Surface-based TEE-CT image registration for bicuspid aortic valve repair

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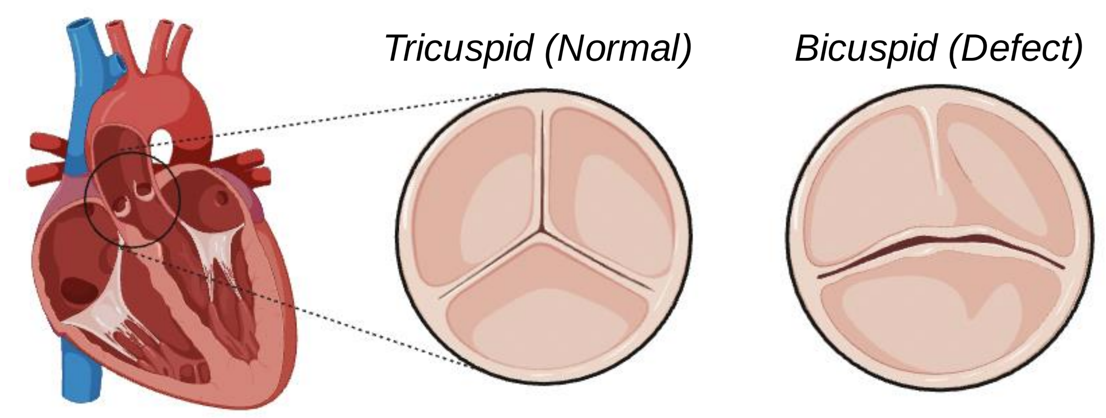
INTRODUCTION

Bicuspid aortic valves (BAV) are the most common congenital cardiovascular defect and can results in adverse effects including aortic regurgitation (AR) and/or aortic valve stenosis (AVS), requiring major surgical intervention to mitigate severe outcomes. In fact, BAV repair constitutes ~40% of patients undergoing AV repair [1], and is preferable in young patients to complete valve replacement. However, the current state of BAV repair relies heavily on taking critical measurements manually during intraoperative open-heart inspection. Thus, there exists an increased need to understand the precise pathoanatomical mechanisms of BAV cusp phenotypes to improve surgery and reproducibility.



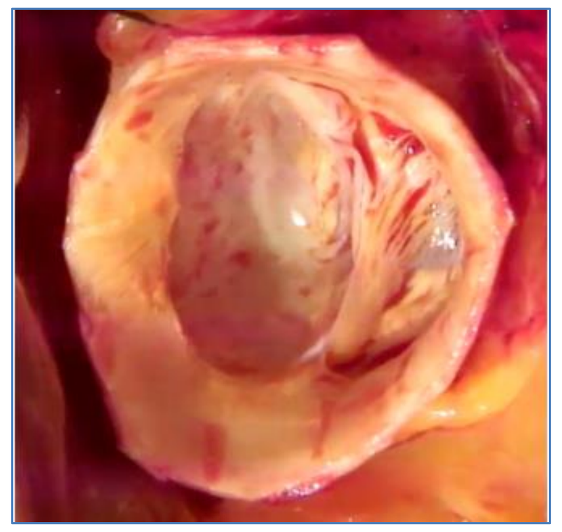


Figure 1: Diagram of tricuspid versus bicuspid aortic valves (above). Image of a bicuspid aortic valve in open heart surgery (right).

OBJECTIVE: TEE-CT IMAGE REGISTRATION

Routine **Transesophageal Echocardiography (TEE)** provides continuous visualization of heart valve motion during cardiac cycle but often lacks the ability to capture detailed anatomical cardiac structure. Conversely, routine **Computed Tomography (CT)** generates high resolution cross-sectional images of AV morphology.

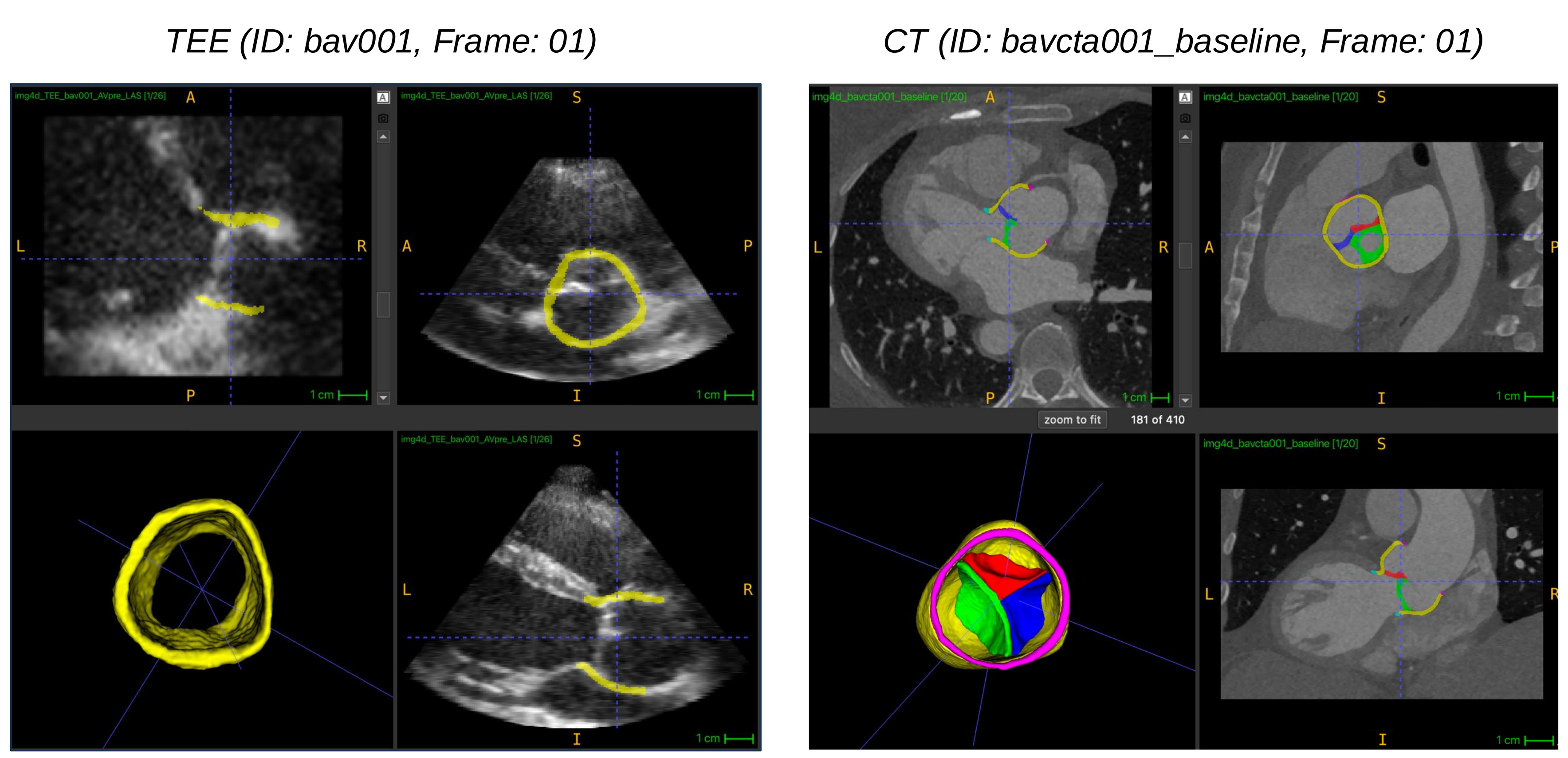
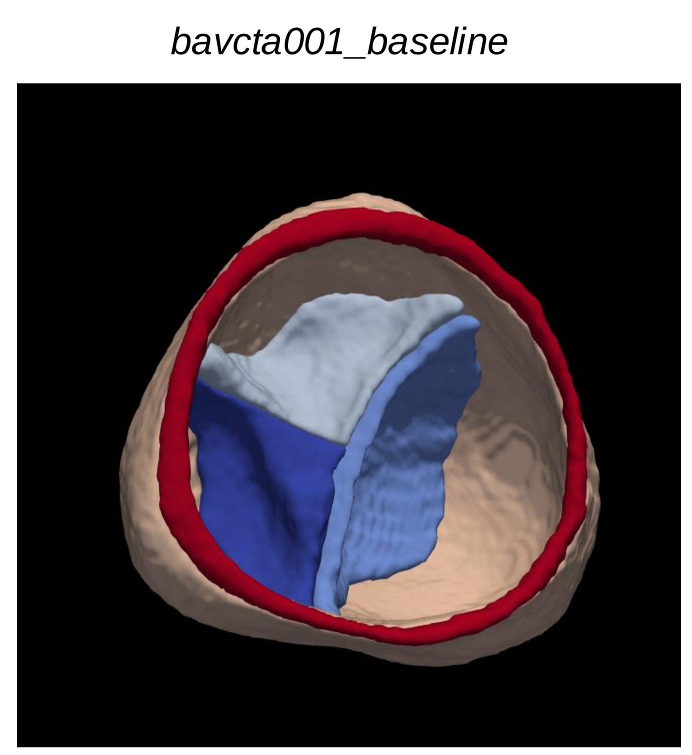


Figure 2: TEE and CT-modality BAV images opened in ITK-SnAP, an open-source medical imaging software. Figure 2a, depicts a TEE image with an aortic root wall segmentation image overlayed and shown in the 3D viewer on the bottom left. Figure 2b, depicts a CT image with a multi-label segmentation image overlayed.

With TEE and CT images unaligned in space during acquisition, TEE-CT image registration will overlay the images allowing for dynamic assessment of BAV disease over time, while also effectively bridging the knowledge gap in anatomical structure.

EXTRACTING SURFACE MESHES FROM SEGMENTATIONS

Using 3D alignment as a foundational step towards 4D alignment during a full cardiac cycle, we extracted **Visualization Toolkit (VTK) meshes** of 3D CT and specific time frames of 4D TEE from segmentation images via Python. The **Marching Cubes Algorithm** was implemented in Python, which is a common computer graphics algorithm for extracting 2D surface polygonal meshes from 3D segmentation regions.



Extracted meshes can be visualized in **ParaView**, an open-source interactive application for 3D data analysis. Segmentation images are multi-component, with individual labels corresponding to different anatomical structures or regions within the valve. These labels are maintained within the VTK mesh and were used for label-specific feature extraction for subsequent alignment outlined below.

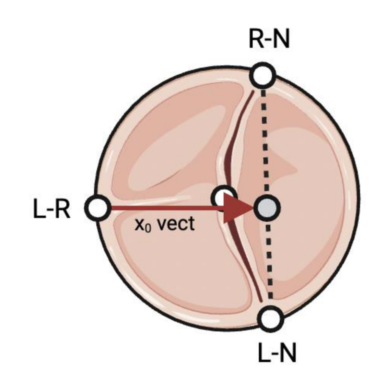
Figure 3: A VTK multi-label surface mesh opened in ParaView. Color labels for AV anatomical structures and regions are outlined below. The VAJ is not depicted in this specific viewpoint of the valve.

- *Sinotubular Junction (STJ)*
- *Ventriculoaortic Junction (VAJ)*
- *Whole Aortic Root Wall*
- *Right Coronary Cusp (RCusp)*
- *Non-Coronary Cusp (NCusp)*
- *Left Coronary Cusp (LCusp)*

REGISTRATION TO STANDARDIZED AXES

Extracted surface meshes were registered to standardized axes via the following steps:

1. Translation of the centroid point of the whole aortic root wall mesh to the origin at (0, 0, 0) in physical space.
2. Rotation of the principal component eigenvector parallel to the root to the z-axis in the direction of aortic valve blood flow.
3. Rotation of the NCusp bisection vector (x_0), calculated from cusp commissure points* depicted on the right, to the x-axis.



*Commissure points (L-N, L-R, and R-N) were determined by iterating through point data generated by surface meshes of individual cusp labels and closest point algorithms.

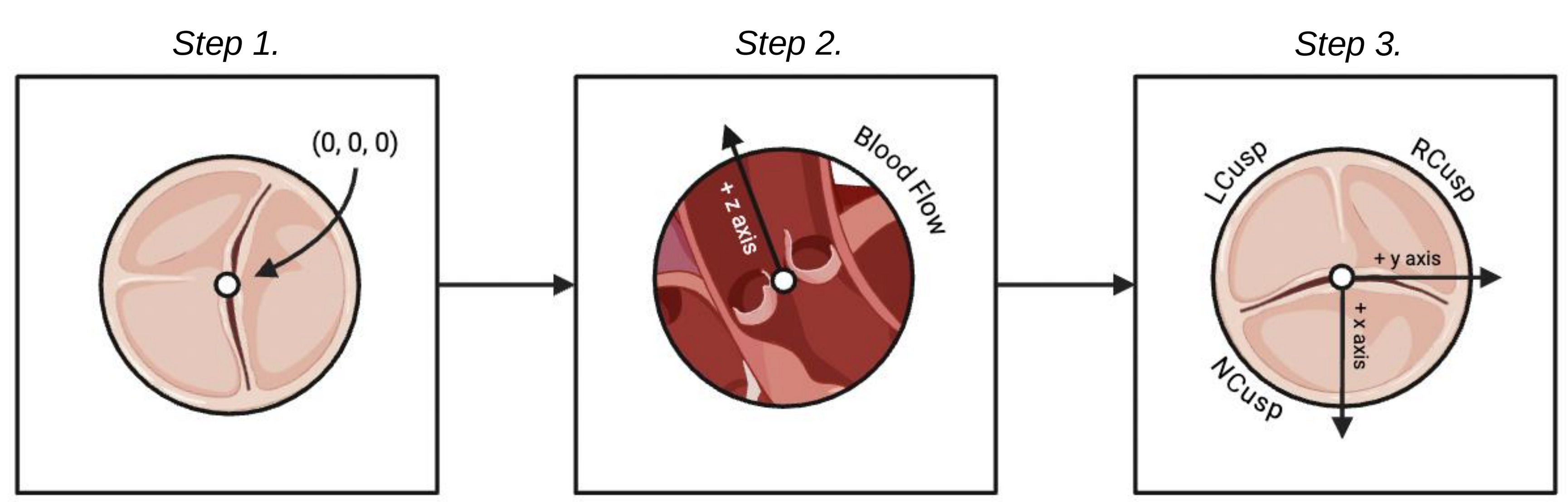
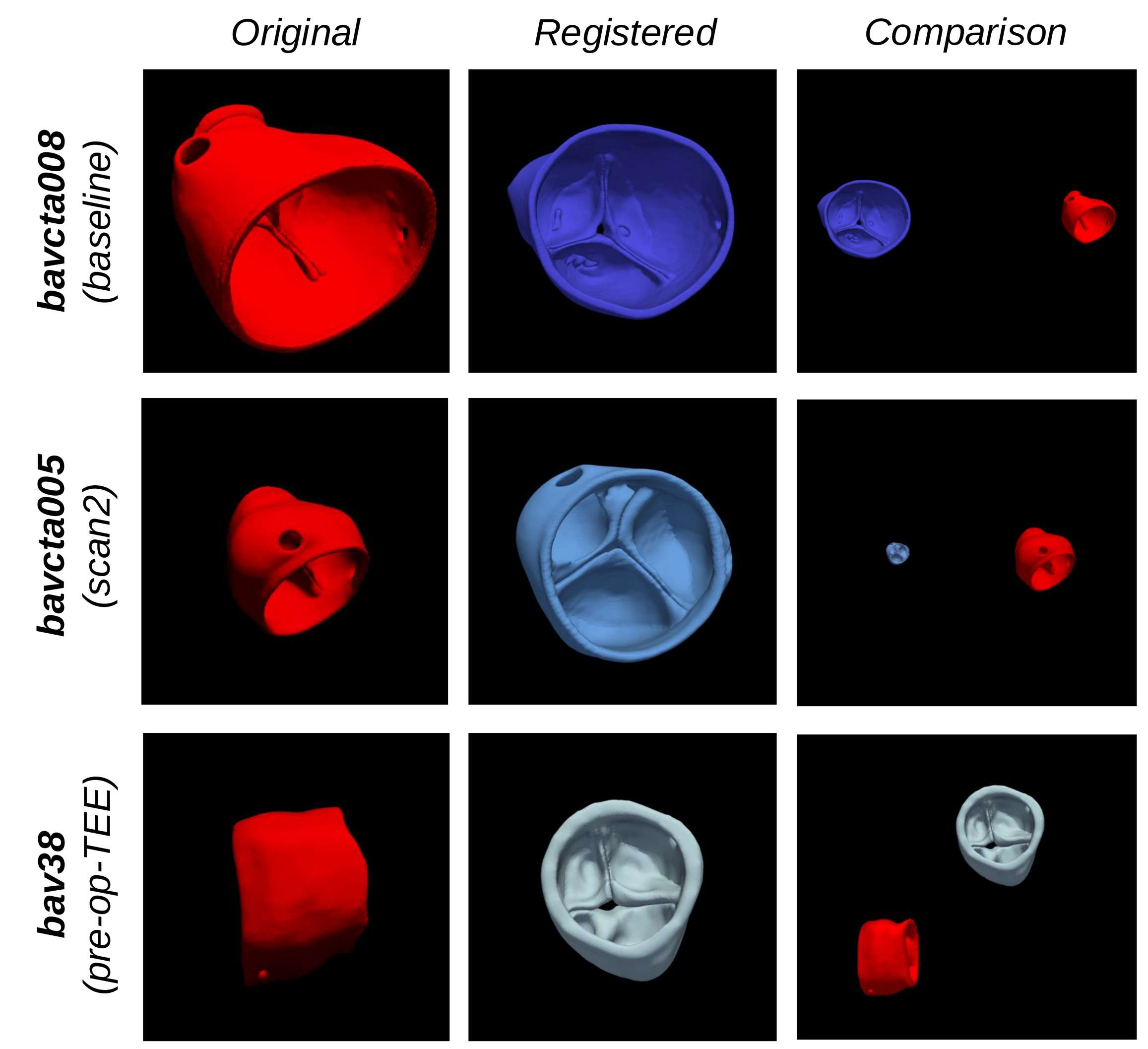


Figure 4: Visualization of each step for registering surface meshes to standardized axes.

Sequential time frames of surface meshes are registered with respective to the transformation of Frame 01 to the standardized axes. Oriented meshes are then run through a Python script to output a single video adjusted to mimic the dynamic motion of the BAV throughout the cardiac cycle.

RESULTS

Orientation algorithms were tested on multiple TEE and CT segmentation and mesh datasets of multi-label diastolic BAV. Some results are shown below for qualitative analysis.



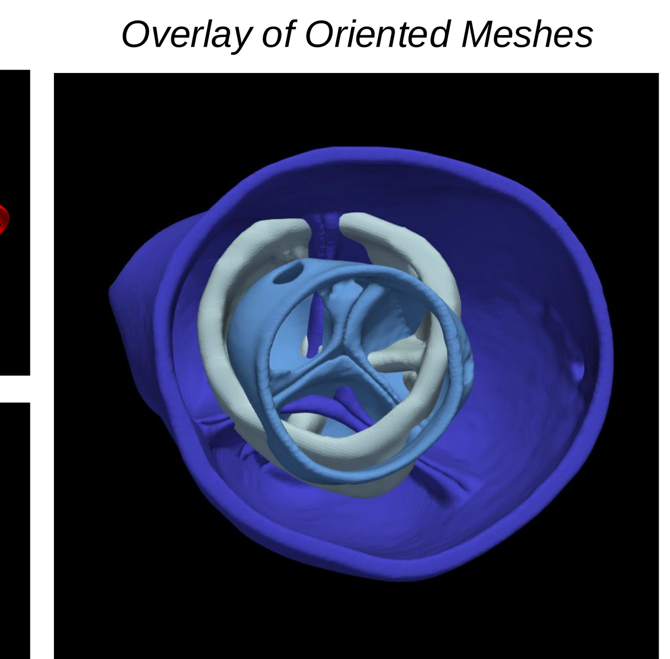


Figure 5: Comparison of original, registered valves on the left. Overlayed oriented valves at the origin above. All meshes are oriented to standardized axes shown here:

- bavcta008_baseline
- bavcta005_scan2
- bav38

+Z, +Y, +X

SIGNIFICANCE AND FUTURE WORK

Future work in this research involves optimization of similarity metrics to quantify the degree of similarity between TEE and CT images overlayed on the standardized axes, such as by using Mutual Information, a common metric for multi-modality registration. The optimized transformation matrix obtained from the registration algorithm will be implemented to resample the original moving image.

Ultimately, this research aims to register and overlay TEE and CT images in physical space for side-by-side visualization in spatial and temporal domains. The goal is to contribute to a larger PICSL project developing a web-based tool that generates interactive 4D models of the BAV and other phenotypes from multimodal image data, enabling surgeons to visualize and measure patient-specific valve models prior to surgery.

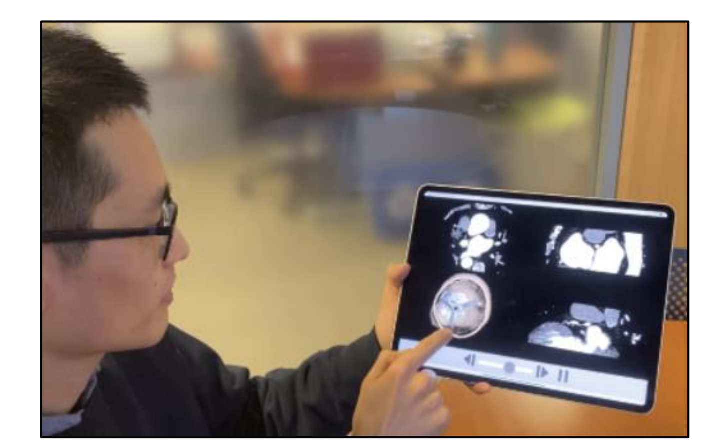


Figure 6: Demonstration of the image analysis application on an iPad.

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