Computational Modeling, 3D Printing and Artificial Intelligence

Case Planning for Trans-catheter Mitral Valve Replacement

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Disclosures

Siemens – Speakers Honorarium, Research Support

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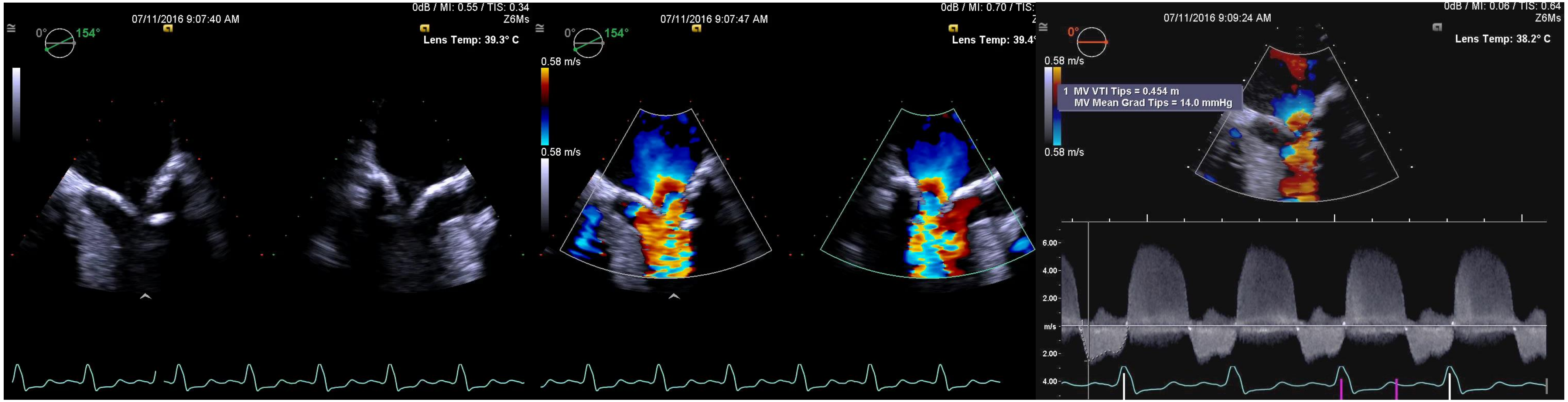
Pre-Procedural 2D TEE

83 yo, Female, Severe MR, MS, Severe MAC, Sigmoid septum, TMVR for MS/MR



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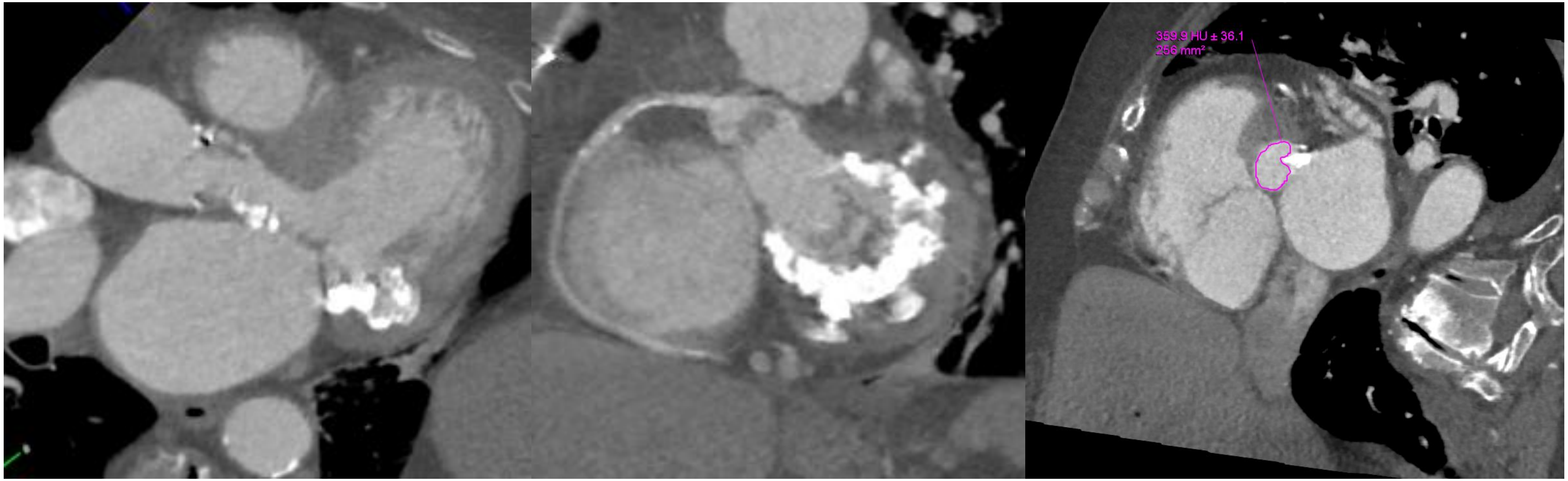
Pre-Procedural CT

Severe MAC, Sigmoid septum, High risk of post-TMVR LVOT obstruction



Case Planning Workflow for TMVR

3D Imaging → **3D Modeling** → **Selection of Printing Materials** → **Selection of 3D Printing Technique** → **Benchtop Testing**

3D Imaging

- 3D Echo;
- 3D CT;
- 3D MRI

3D Modeling

MV annulus;
MV leaflets;
MV vicinity
- LV;
- LA;
- Chordae;
- Papillary muscles

Cardiac phase

Selection of Printing Materials

Multi-material
- Soft;
- Rigid, Meta-material
- Strain-stiffening;
- Anisotropic

Selection of 3D Printing Technique

Considerations
- Materials
- Printing speed
- Cost

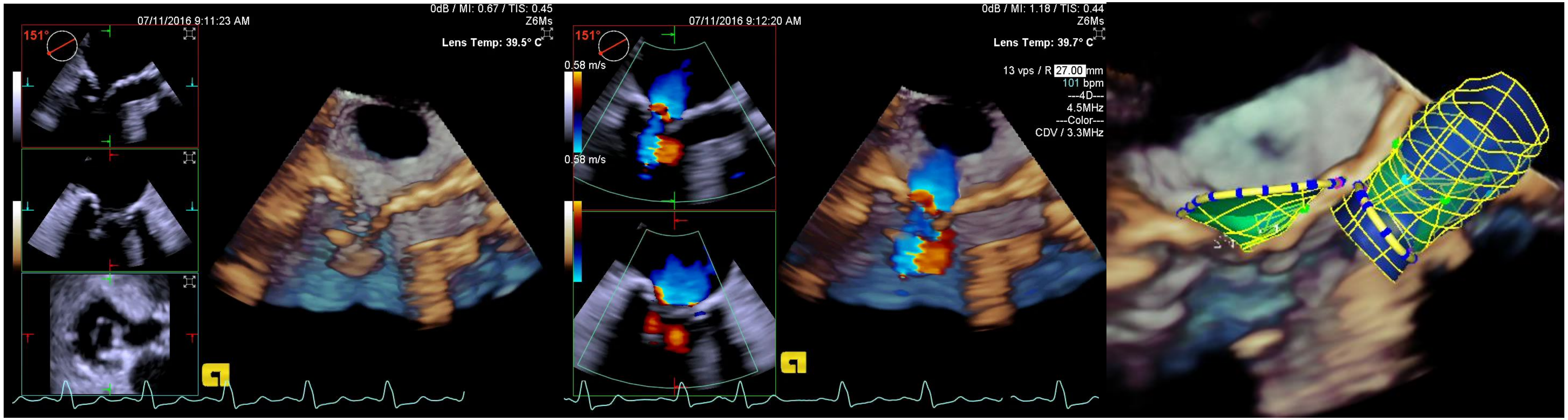
Benchtop Testing

- TMVR
- MitraClip
- Annuloplasty
- Perforation repair

Qualitative
Quantitative

Pre-Procedural 3D TEE

- Real-Time 3D Color Flow Doppler and Automated Modeling of the MV , LVOT and Aortic Root



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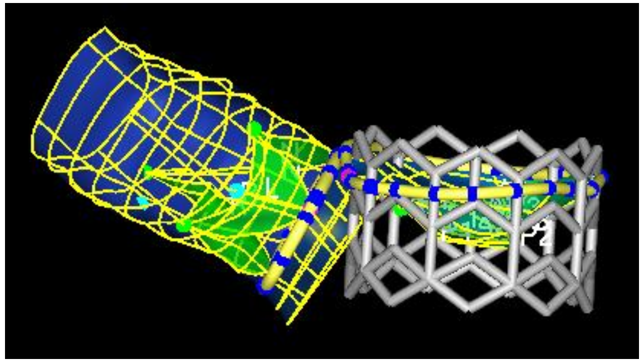
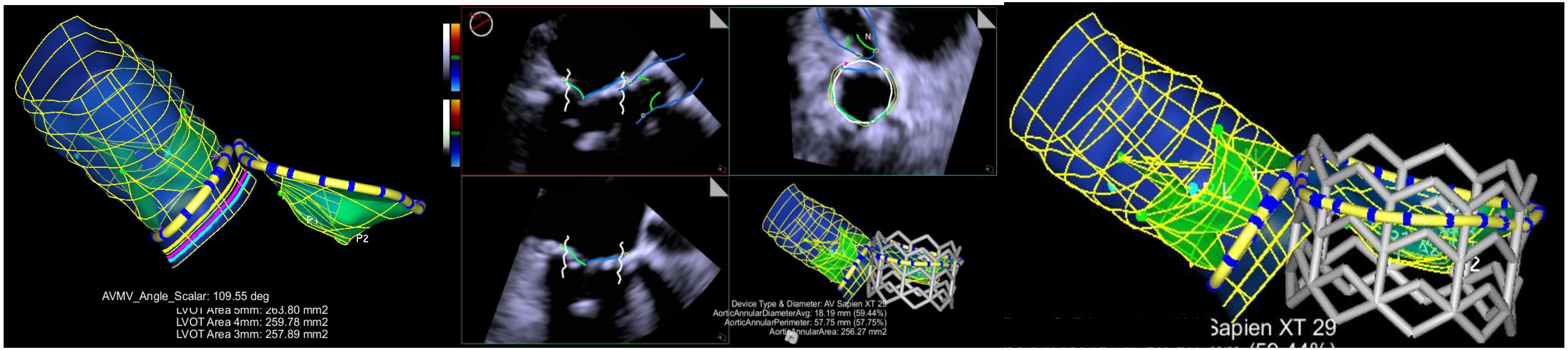
Computational Modeling of TMVR - Echo

- Valve model overlaid to the heart model
- <u>Limitations:</u>
  - Visual assessment
  - No physical interaction between the valve and the heart





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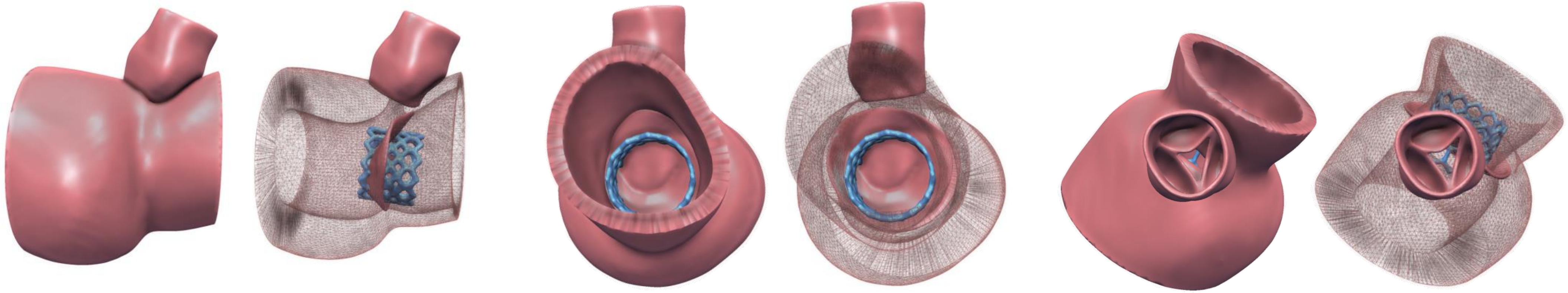
Computational Modeling of TMVR - Echo

Systolic phase: LVOT assessment

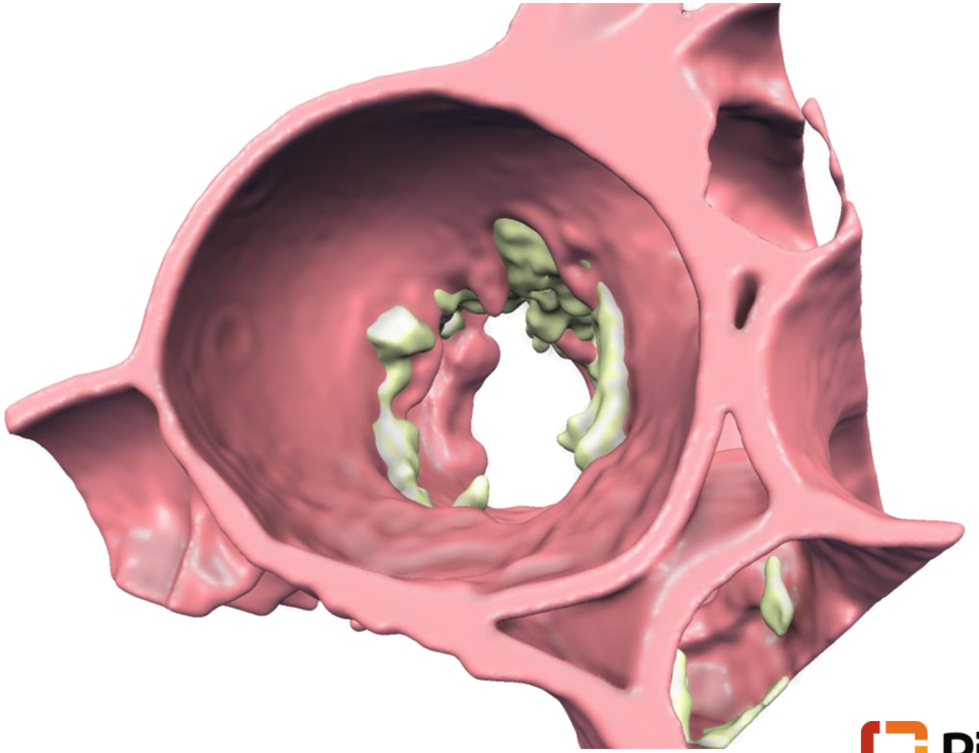
Limitations:

- Incomplete / less detailed LV LA boundaries
  - Image fusion with 3D TTE
  - Prone to registration error
- Calcium is not well visualized



3D CT Modeling of the MV/LVOT

- 3D segmentation and modeling of the soft tissue and calcification in the heart



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Computational Modeling of TMVR - CT

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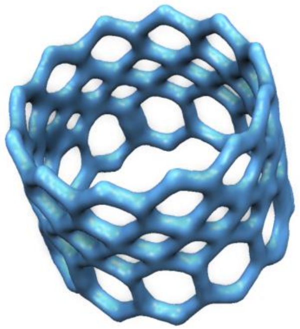
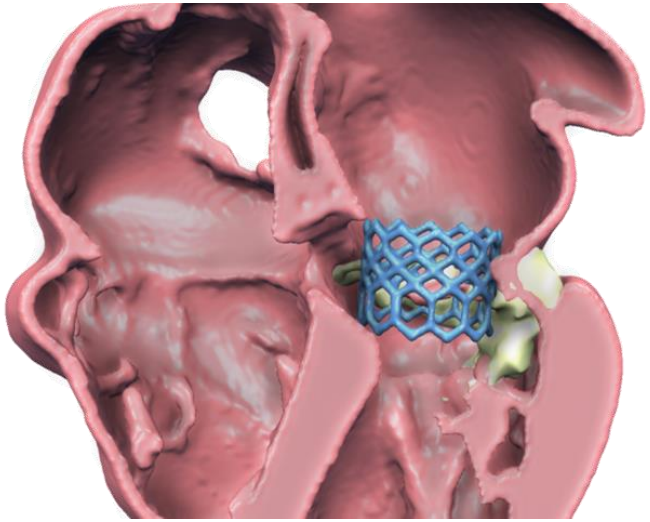
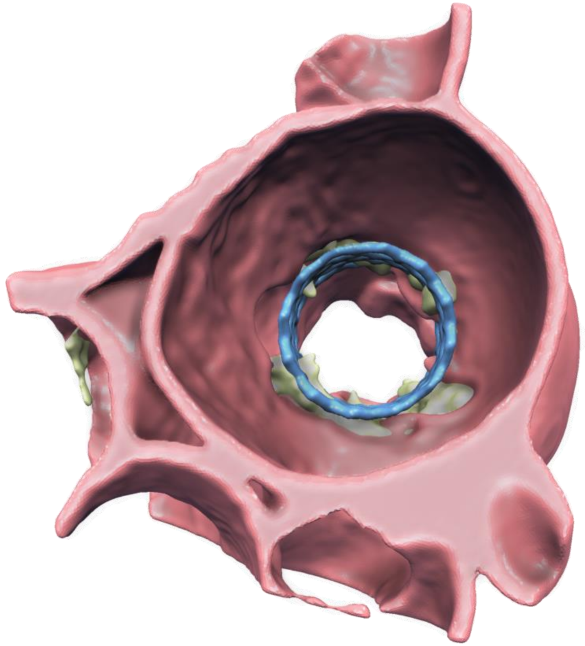


Sapien
29mm





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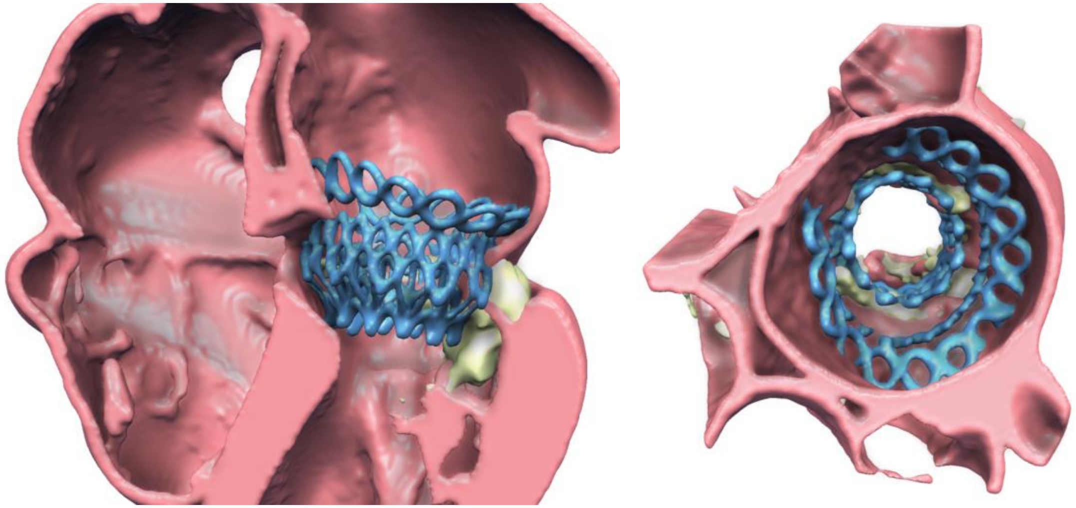
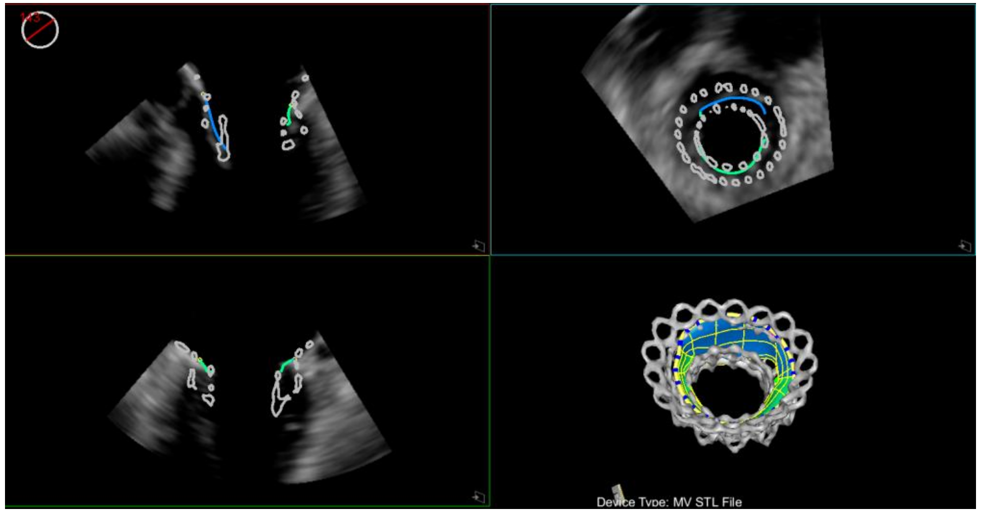
Computational Modeling of TMVR - CT/Echo

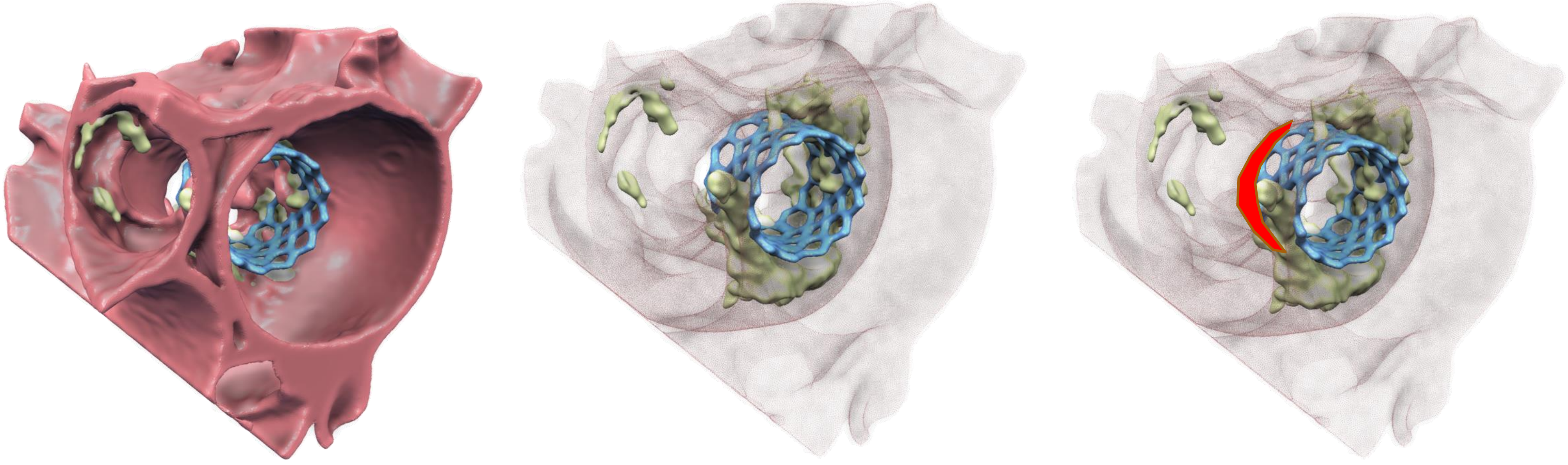
- MAC and Non MAC MR





Computational Modeling of TMVR - CT

- Neo-LVOT Assessment
  - Deployment depth and angle are hypothetical



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3D Printing for TMVR Planning

- Assess how the prosthetic valve fits the native MV annulus
  - Deformations of prosthetic valve, the native soft tissues and MAC
  - Assess the risk of PVL
  - Select the optimal valve type / size
- Assess Neo-LVOT
  - Deployment depth and angle are tested in vitro

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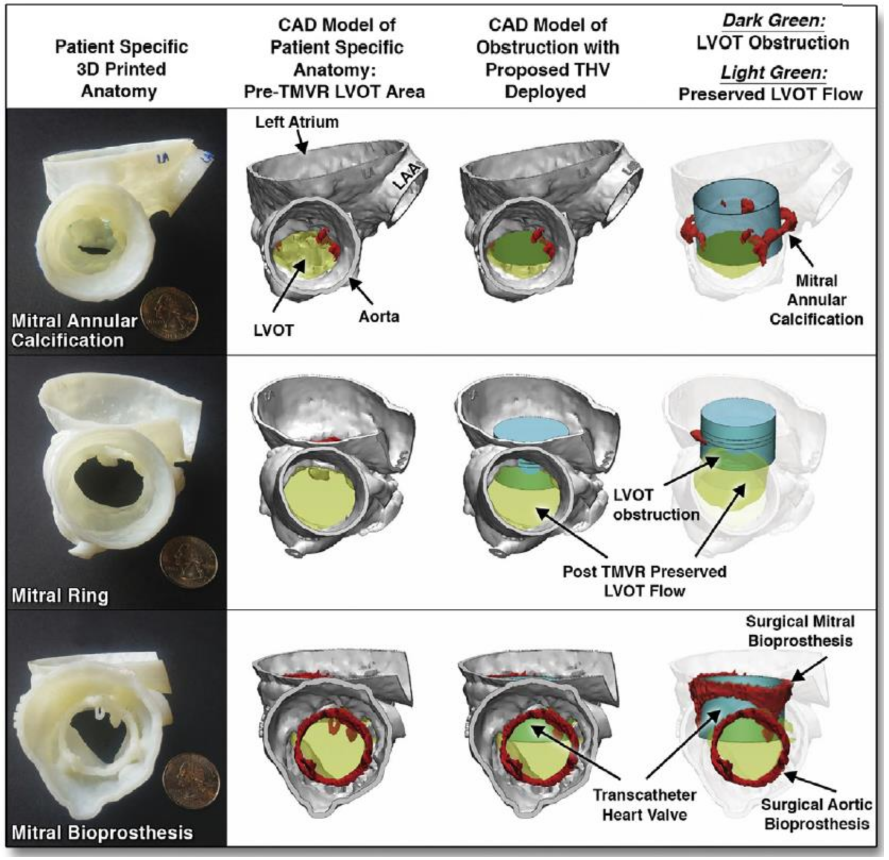
3D Printing for TMVR – Current State

Workflow

- Imaging: 3D CT
- 3D modeling: MV annulus and vicinity
- Printing materials: rigid plastic
- Printing technique: Fused Deposition Modeling

TMVR Planning

- Better visualization of pathology
- Benchtop simulation
- Neo-LVOT assessment on a physical model



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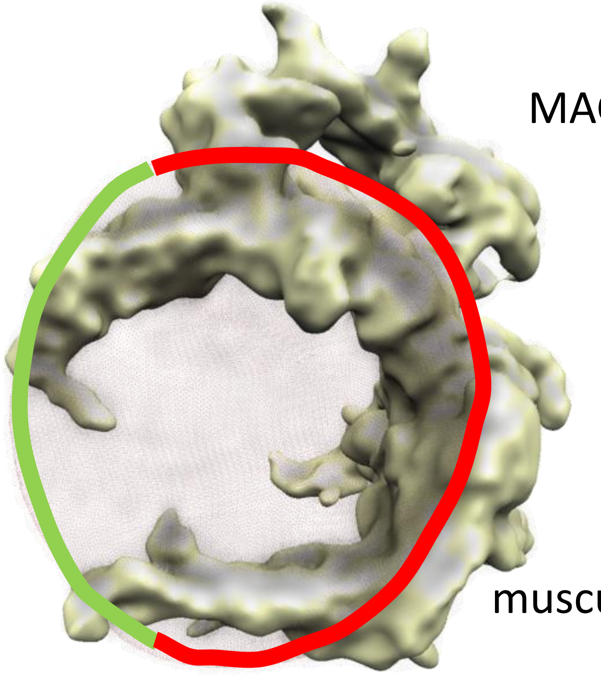
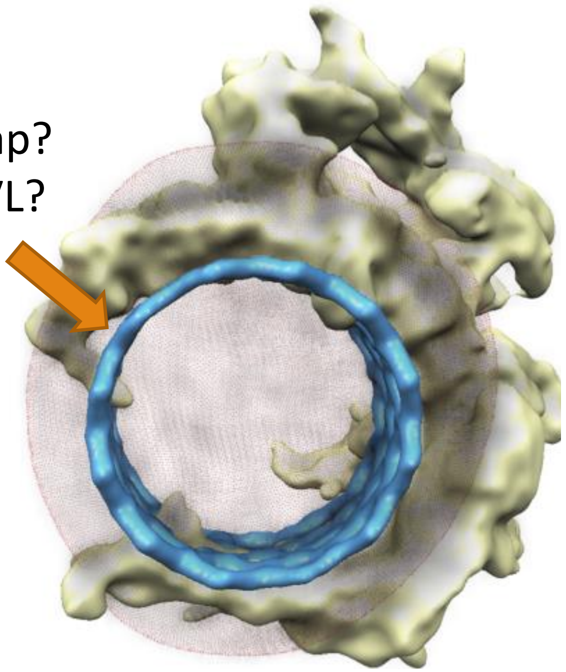
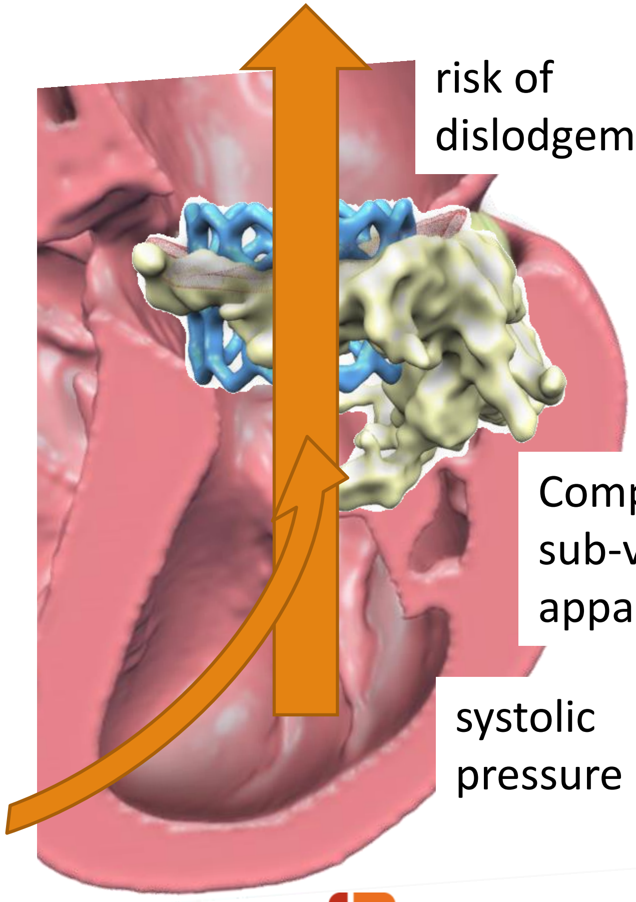
Challenges in 3D Printing for TMVR







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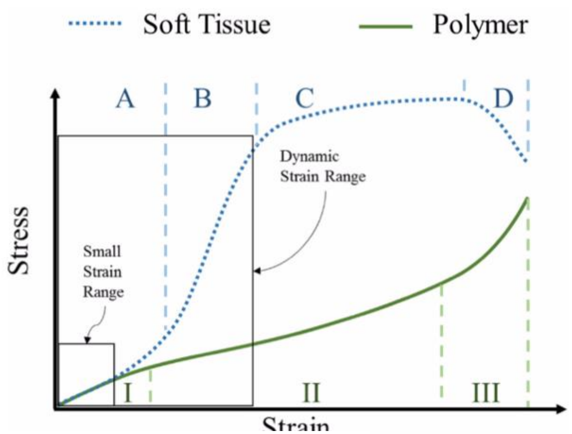
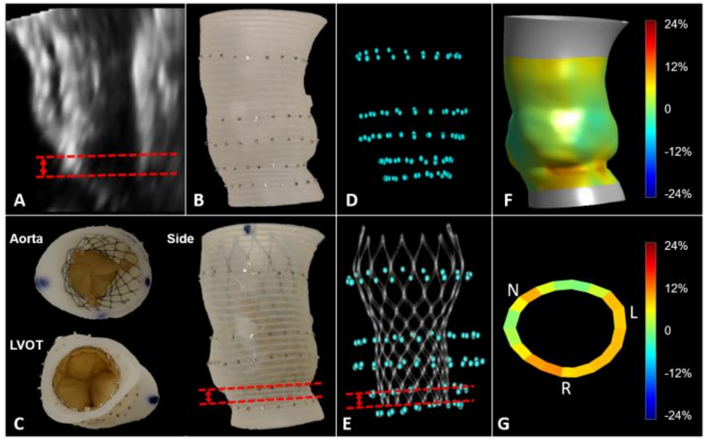
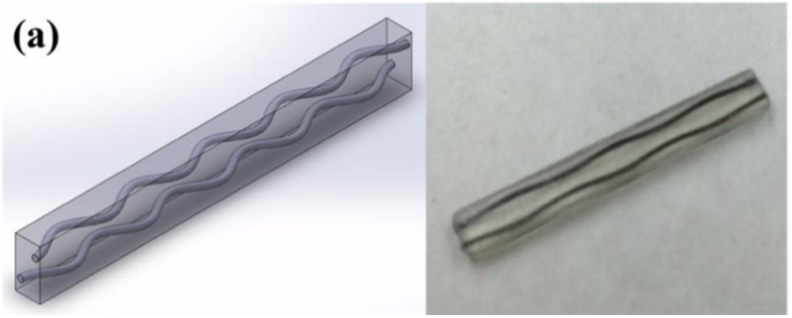
‘Smart” 3D Printing

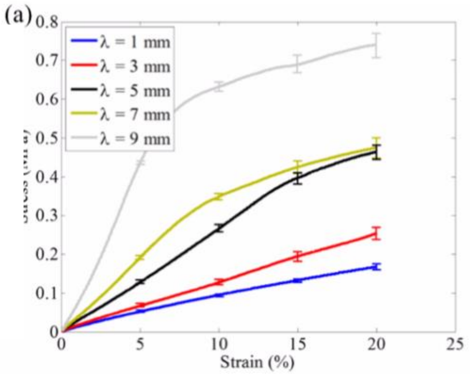
Meta-materials

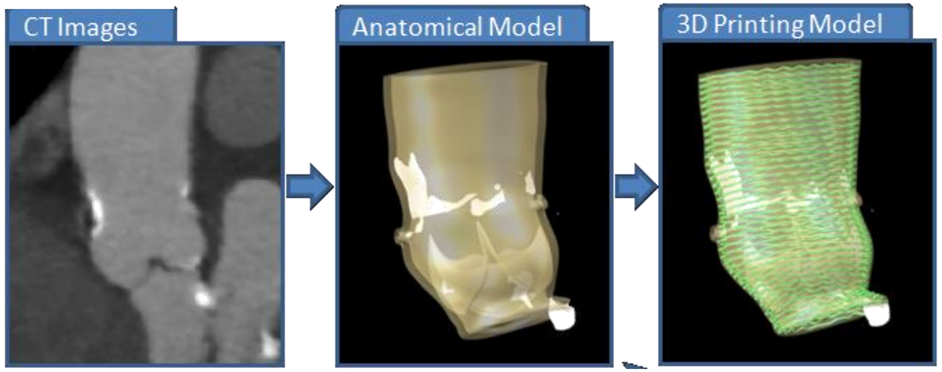
- Embedding tunable reinforcement fibers
- Strain-stiffening nonlinear property
- Controllable anisotropy











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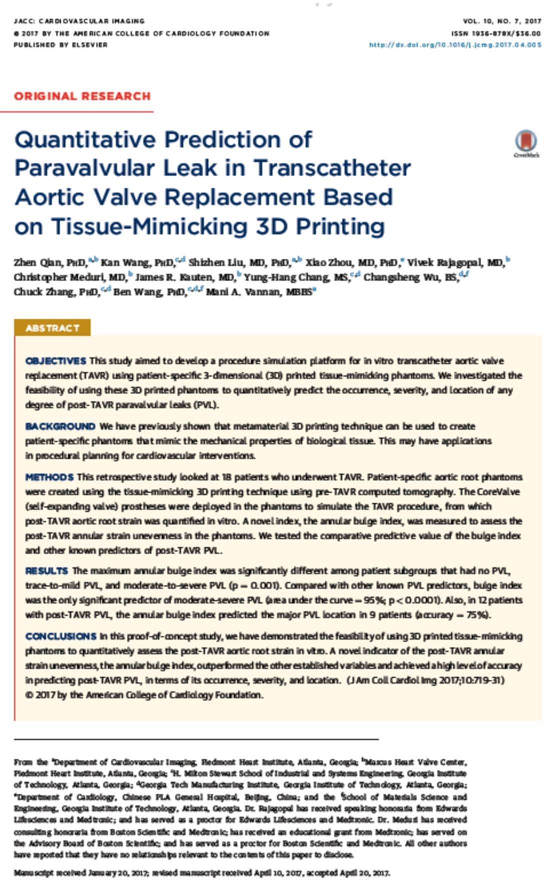
- Wang K., Wu C., Qian Z., et al. Dual-material 3D printed metamaterials with tunable mechanical properties for patient-specific tissue-mimicking phantoms. Additive Manufacturing 2016;12:31–7.

‘Smart” 3D Printing for Planning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ORIGINAL RESEARCH

Quantitative Prediction of Paravalvular Leak in Transcatheter Aortic Valve Replacement Based on Tissue-Mimicking 3D Printing

Zhen Qian, PhD,[a,b] Kan Wang, PhD,[c,d] Shizhen Liu, MD, PhD,[a,b] Xiao Zhou, MD, PhD,[e] Vivek Rajagopal, MD,[b] Christopher Meduri, MD,[b] James R. Kauten, MD,[b] Yung-Hang Chang, MS,[c,d] Changsheng Wu, BS,[d,f] Chuck Zhang, PhD,[c,d] Ben Wang, PhD,[c,d,f] Mani A. Vannan, MBBS[a]

ABSTRACT

OBJECTIVES This study aimed to develop a procedure simulation platform for in vitro transcatheter aortic valve replacement (TAVR) using patient-specific 3-dimensional (3D) printed tissue-mimicking phantoms. We investigated the feasibility of using these 3D printed phantoms to quantitatively predict the occurrence, severity, and location of any degree of post-TAVR paravalvular leaks (PVL).

BACKGROUND We have previously shown that metamaterial 3D printing technique can be used to create patient-specific phantoms that mimic the mechanical properties of biological tissue. This may have applications in procedural planning for cardiovascular interventions.

METHODS This retrospective study looked at 18 patients who underwent TAVR. Patient-specific aortic root phantoms were created using the tissue-mimicking 3D printing technique using pre-TAVR computed tomography. The CoreValve (self-expanding valve) prostheses were deployed in the phantoms to simulate the TAVR procedure, from which post-TAVR aortic root strain was quantified in vitro. A novel index, the annular bulge index, was measured to assess the post-TAVR annular strain unevenness in the phantoms. We tested the comparative predictive value of the bulge index and other known predictors of post-TAVR PVL.

RESULTS The maximum annular bulge index was significantly different among patient subgroups that had no PVL, trace-to-mild PVL, and moderate-to-severe PVL ($p = 0.001$). Compared with other known PVL predictors, bulge index was the only significant predictor of moderate-severe PVL (area under the curve = 95%; $p < 0.0001$). Also, in 12 patients with post-TAVR PVL, the annular bulge index predicted the major PVL location in 9 patients (accuracy = 75%).

CONCLUSIONS In this proof-of-concept study, we have demonstrated the feasibility of using 3D printed tissue-mimicking phantoms to quantitatively assess the post-TAVR aortic root strain in vitro. A novel indicator of the post-TAVR annular strain unevenness, the annular bulge index, outperformed the other established variables and achieved a high level of accuracy in predicting post-TAVR PVL, in terms of its occurrence, severity, and location. (J Am Coll Cardiol Img 2017;10:719–31)
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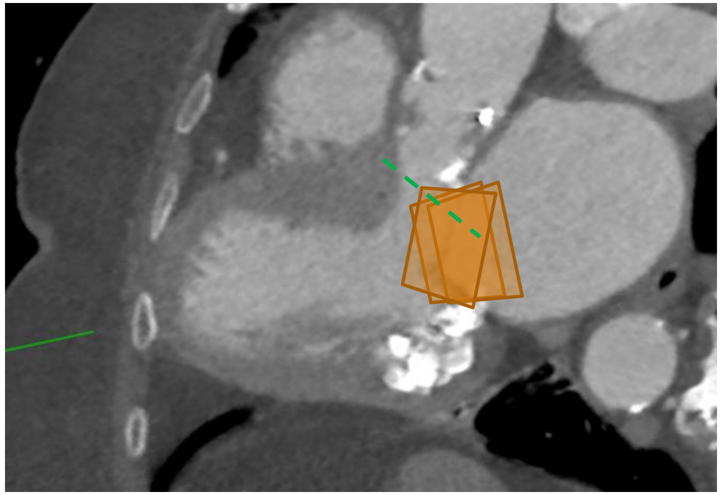
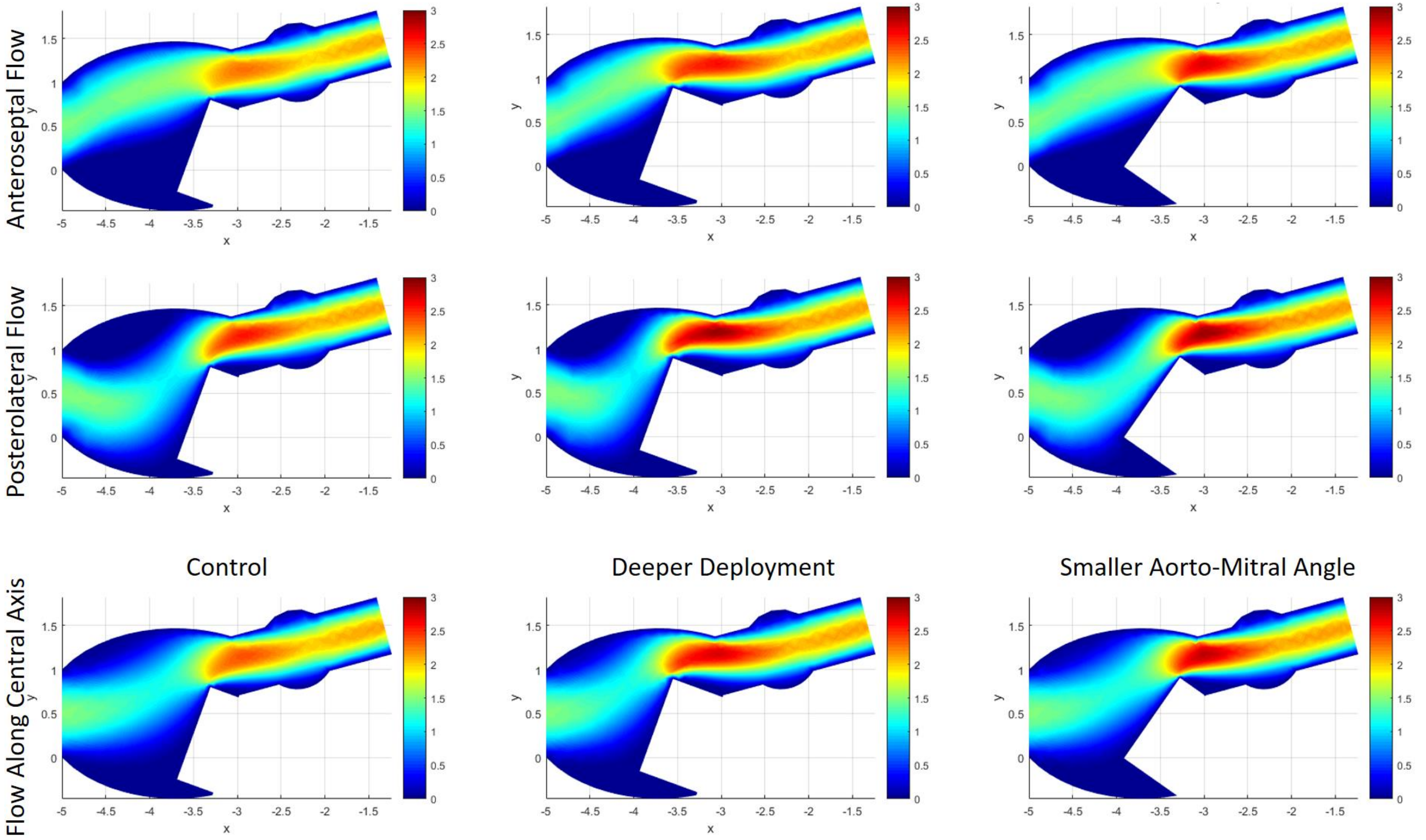
Computational Flow Modeling

- LVOT (flow) obstruction
  - Depth and angle
  - Neo-LVOT
  - Intra-ventricular Flow





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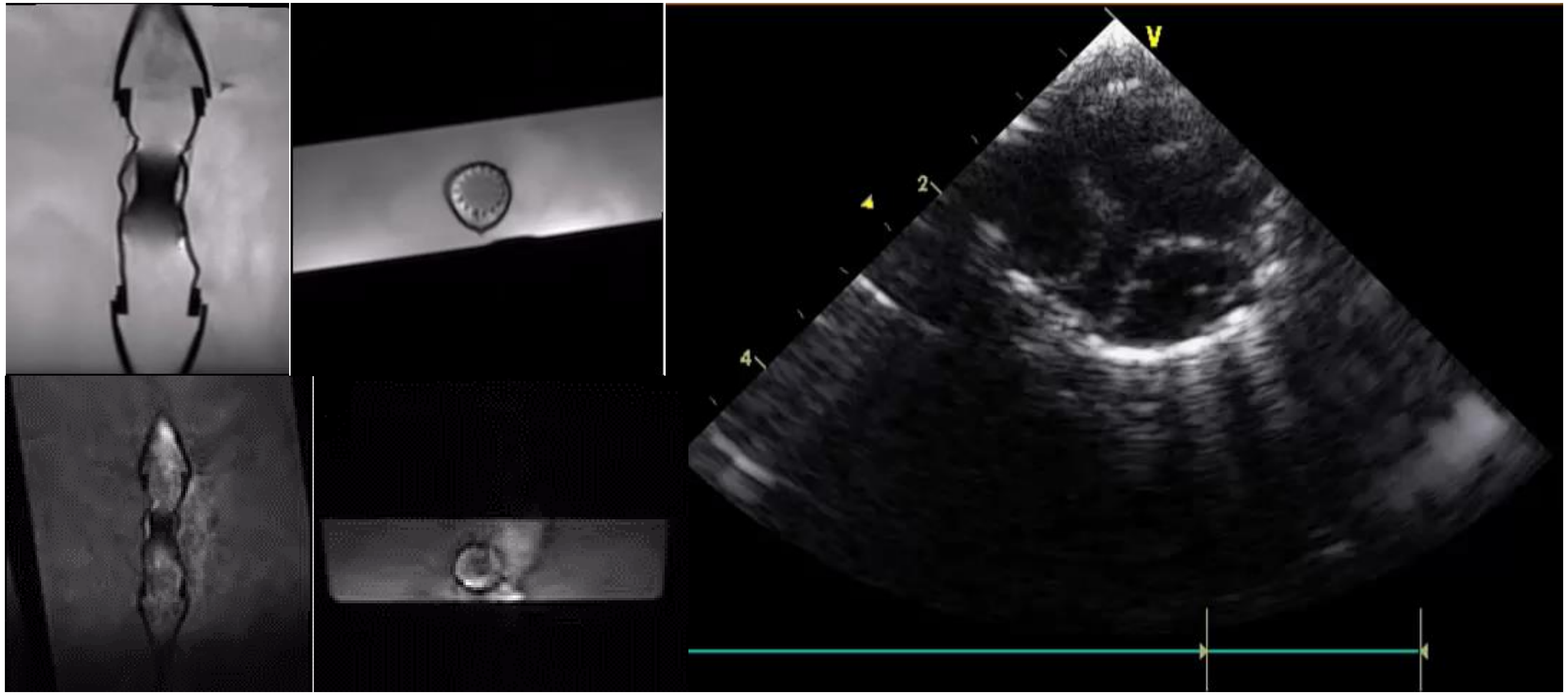
Flow in Smart 3D Printed Models

- 3D flow imaging provides a tool for a better understanding of the complex interactions between the blood flow, the native aortic root, and the TAVR valve.



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3D Printing for SHD - Prerequisites

- High quality imaging
  - Preferably a modern fast ≥64MDCT CT scanner
  - Designated imaging protocols for MV 3DP
- A 3D image processing and modeling specialist / lab
  - Preferably with a clinical background
  - Good communication with the clinical team
- A 3D printing lab
  - Preferably a multi-material PolyJet printer using both rigid and flexible materials
    - Printer price: $100,000 – 300,000
    - Maintenance: NOT cheap
  - Lower options: FDM / Binder Jetting printers using rigid material
    - Printer price: $500-50,000
  - Outsourcing is a good option

Hospital

Hospital, or
academic collaborator

Hospital, or
academic collaborator, or
outsourcing

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3D Printing for SHD - Challenges

- Limitations in printing technique
  - Limited printing resolution
    - PolyJet: up to 16-100 micron
  - 3D printed touching surfaces are not separable
    - Co-apted leaflets are fused
    - Difficult to reproduce certain pathologies
- Lengthy turnaround time
  - Hours to days
- Cost
  - Printing cost $100-1000 per item

Artificial Intelligence in Interventional SHD Planning

Prediction of Paravalvular Leak Post Transcatheter Aortic Valve Replacement Using a Convolutional Neural Network

Zih Huei Wang[1,2,3], Geet Lahoti[1,4], Kan Wang[1,4], Shizhen Liu[2], Chuck Zhang[1,4], Ben Wang[1,4,5], Chien-Wei Wu[3], Mani Vannan[2], Zhen Qian[2]

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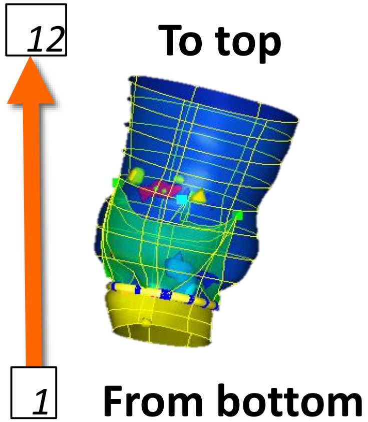
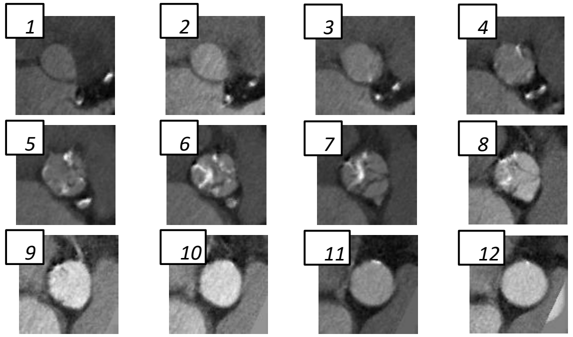
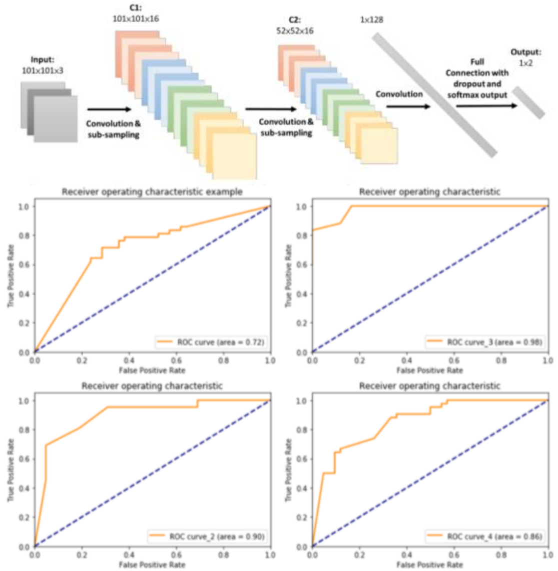
[3]Department of Industrial Engineering and Engineering Management, National Tsing Hua University
[4]H. Milton Stewart School of Industrial and Systems Engineering, Georgia Tech,
[5]School of Materials Science and Engineering, Georgia Tech







K-fold CV	Test accuracy	Sensitivity	Specificity
1	71.43%	67.65%	87.50%
2	80.95%	77.14%	100%
3	88.10%	87.18%	100%
4	73.81%	75.68%	60.00%
Average	78.57%	76.91%	86.88%

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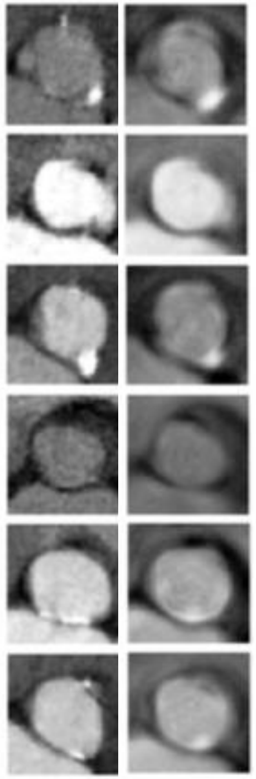
Artificial Intelligence in Interventional SHD Planning

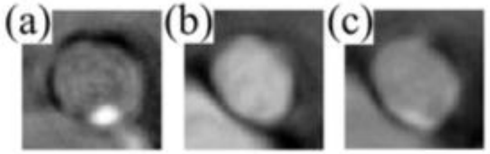
Generative Invertible Networks (GIN): Pathophysiology-Interpretable Feature Mapping and Virtual Patient Generation

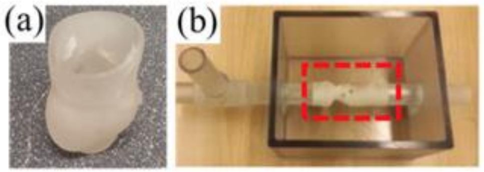
Paper ID: 442

Abstract. Machine learning methods play increasingly important roles in pre-procedural planning for complex surgeries and interventions. Very often, however, researchers find the historical records of emerging surgical techniques, such as the transcatheter aortic valve replacement (TAVR), are highly scarce in quantity. In this paper, we address this challenge by proposing novel generative invertible networks (GIN) to select features and generate high-quality *virtual patients* that may potentially serve as an additional data source for machine learning. Combining a convolutional neural network (CNN) and generative adversarial networks (GAN), GIN discovers the pathophysiologic meaning of the feature space. Moreover, a test of predicting the surgical outcome directly using the selected features results in a high accuracy of 81.55%, which suggests little pathophysiologic information has been lost while conducting the feature selection. This demonstrates GIN can generate virtual patients not only visually authentic but also pathophysiologic interpretable.

Keywords: Virtual patients, Generative neural networks







K-fold CV	Accuracy	Sensitivity	Specificity
1	80.95%	75.00%	81.58%
2	76.19%	66.67%	76.92%
3	78.57%	71.43%	79.49%
4	90.48%	83.33%	91.67%
Average	81.55%	70.76%	82.42%