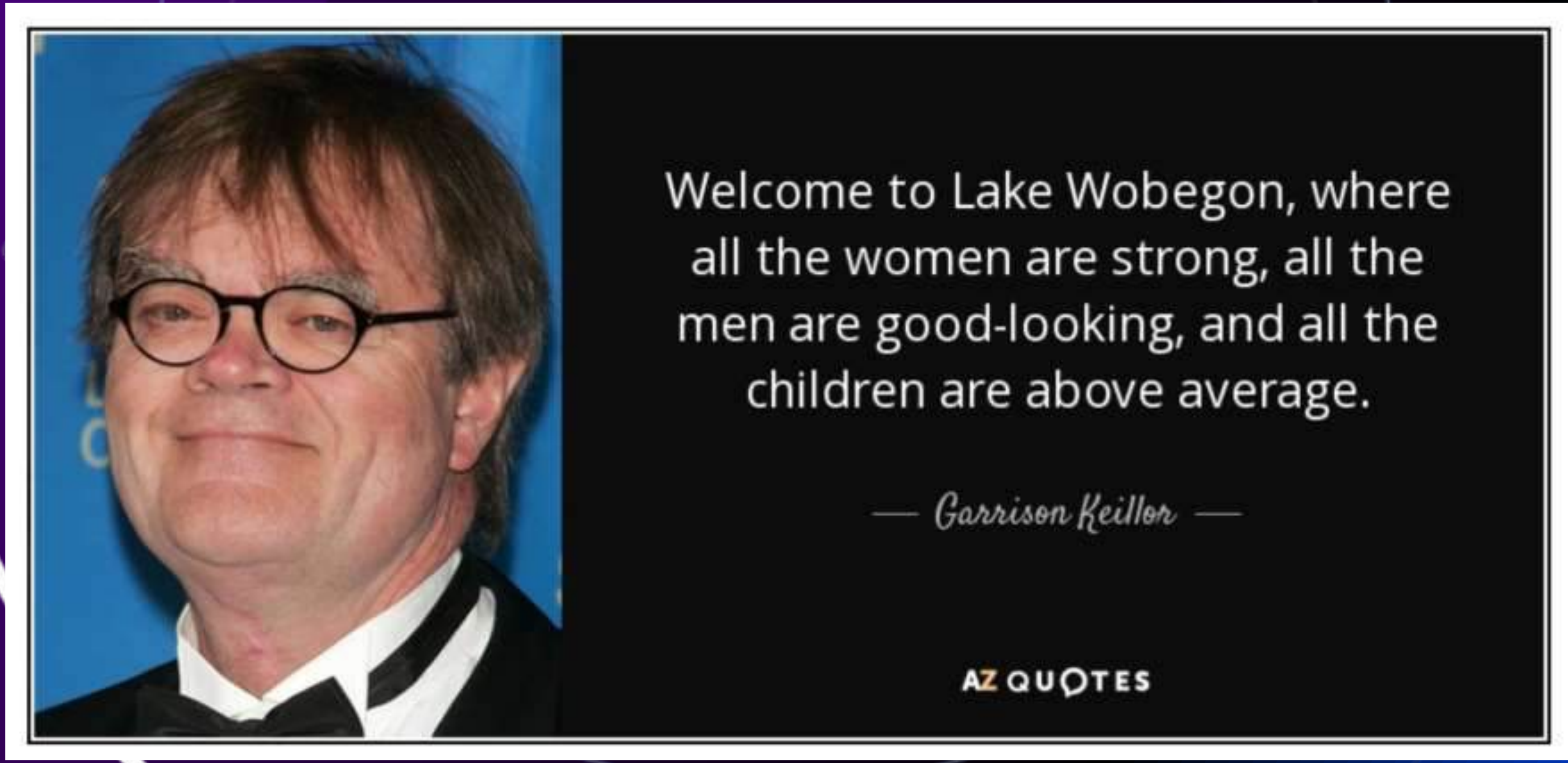
Jack Rome, Matt Gillespie, Jessica Tang,
Mike Obyrne, Yoav Dori

Cardiac Scheduling

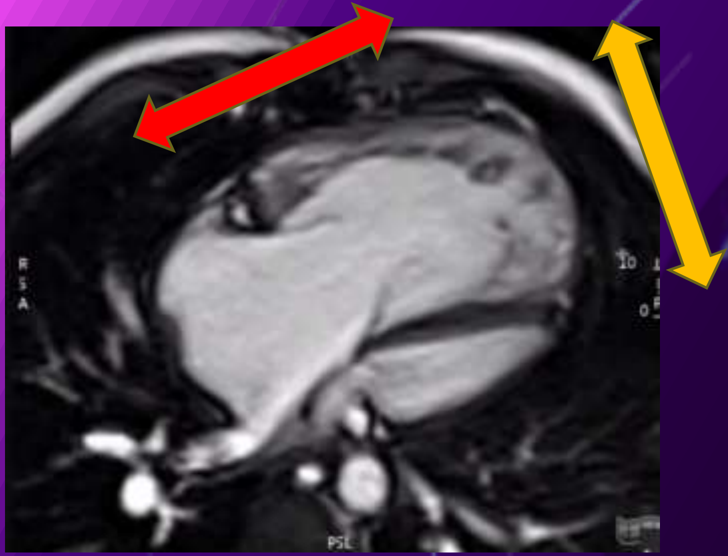
Heather Meldrum

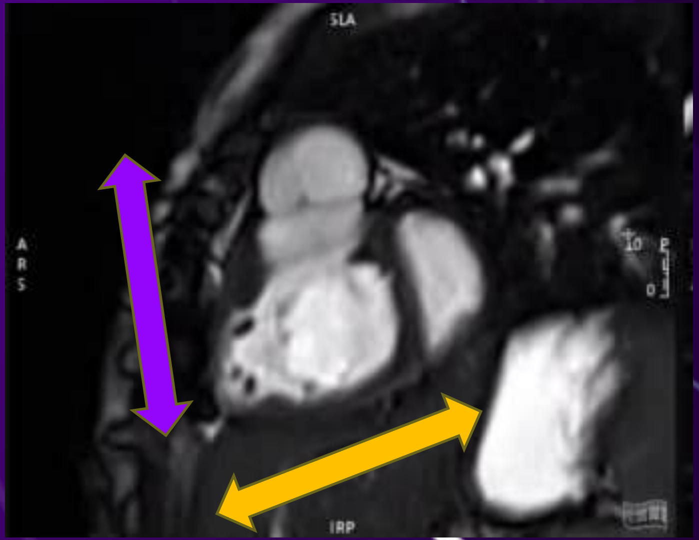
3D Post-processing Lab

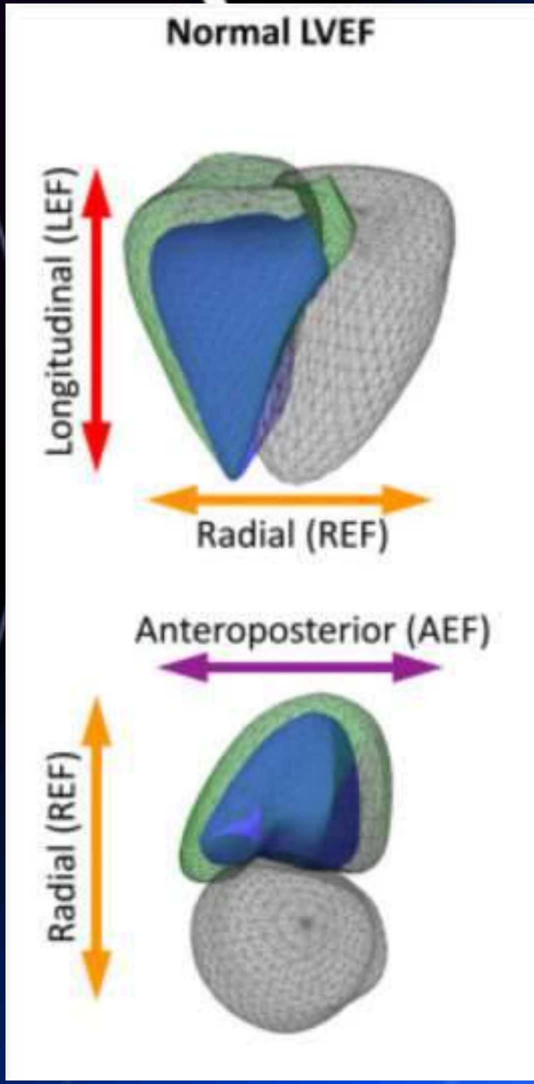
IT MAY BE DISHEARTENING TO THINK OF AN "AVERAGE" PERSON AND SOME OF US BELOW IT BUT…



MODELING THE RV – MOTION

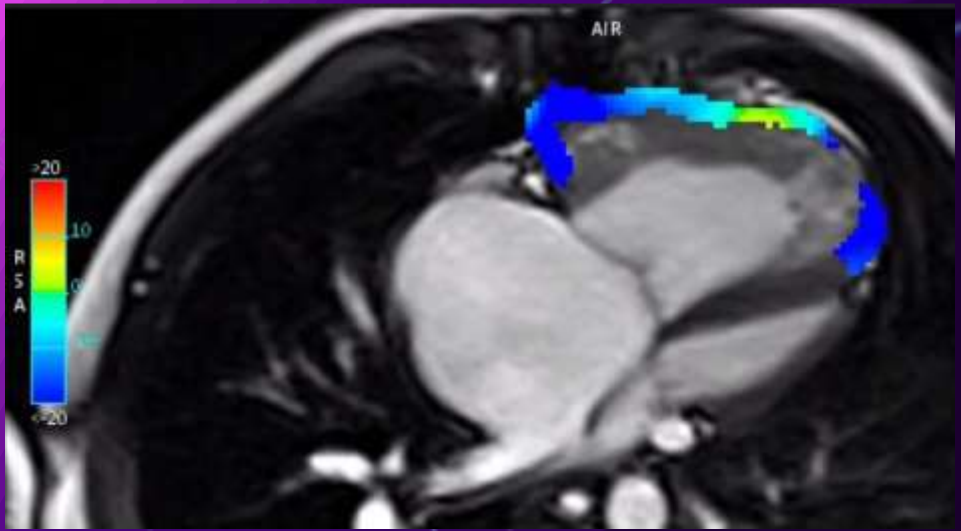


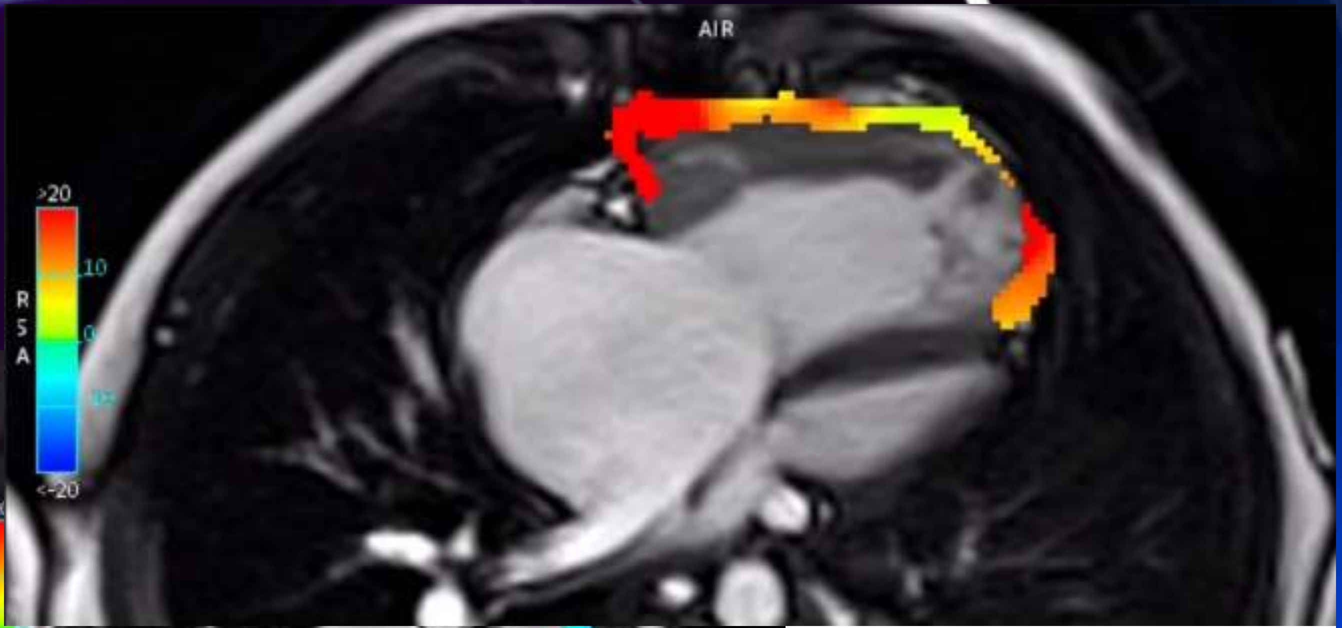


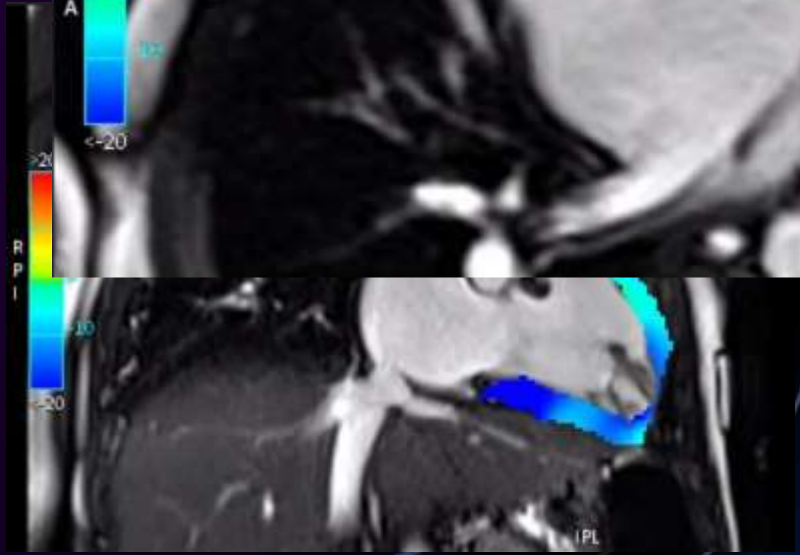


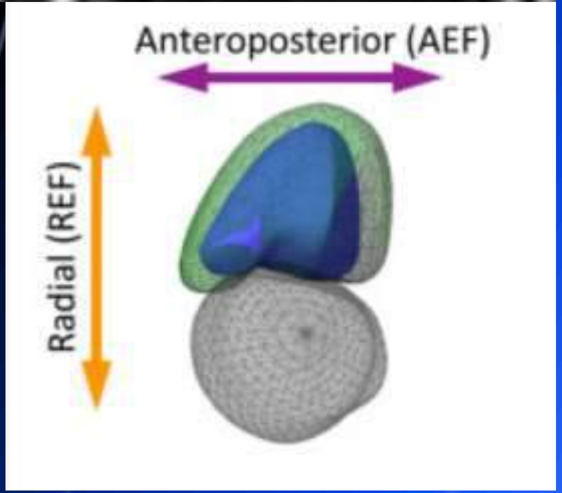
Using REALIZE software

MODELING THE RV









RV FINITE ELEMENT ANALYSIS (FE)

Can RV pre-PVR stress and strain predict RV performance after PVR?

RV pre-PVR stress and strain

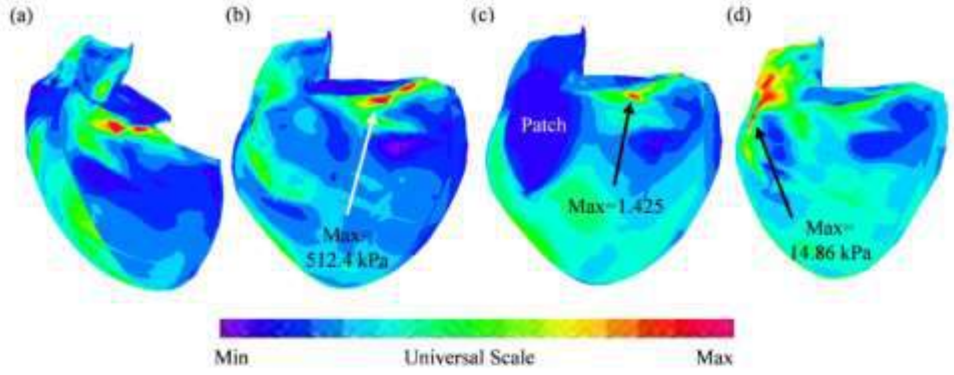


Figure 4 (online).
Selected cut-surface, maximum principal stress (Stress-P_1) and strain (Strain-P_1) corresponding to end-of-diastole and end-of-systole pressure conditions. (a) Position of the cut surface; (b) Stress-P_1, end-of-diastole; (c) Strain-P_1, end-of-diastole; (d) Stress-P_1, end-of-systole.

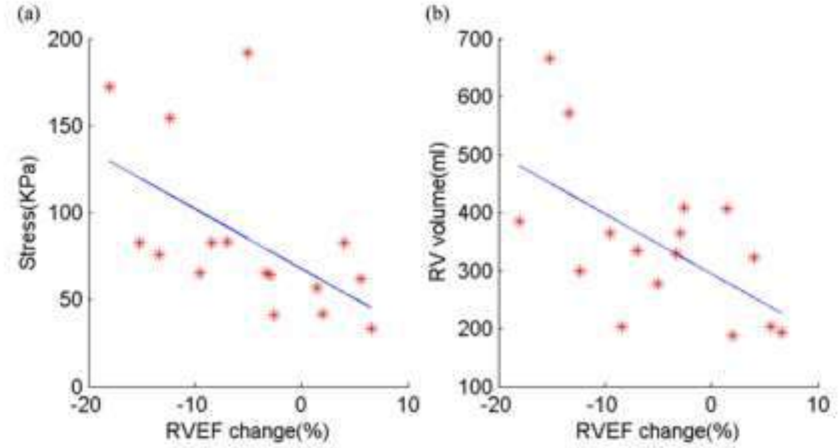


Figure 5 (online).
RVEF change correlated negatively with stress (r= – 0.56, p=0.025) and with pre-PVR RV volume (r= – 0.60, p= 0.015). (a) Stress vs. EF change; (b) pre-PVR RV volume vs. EF change.

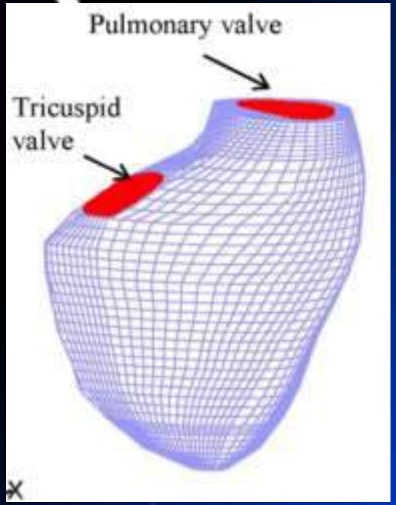
Tang D, et al *J Thorac Cardiovasc Surg.* 2016 March ; 151(3): 687–694.e3.

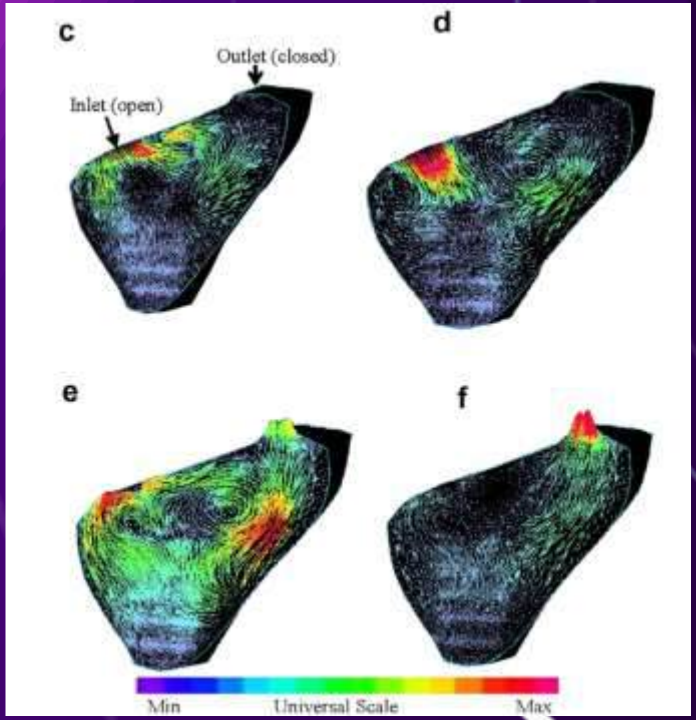
RV FLUID STRUCTURE INTERACTION (FSI)

In vivo MRI-based 3D FSI RV/LV models for human right ventricle and patch design for potential computer-aided surgery optimization

Chun Yang [a], Dalin Tang [b,*], Idith Haber [c], Tal Geva [d], Pedro J. del Nido [c]

Computers and Structures 85 (2007) 988–997





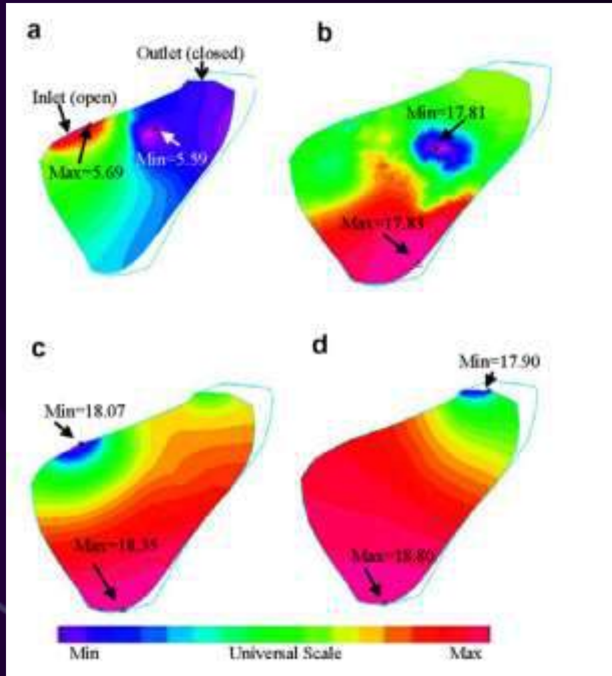


Fig. 6. Contour plots of pressure distributions on the cut-surface corresponding to different RV filling and ejection phases as shown in

Combination of flow and stress strain associated with RV morphology, material properties and BP

RV INTRAVENTRICULAR FLOW

Intraventricular Flow Simulations in Singular Righ[...]entricles Reveal Deteriorated Washout and Low Vor[...]tion

Cardiovascular Engineering and Technology, Vol. 13, No. 3, [...] 495–503

Anna Grünwald,[1] Jana Korte,[1] Nadja Wilmanns,[3] Chr[...] Linden,[2] Ulrike Herberg,[2] Sascha Groß-Hardt,[1] Ulrich [...]dlin[1]

[1]Department of Cardiovascular Engineering, Institute [...] Faculty, RWTH Aachen University, Aachen, Germany; [2]Department of P[...] of Bonn, Bonn, Germany; and [3]Institute of General Me[...]chen, Germany

Lower vortex formation, kinetic energy and blood washout in single RVs compared to normal LVs

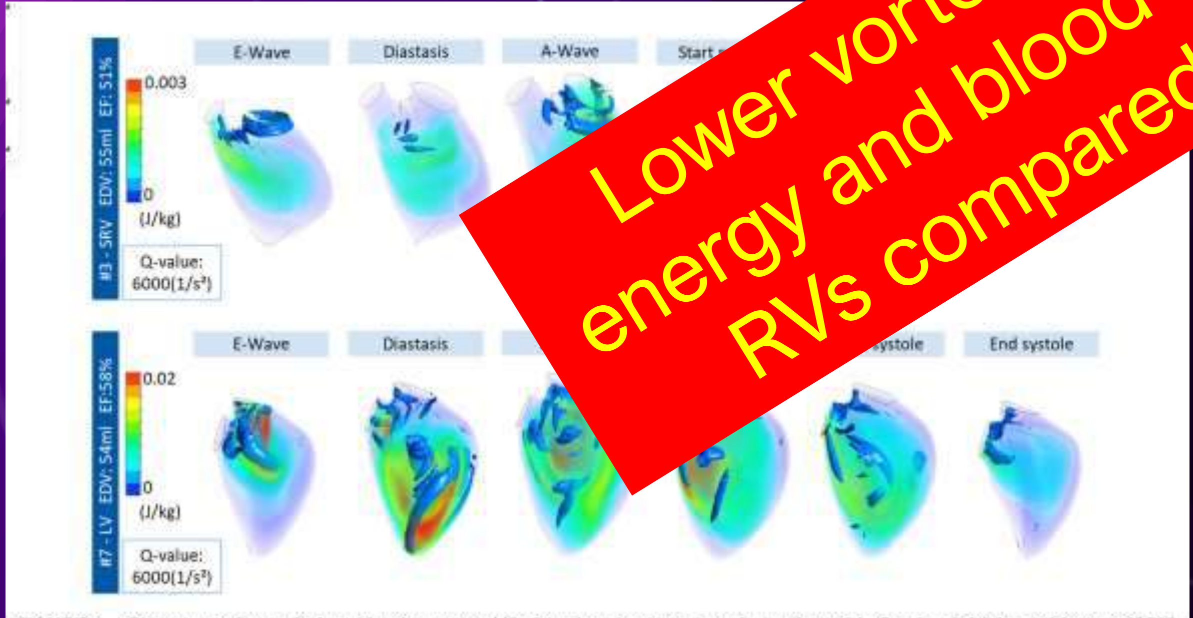


FIGURE 1. Representative turbulent kinetic energy (J/kg) and vortex structure formation with *Q*-value (1/s) for subject #3 (SRV) and subject #7 (LV). TKE represented by different scales, subject #3 max 0.003 J/kg, subject #8 max 0.02 J/kg.

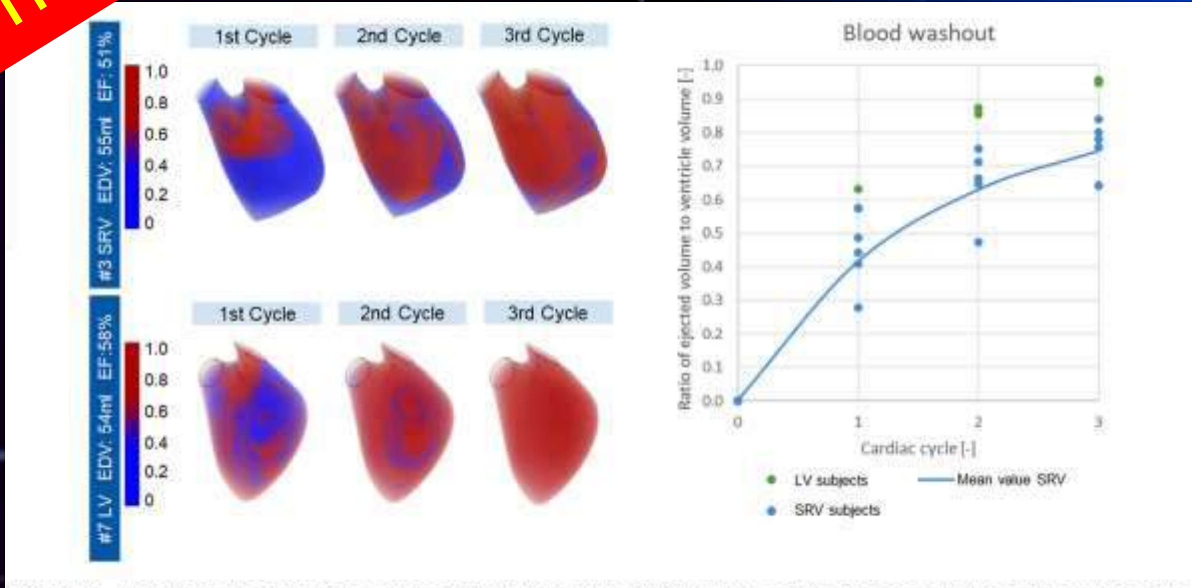


FIGURE 3. Left: Washout simulation for subject #3 (SRV) and subject #7 (LV). Time point of diastase for three cardiac cycles. Blue old blood, red new blood. Right: Volume percentage distribution of ejected volume to the total ventricle volume for SRV subjects (blue) and LV subjects (green).

RV INTRAVENTRICULAR FLOW

Intraventricular Flow Simulations in Singular Right Ventricles Reveal Deteriorated Washout and Low Vortex Formation

Cardiovascular Engineering and Technology, Vol. 13, No. 3, June 2022 (*© 2021*) pp. 495–503

Anna Grünwald,[1] Jana Korte,[1] Nadja Wilmanns,[3] Christian Winkler,[2] Katharina Linden,[2] Ulrike Herberg,[2] Sascha Groß-Hardt,[1] Ulrich Steinseifer,[1] and Michael Neidlin[1]

[1]Department of Cardiovascular Engineering, Institute of Applied Medical Engineering, Medical Faculty, RWTH Aachen University, Aachen, Germany; [2]Department of Pediatric Cardiology, University Hospital of Bonn, Bonn, Germany; and [3]Institute of General Mechanics, RWTH Aachen University, Aachen, Germany

Applied CFD to echocardiographic data to simulate flows in 5 single RV vs 2 normal LVs

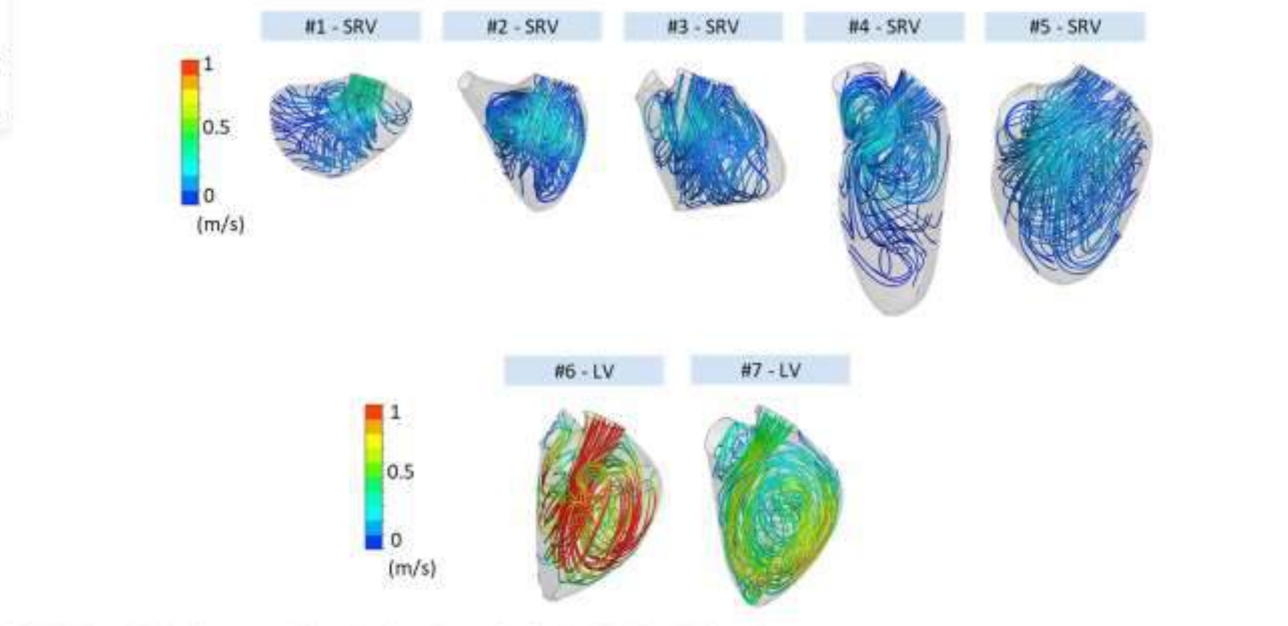


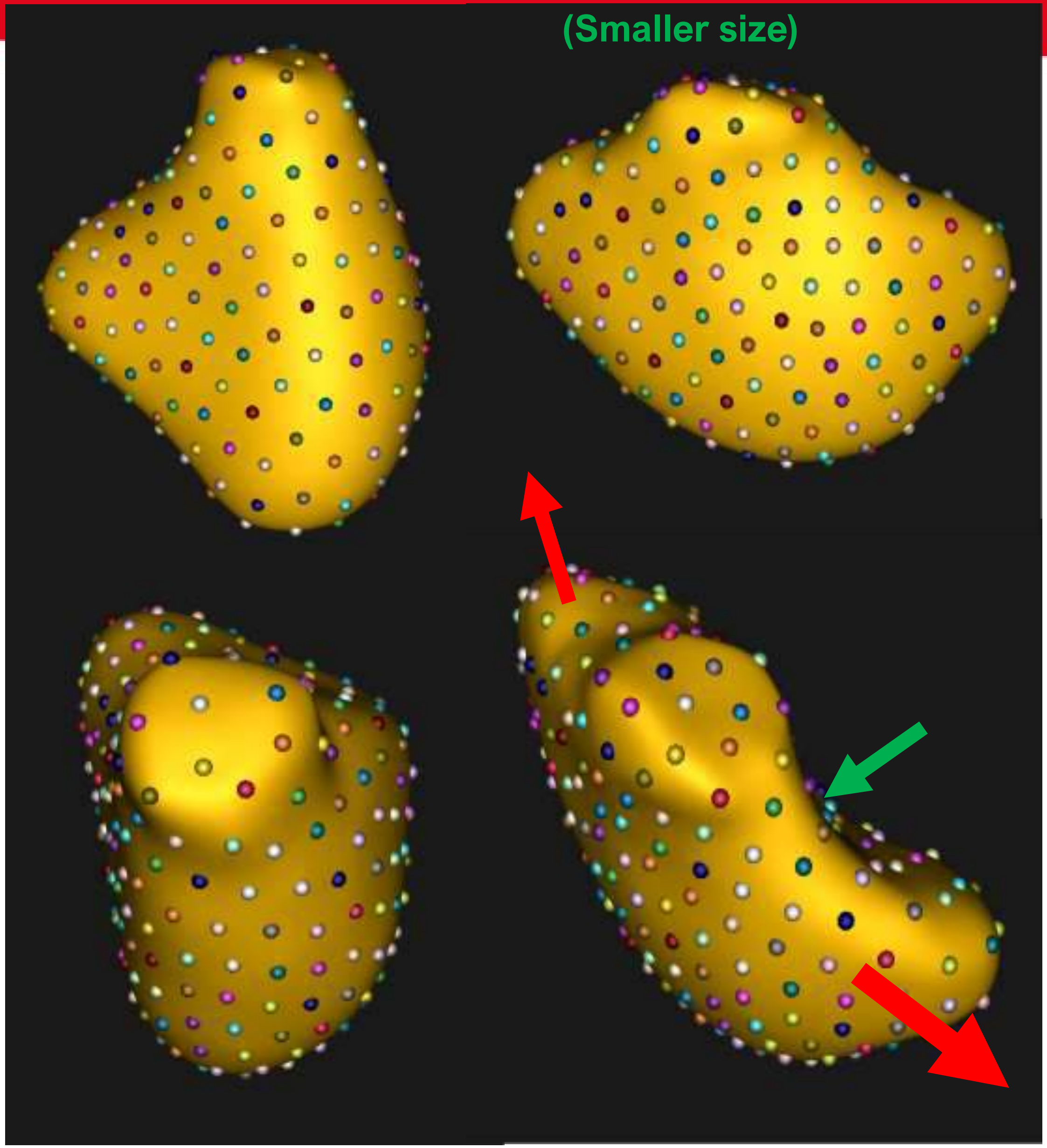
FIGURE 2. Velocity streamlines during diastasis for the SRV and LV cohorts.

Statistical Shape Modeling of HLHS (FORCE)

- Shapeworks Studio (NIH/NIGMS CIBC) to derive mean template from 329 HLHS patients

- Quantified shape variations (shape mode) representing deviation from the mean.

- Relationships between RV shape and adverse outcomes (mortality/transplant, heart failure, plastic bronchitis, protein losing enteropathy) assessed



Shape Mode	Score for SV_25
p0	-141.724
p1	64.0497
p2	22.1053
p3	-59.9196
p4	-19.135
p5	26.0906

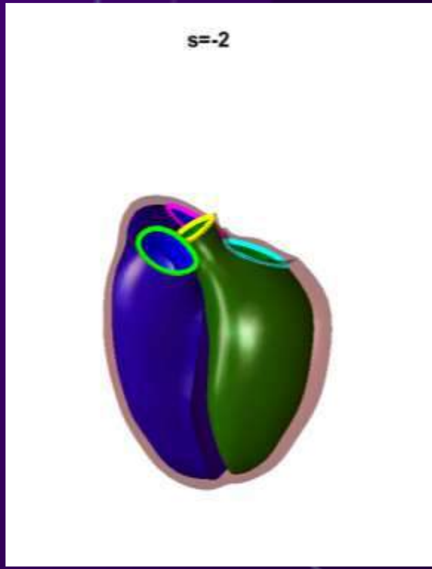
Loke et al. Shape Variations in Right Ventricular 3D Geometry are associated with adverse outcomes in Hypoplastic Left Heart Syndrome Patients: A Fontan Outcomes Registry using CMR Examination (FORCE) Study. AHA Scientific Sessions 2024 Circulation Volume 150, Number Suppl_1 https://doi.org/10.1161/circ.150.suppl_1.4114497

SSM OF THE RV

Right-left ventricular shape variations in tetralogy of Fallot: associations with pulmonary regurgitation

Charlène A. Mauger[1,2†], Sachin Govil[3†], Radomir Chabiniok[4,5,6,7], Kathleen Gilbert[2], Sanjeet Hegde[3,8], Tarique Hussain[4], Andrew D. McCulloch[3], Christopher J. Occleshaw[9], Jeffrey Omens[3], James C. Perry[3,8], Kuberan Pushparajah[10], Avan Suinesiaputra[11], Liang Zhong[12,13] and Alistair A. Young[1,10*]

J Cardiovasc Magn Reson (2021) 23:105



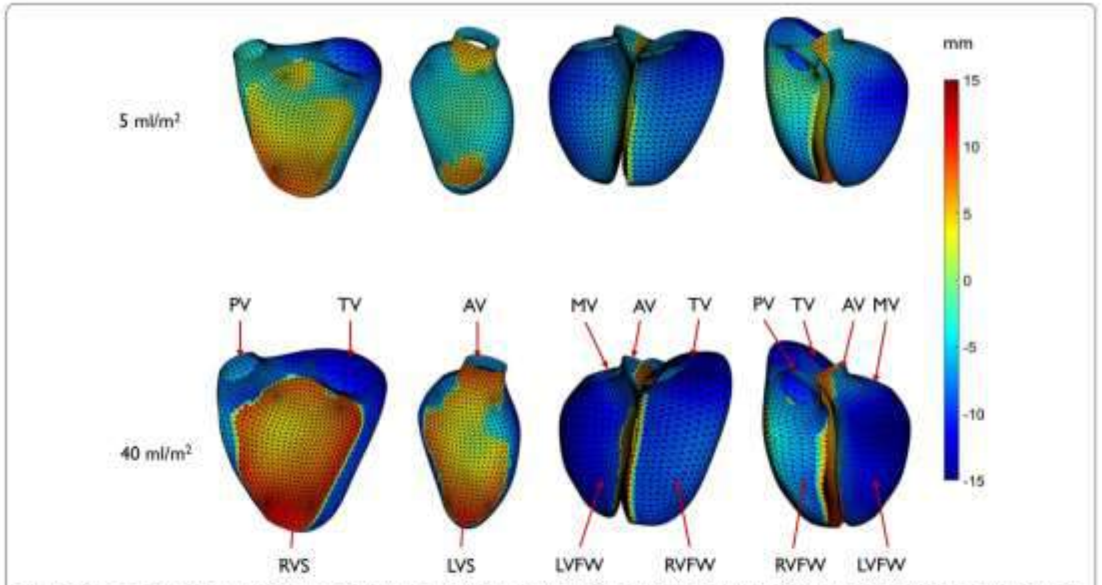


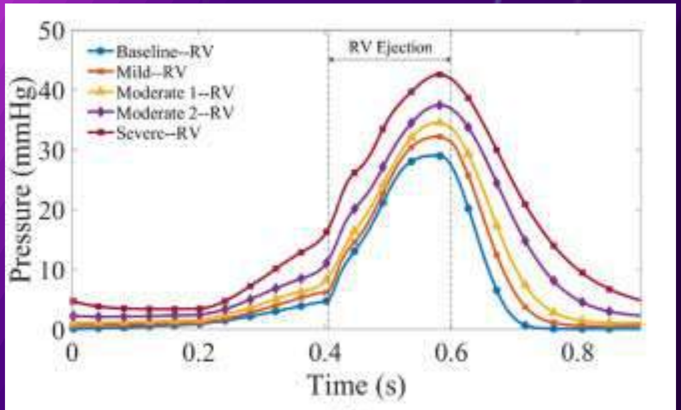
Fig. 5 Changes in contraction patterns associated with increasing pulmonary regurgitation. Paradoxical septal motion is observed as regurgitation increases, as shown by an outward displacement of the septum toward the RV. *AV* aortic valve, *PV* pulmonary valve, *TV* tricuspid valve, *MV* mitral valve, *RVFW* right ventricular free wall, *LVFW* left ventricular free wall, *RVS* right ventricular septum, *LVS* left ventricular septum

Using SSM, increasing PR: a) RV dilation b) RV basal bulging, c) decreased LV septal-lateral dimension (LV fattening) and d) paradoxical septal motion

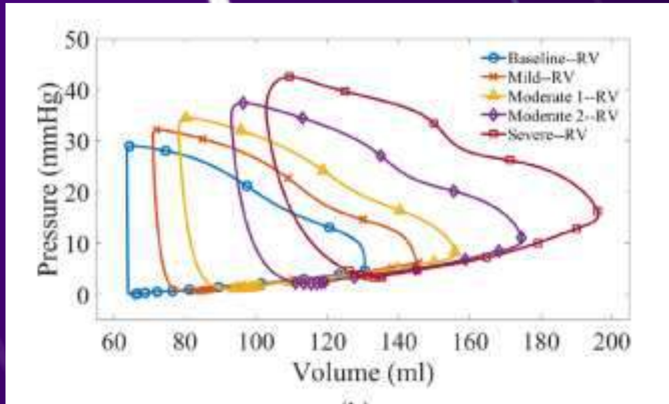
RV FINITE ELEMENT ANALYSIS (FE)

Effect of pulmonary regurgitation on cardiac functions based on a human bi-ventricle model

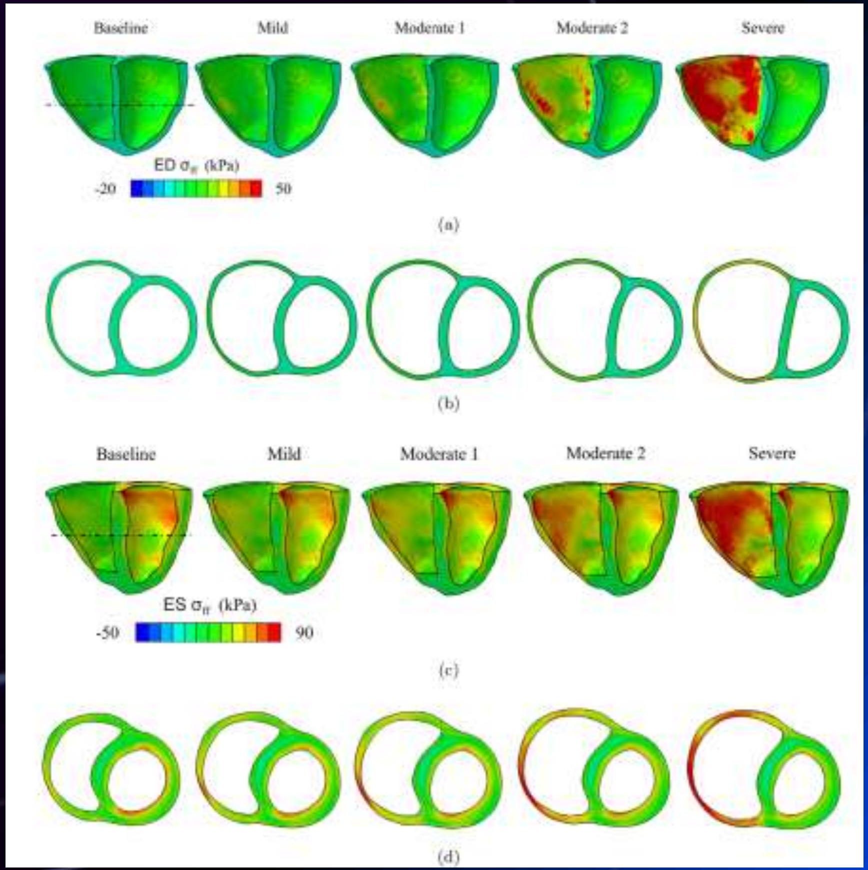
Xueqing Yin[a], Yingjie Wang[a,*] Computer Methods and Programs in Biomedicine 238 (2023) 107600



(d)



(b)

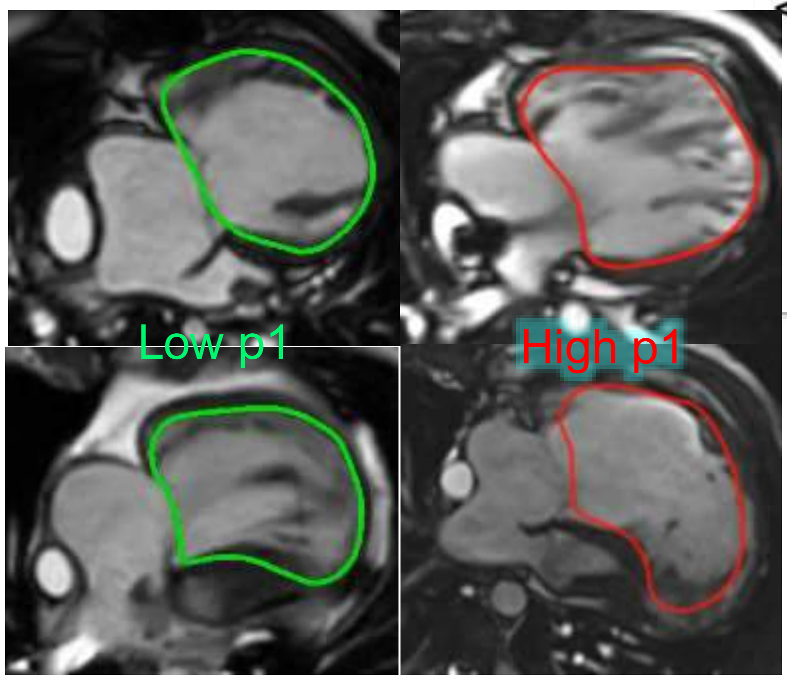


- Circumferentially dilated RV with loss of concavity in septal wall.
- p1 – apical bulge variant
- p3/p5 –crescent-shaped RV body to a spherical RV body

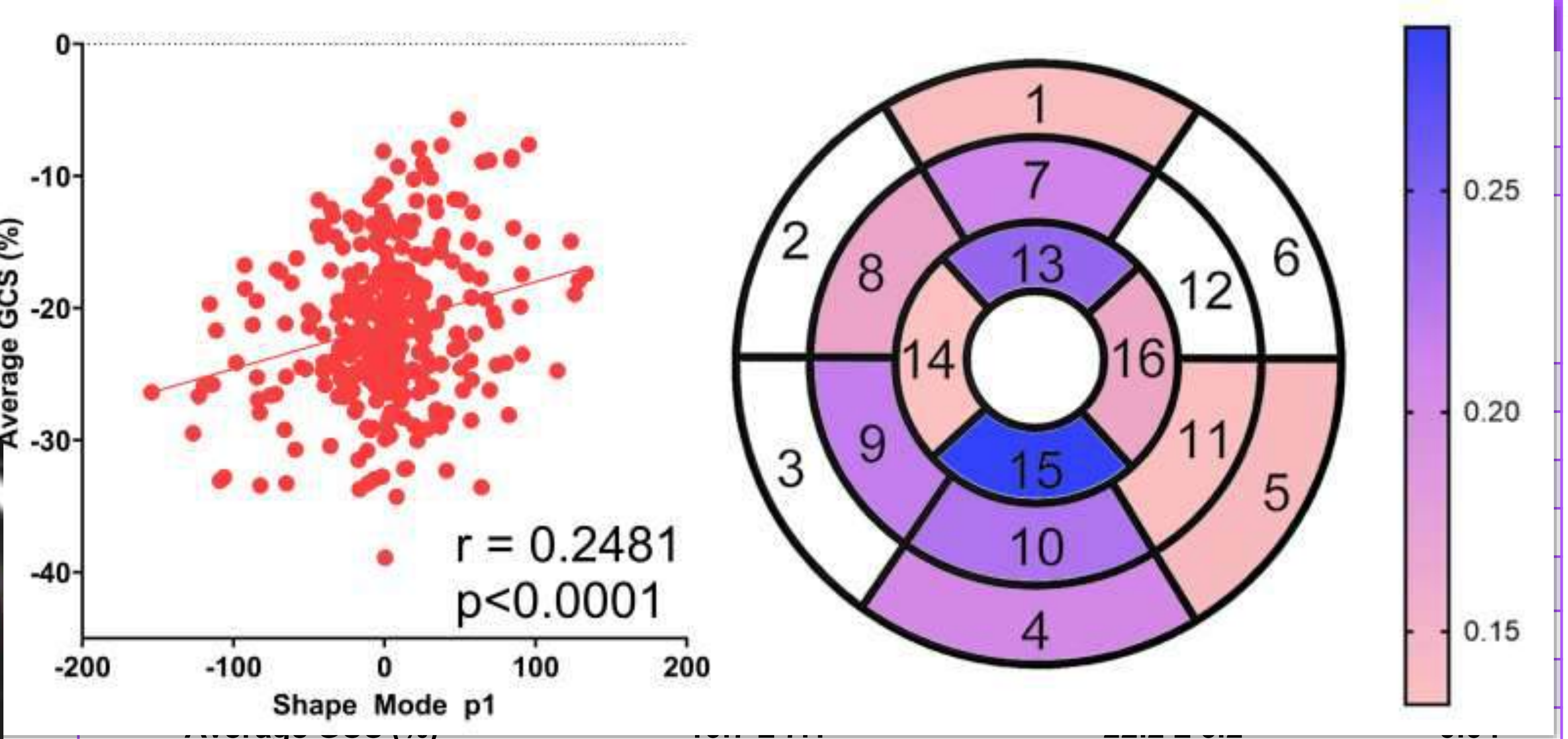
329 patients

Mean Shape Template

- Twenty-eight patients (8.5%) with mortality/heart transplant at 2.5±2.4 years after CMR.
- p1 associated with mortality/heart transplant
- Independent of size/mass; corresponded to reduced GCS (inferior and apical segments).



Bivariable Analysis	Mortality/Transplant (n = 28)	No Mortality/Transplant (n = 300)	p-value
Presence of ≥ Moderate TR	8 (29%)	49 (16%)	0.08

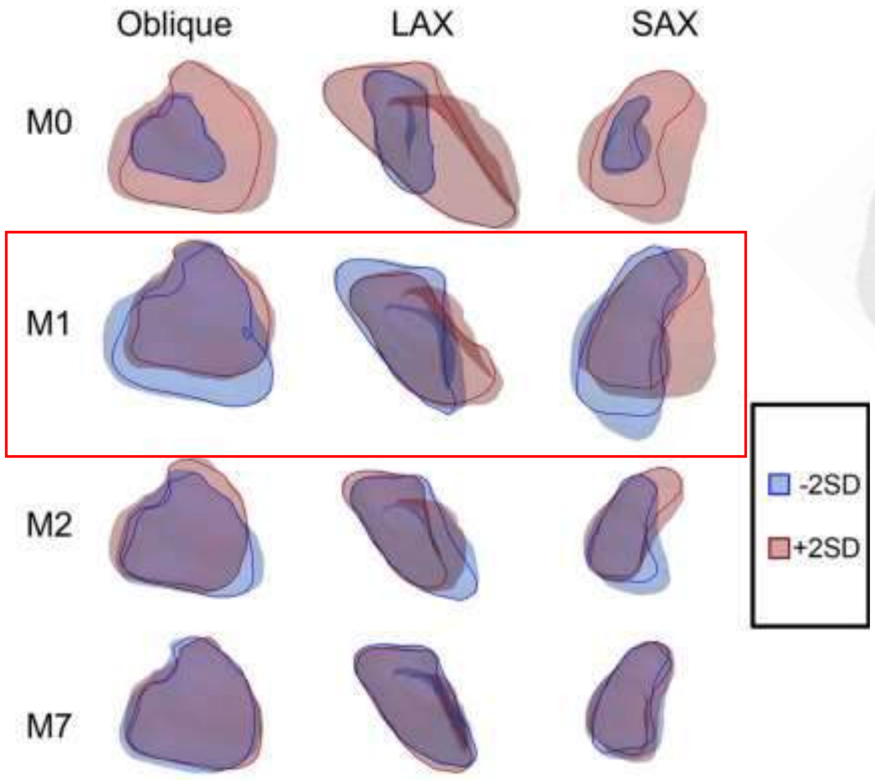


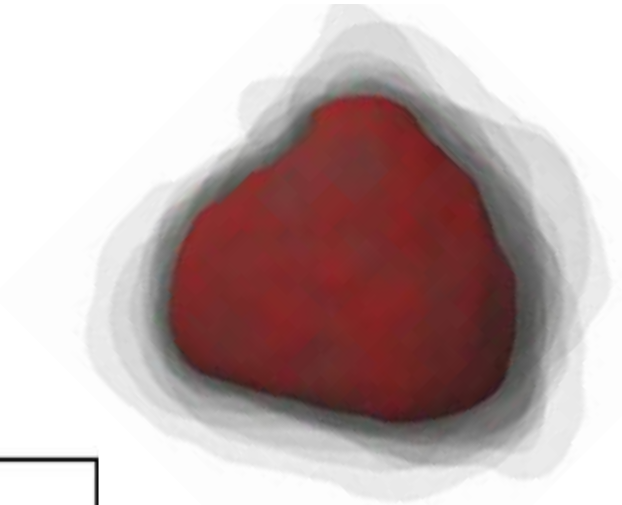
Multivariable Analysis	Odds Ratio	(95% CI) 2.5 % 97.5 %	p-value
Shape Mode p1*	2.67	1.44, 10.67	<0.01
RV Mass$_i$ (gm/m^2)	1.025	1.005, 1.041	0.01

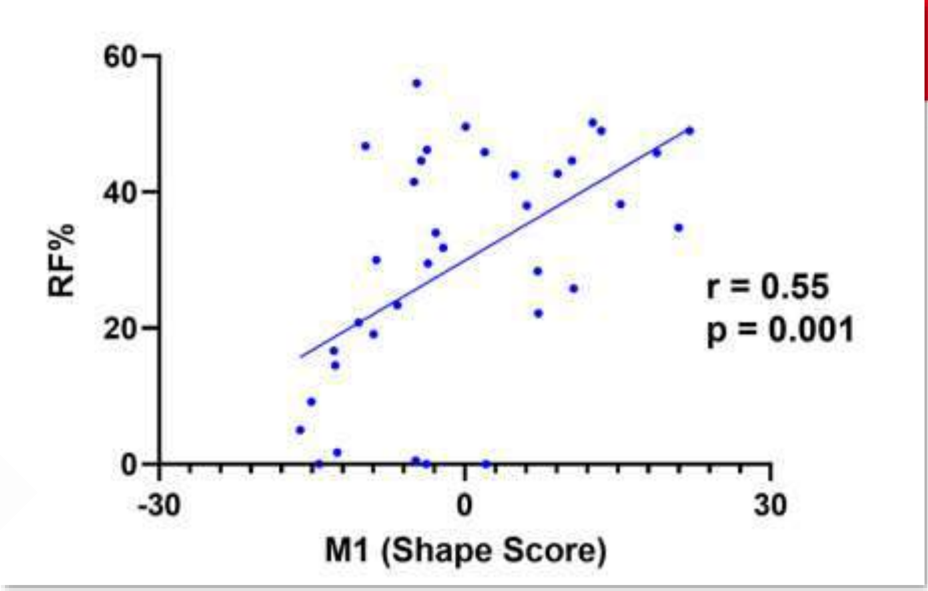
american physiological society
AMERICAN JOURNAL OF PHYSIOLOGY
HEART AND CIRCULATORY PHYSIOLOGY
Am J Physiol Heart Circ Physiol 323: H449–H460, 2022.
First published July 15, 2022; doi:10.1152/ajpheart.00228.2022

RESEARCH ARTICLE

Statistical Shape Modeling Reveals the link between RV shape, hemodynamic force, and myocardial function in patients with rTOF







Shape mode M1 – related to PI and alterations in intraventricular forces; apical bulge and enlargement of RVOT diameter

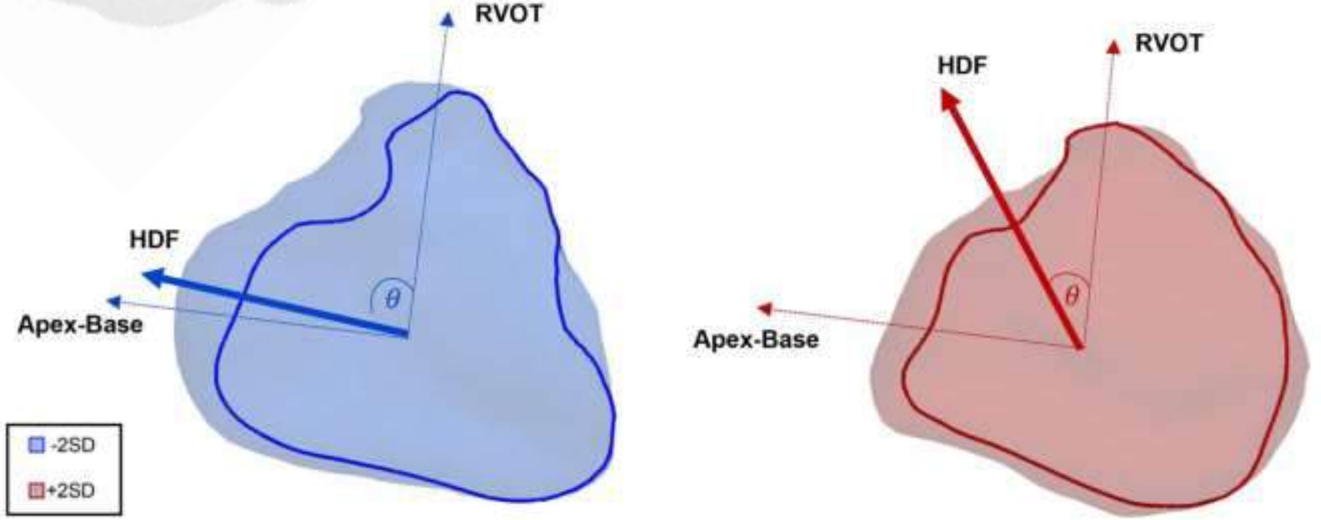
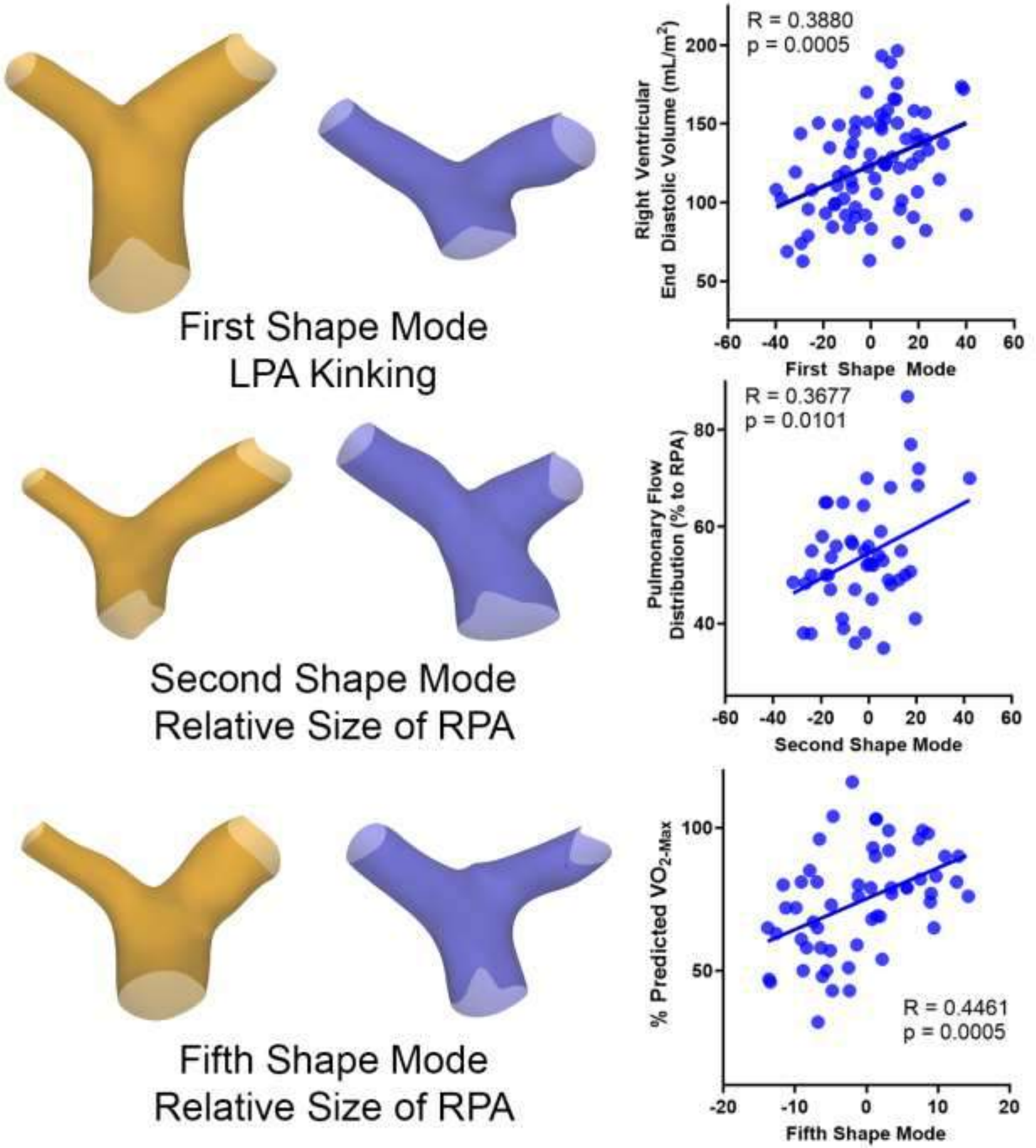


Figure 8. Outline of right ventricle (RV) in the oblique/frontal view. Blue outline denotes −2SD from the template shape and red outline denotes +2SD toward the shape variation of interest. An increased propensity toward *M1* (red) is associated with a more acute angle between the direction of the total force vector (hemodynamic force, HDF) and the right ventricular outflow tract (RVOT) axis. There is increased contribution of the RVOT force to the overall HDF as the two vectors become more parallel to each other (red).

Pulmonary artery shape variations in repaired Tetralogy of Fallot

Mean template of pulmonary arteries (n = 103)



*Unpublished. To be presented at ACC 2025

STATISTICAL SHAPE MODELING (SSM)

Figure 1: the shape variation represented by the first principal component of the hand model, where the hand on the left shows a deformation with $\hat{\alpha}_1 = -3$, the middle hand shows the mean deformation ($\hat{\alpha}_1 = 0$) and the hand on the right the deformation with $\hat{\alpha}_1 = 3$.