Design and development of benchtop circulatory model with interchangeable, patient-derived left atrial appendage geometries

Keegan Mendez, Megan Lim, Elijah Lee, Ellen Roche

Massachusetts Institute of Technology, Cambridge, MA, USA

Background:

Comprehensive testing and evaluation of cardiovascular device performance is critical for successful clinical implementation, especially for device implantation procedures that involve significant intra-patient anatomical variability, such as left atrial appendage (LAA) occlusion. Current state-of-the-art benchtop circulatory models fail to simultaneously recapitulate the complex motion, fluid flow, and anatomical features of the heart, particularly those of the LAA. There is a significant need for benchtop models that maintain sufficient biomimicry, while also incorporating patient heterogeneity, to enable testing and validation in a more robust and inclusive patient population.

Objectives:

We aim to develop a benchtop circulatory model for LAA occlusion that is based on patient imaging, modular, and biomimetic. This model will allow testing in a spectrum of diverse geometries (e.g., the four LAA morphological categories: chicken-wing, cactus, windsock, cauliflower) and the possibility for patient-specific procedure simulation and evaluation. This model will replicate tissue mechanical properties (e.g., topography and stiffness) and physiological motion (e.g., healthy and pathological pressure waveforms). Overall, this model will support repeatable and reliable occlusion testing, and enable patient-specific testing that offers unique insight into the optimal occlusion device and procedure for the given patient's appendage anatomy.

Methods:

The model was designed by combining existing benchtop cardiac simulators (structurally rigid model; HEARTROID model) with patient-derived LAA geometries. MRI data was segmented in 3DSlicer (Fig.1A). Following post-processing, smoothing, and shelling, each LAA geometry was 3D printed (Objet Connex 500) and used to make a silicone casting (Ecoflex00-20) that was integrated into the cardiac simulator (Fig.1B-C). Pneumatic artificial muscles (PAMs), a type of soft-robotic actuator, were used to make the LAA contract cyclically (Fig.1D). Pressure was measured inside the LA/LAA while the actuation regime of the PAMs was varied (input pressure: 5-15psi).

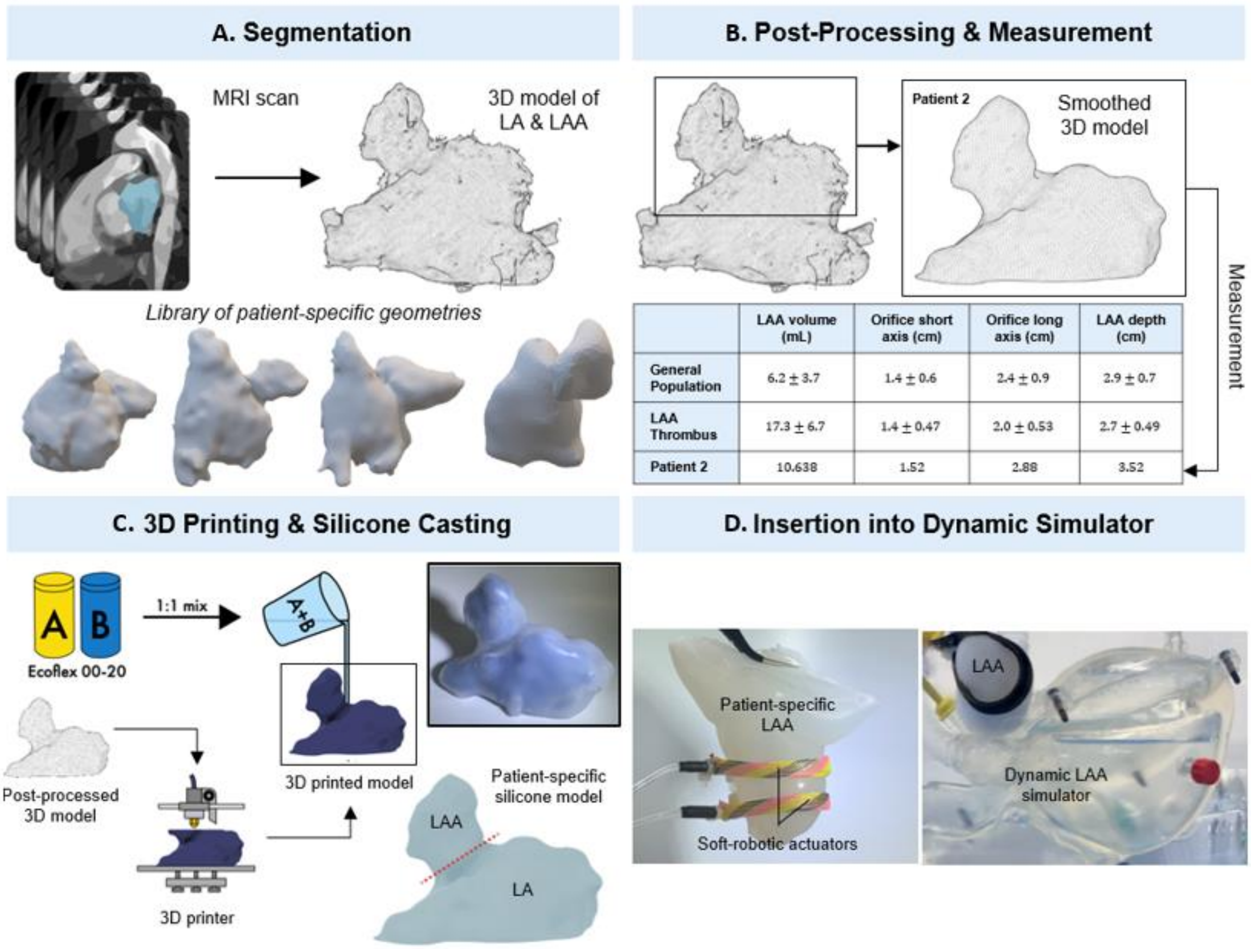
Results:

We demonstrate the fabrication of multiple patient-derived LAA geometries that can be incorporated into a cardiac simulator and made active with pneumatic artificial muscles (PAMs). We develop a workflow whereby MRI data is segmented, post-processed and measured, 3D printed and used to create a silicone casting, and incorporated into a cardiac simulator (Fig.1). We generate a diverse library of anatomies that encompass underlying intra-patient heterogeneity and span physiological parameters, such as LAA volume, seen in geometries with and without thrombus (Fig.2). We make these geometries dynamic and recreate physiologically relevant pressure waveforms by varying the actuation regime of the PAMs

(Fig.3). We recreate typical LA/LAA pressures seen in normal sinus rhythm (3-12mmHg; 5psi input pressure) and generate a range of pressure measurements (0-18mmHg) by varying the actuation pressure (5-15psi input pressure).

Conclusion:

We present the design and development of a benchtop circulatory model with interchangeable, patient-derived LAA geometries. We use patient imaging to manufacture LAA geometries that can be incorporated into a benchtop model and made active with soft-robotic actuators. We generate physiological and pathological pressure waveforms by varying the actuation pressure of the soft-robotic actuators. By generating a diverse library of appendages that includes a wide range of shapes and geometrical features, our dynamic, patient-specific benchtop circulatory model can be used for more robust LAA occlusion device testing and validation.



	LAA volume (mL)	Orifice short axis (cm)	Orifice long axis (cm)	LAA depth (cm)
General Population	6.2 ± 3.7	1.4 ± 0.6	2.4 ± 0.9	2.9 ± 0.7
LAA Thrombus	17.3 ± 6.7	1.4 ± 0.47	2.0 ± 0.53	2.7 ± 0.49
Patient 2	10.638	1.52	2.88	3.52

Figure 1: Workflow from MRI scan to cardiac simulator with dynamic, patient-derived LAA geometry. (A) MRI segmentation. (B) Post-processing and measurement. Table comparing measurements of Patient 2 to general population and patients with known LAA thrombus. (C) 3D printing of mold and silicone casting of LAA geometry. (D) Insertion of LAA geometry into cardiac simulator. Soft-robotic actuators are used as artificial muscles to make the LAA contract cyclically.

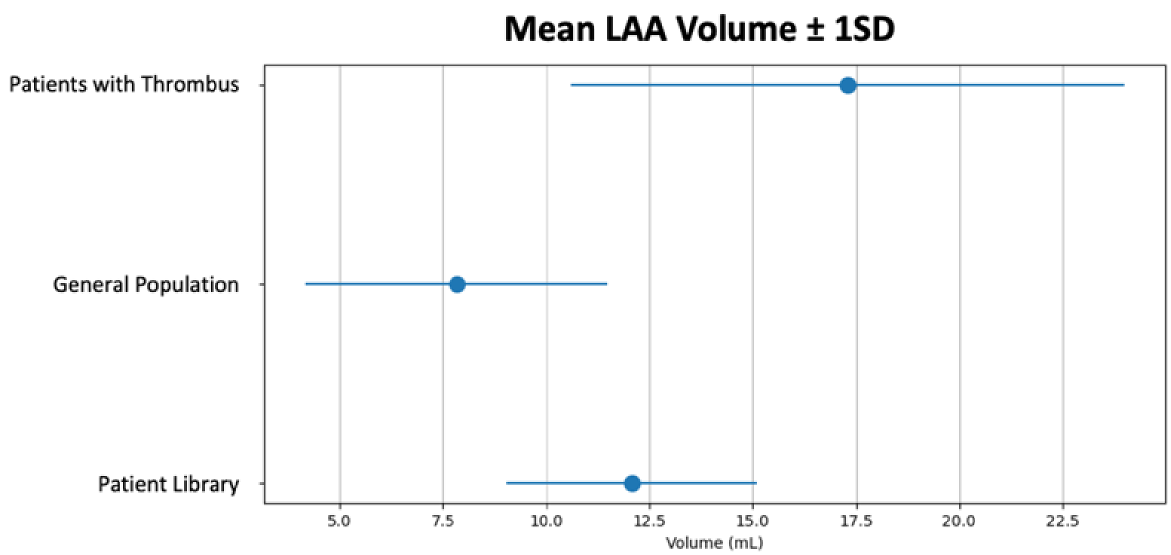


Figure 2: Generation of a patient library of diverse LAA geometries. Comparison of mean LAA volume of patient library to general population and patients with known LAA thrombus. Data are mean ± 1SD.

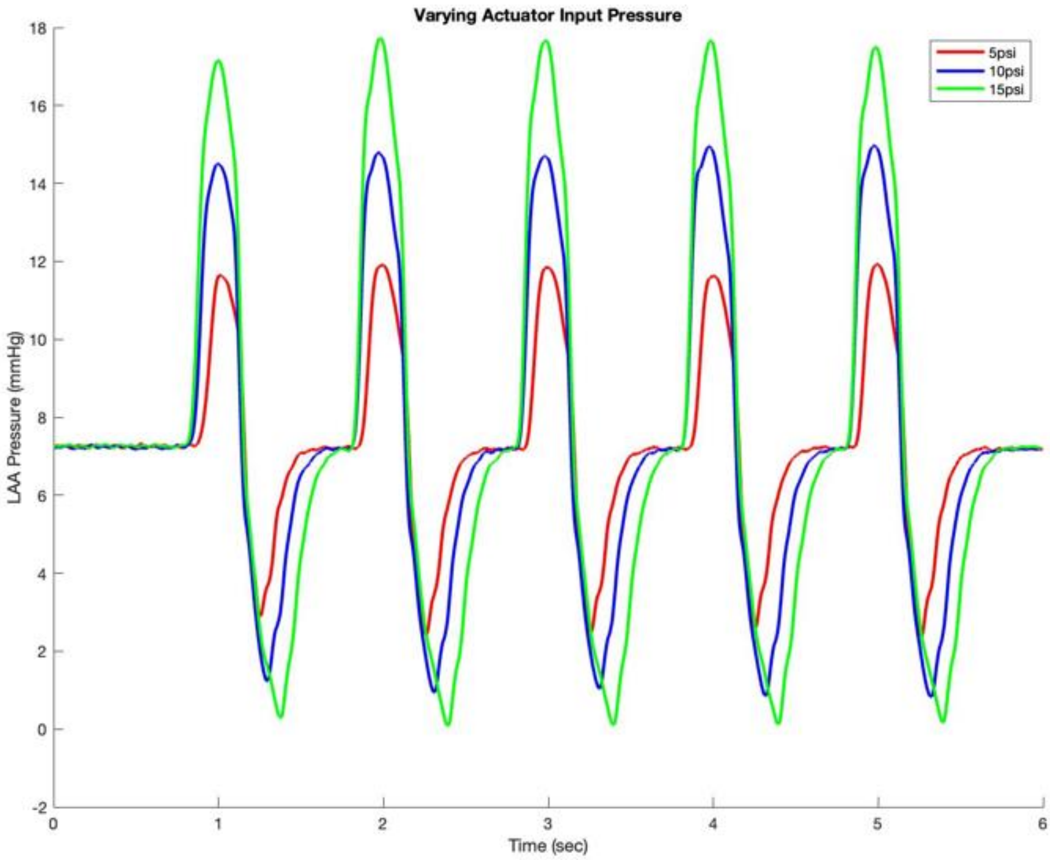


Figure 3: Representative LA/LAA pressure data generated by actuating the patient-derived LAA at varying actuation pressures (5-15psi input pressure).