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Patient-Specific Mitral Valve Modeling: Development, Hemodynamic Validation, and Biomechanical Analysis

Katell Delanoë[a], Erwan Salaun[a], Lionel Thollon[b], Régis Rieu[b], Philippe Pibarot[a], Viktória Stanová[a]

a Institut Universitaire de Cardiologie et de Pneumologie de Québec – Université Laval, Québec, Canada
b Aix-Marseille University/ Gustave Eiffel University, LBA-UMRT24, France
* Corresponding author: viktoria.stanova@criucpq.ulaval.ca

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1. Introduction

Mitral valve regurgitation (MR), defined by a backward flow from the left ventricle to the left atrium during systole, affects 10% of the population over 70 years (Nkomo et al., 2006). To treat MR in high surgical risk patients, percutaneous mitral valve interventions were introduced in early 2000. However, due to the novelty of these procedures, their long-term hemodynamic and biomechanical consequences remain unclear, as does the impact of patient anatomy and etiology on device effectiveness. The introduction of percutaneous techniques to lower risk patients requires even more personalized strategies to enhance device durability and patient quality of life. This study aims to validate a patient-specific mitral valve development process by accurately replicating the anatomy and rheological behavior of a native healthy mitral valve.

2. Methods

2.1 Patient specific mitral valve development

A patient-specific, healthy mitral valve model was developed based on transesophageal echocardiographic (TEE) images obtained during clinical examinations at IUCPQ-ULaval (708*1016 pixels, 33fps). Patient consent was obtained before image analysis in accordance with ethical research protocol 2024-4136, 22415. 3D TEE anonymized images were then used to segment the mitral valve using Mimics software (Materialize, Belgium) (Figure 1a, b and c). The resulting 3D valve model was imported into Fusion 360 (Autodesk Inc., USA) to generate a negative mold, which was then 3D printed (Lulzbot Taz Pro, USA). To mimic the native mitral valve's rheological properties, two silicons (EcoFlex00-50 and DragonSkin10, Smooth-On Inc., USA) were used based on previous research (Delanoë et al., 2025). The silicons were poured layer-by-layer into the 3D-printed mold to ensure homogeneity and control leaflet thickness. To replicate the subvalvular apparatus, 16 de-braided polyester strings (Gütterman GmbH, Germany) were embedded between silicon layers, simulating mitral chordae with tension application points distributed across the leaflet surface.

2.2 Hemodynamical testing

To validate the reproduction of the rheological characteristics of the patient's healthy mitral valve, a double activation left heart duplicator system was used (Tanné, Bertrand, Kadem, Pibarot, & Rieu, 2010). The silicon mitral valve was tested under the same hemodynamic conditions as the patient during the TEE image acquisition (Stroke Volume=40mL, Mean Aortic Pressure=110mmHg, Heart Rate=70bpm). Hemodynamic responses were evaluated using Continuous Wave Doppler collected by transthoracic echocardiography (iE33, Philipps Healthcare, USA) for *in vitro* values and by transesophageal echocardiography (Vivid E9, GE Healthcare, USA) for *in vivo* values. Ventricular diastolic filling patterns and associated energy loss were analyzed using vector flow mapping

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Table 1. Anatomic and rheological reproduction of patient mitral valve characteristics.

	Leaflet Thickness (mm)	Annulus Area (cm^2)	Commissural Diameter (cm)	Antero-lateral Diameter (cm)	MPG (mmHg)	EOA (cm^2)	GOA (cm^2)	Energy Loss (mW/m)	E1
Patient	2.0 ± 0.2	9.66	3.83	2.92	0.63±0.11	4.69±0.40	4.93±0.00	0.05±0.03	N/a
Silicon	2.0 ± 0.2	9.48	3.78	2.81	0.88±0.05	3.98±0.39	4.64±0.18	0.18±0.22	0.08±0.04

(VFM) (ITEcho, Cardiac Flow Design, Japan) of Color Doppler images of both *in vitro* and *in vivo* acquisition.

2.3 Biomechanical analyses

Mitral valve leaflets motion was captured using two high-speed video cameras (FASTCAM Mini AX50, Photron Inc., USA) (1024*1024 pixels, 1000fps). Strain measurements were performed using 3D digital image correlation (VIC-3D, Correlated Solutions, Inc., USA). To ensure measurement accuracy, a double calibration was performed prior to each computation. Lagrangian strain distribution and Z displacement during systolic closure were determined across the entire leaflet surface.

3. Results and discussion

3.1 Anatomical characteristics

Visual assessment of the patient-specific mitral valve revealed a strong correlation (<5% difference) between the 3D TEE mitral valve structure and the silicon replica (Figure 1, Table 1). A custom-coded MATLAB program was used to compare and confirm the anatomical accuracy of the silicon mitral valve, demonstrating close similarities in annular area, leaflet thickness, commissural width, and anterolateral diameter (Table 1).

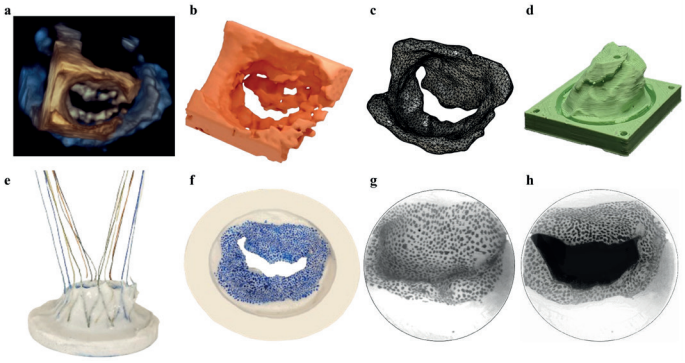

Figure 1. Fabrication process of the patient specific silicon mitral valve; (a) Patient 3D TEE images, (b) 3D Segmentation of the valve, (c) 3D Valve Refinement, (d) 3D printed mold, (e) Lateral and (f) En Face view of the valve, (g) Systolic closure and (h) Diastolic opening of the valve.

3.2 Hemodynamic and biomechanical behaviour

The exact mitral leaflet motion was replicated with similar diastolic opening and systolic closure leaflet deployment (Figure 1). The silicon mitral valve enabled an accurate reproduction of the patient hemodynamic profile with similar mean pressure gradient (MPG), effective orifice area (EOA) and geometrical orifice area (GOA)(Table 1). Furthermore, VFM revealed comparable energy loss values, indicating similar diastolic filling and systolic ejection patterns. Finally, the major principal strain (E1) applied to the leaflet silicon replica during systolic closure corroborated a healthy behaviour with a strain value <10% (El-Tallawi et al., 2021) (Table1).

4. Conclusions

This study aims to reproduce the anatomical and rheological behavior of a patient's healthy mitral valve using a silicon replica. The results suggest that the described process can accurately reproduce patient's anatomy, leaflet motion and hemodynamical behavior. Furthermore, physiological major principal strains were induced *in vitro*, indicating appropriate reproduction of a healthy mitral valve. Reproduction of a patient-specific mitral valve *in vitro* can be a useful tool for planning patient-specific percutaneous procedures based on patient's anatomy, physiology and hemodynamic profile.

The next step is to develop patient-specific mitral valves with different types of pathologies and dysfunctions in order to investigate, *in vitro*, the different potential therapeutic strategies to successfully correct these dysfunctions.

Conflict of Interest Statement

Pr. Philippe Pibarot reports research grants from Edwards Lifesciences, Medtronic, and Pi-Cardia.

All other authors have no conflict of interest to disclose.

Contributor Roles

KD: Conceptualization, Methodology, Writing original draft; VS: Conceptualization, Methodology, Validation,

Supervision, Writing- review & editing; PP: Funding acquisition, Validation, Supervision, Writing- review & editing; ES, LT, RR: Validation, Writing- review & editing.

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