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Mock Tricuspid Valve for Right Heart Simulator

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of Master Of Biomedical Engineering

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Abstract

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Contents

ABSTRACT	ii
CONTENTS	iv
LIST OF FIGURES	v
LIST OF TABLES	vii
LIST OF ACRONYMS	viii
I PROLOGUE	1
1 INTRODUCTION	2
1.1 Background	2
1.2 Aims, Scope and Limitations	5
1.3 Research Questions and Hypotheses	6
1.4 Problem Statement	7
2 LITERATURE REVIEW	8
2.1 Heart Valve Anatomy and Physiology	8
2.2 Advances in Heart Valve Disease Treatment	12
2.3 Current Models and Simulators	14
2.4 Materials and Methods in Valve Modeling	18
2.5 Regulatory and Ethical Considerations	22
2.6 Research Strengths and Gaps	24
II METHODOLOGY	27
3 DESIGN AND PROTOTYPING	29
3.1 Conceptualisation and Initial Design	29
3.2 Design Criteria	30
3.3 Modelling and Design Iterations	32
3.4 Prototyping	35
3.5 Design Validation	39
4 EXPERIMENTAL SETUP AND TESTING	41
4.1 Fixturing Assembly	41
4.2 Rig Assembly	42
4.3 Testing Procedure	42
III RESULTS, ANALYSIS, AND DISCUSSION	44
5 RESULTS	46
5.1 Design evaluation and thickness investigation	46
5.2 Pilot Tests	46
5.3 Coaptation Test	46

6 DISCUSSION	48
6.1 Challenges and the Various Explored Approaches	48
6.2 Contextualizing Results	52
IV EPILOGUE	54
7 CONCLUSIONS AND FUTURE WORK	55
7.1 Future Research Directions	55
BIBLIOGRAPHY	58

List of Figures

2 LITERATURE REVIEW

2.1	Heart Valve System [Rock et al. 2014]	8
2.2	Sub-System of Tricuspid Valve [Yost - Drawing Detailed View of Tricuspid Valve - English Labels AnatomyTOOL n.d.]	9
2.3	Illustration of Regurgitation vs Stenosis [Tricuspid Valve Disease n.d.]	10
2.4	Current landscape of TTVR products being used surgically [Curio et al. 2019]	13
2.5	Concept of the WindKessel Model [Westerhof et al. 2009]	14
2.6	Side cross section of simulator with dynamic statecamera attachment [Karl et al. 2024]	17
2.7	Side cross-section with static state surgery attachment [Karl et al. 2024]	17
2.8	Comparison of PU and poly(carbonate-urea)urethane for heart valve performance [Ghanbari et al. 2010]	18
2.9	Comparison surfaces in fatigued (a) PU (b) poly(carbonate-urea)urethane (c) valve leaflets showing tissue failure and fibre dehiscence marked by the yellow arrows in each [Ghanbari et al. 2010]	18
2.10	Video of annuloplasty being performed on silicone mitral valve (click to view video)	19

3 METHODOLOGY

3.1	Flat Valve Model	29
3.2	Billowed Valve Model	29
3.3	Billowed Valve with Chordae Tendineae Model	29
3.4	Anatomical Model	29
3.5	Visual represenation of regurtitant valve morphological progression [Nam et al. 2023]	32
3.6	Netfabb Repair Scripts	34
3.7	Netfabb Shell	34
3.8	Silicone Mould Design	35
3.9	Press Mould Design and casted part for Flat Valve	36
3.10	Iterations of epoxy mould die method	37

3.11 Testing the methods for attaching the chordae tendineae to leaflets	38
3.12 Thickness investigation for experimental model of the valve	40
4 EXPERIMENTAL SETUP AND TESTING	
4.1 Tensioning of chordae tendineae	42
4.2 Removing air bubbles from the system	43
4.3 Birds eye view of the test rig	43
5 RESULTS	
5.1 Frame from video of valve coapting during testing (click to view video)	47
6 DISCUSSION	
6.1 Final cast of anatomical valve	49
6.2 Early revision SLA print of anatomical valve	51

List of Tables

2 LITERATURE REVIEW

2.1 Comparison of key points in the literature review	26
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List of Acronyms

Notation	Description	Page
		List
CVD	Cardiovascular Disease	2
TV	Tricuspid Valve	3
CT	Computed Tomography	20
FSI	Fluid Structure Interaction	14
BHV	Bioprosthetic Heart Valve	16
PU	Polyurethane	v
PET	Polyethylene Terephthalate	19
TTVR	Transcatheter Tricuspid Valve Replacement	v
TAVR	Transcatheter Aortic Valve Replacement	18
CAD	Computer Aided Design	6
PLA	Polylactic Acid	35
MRI	Magnetic Resonance Imaging	20
PIV	Particle Image Velocimetry	17
SLA	Stereolithography	vi
FDM	Fusion Deposition Moulding	51

Part I

PROLOGUE

1

Introduction

1.1 BACKGROUND

1.1.1 *Understanding the Need for Heart Valve Simulators*

► CARDIOVASCULAR DISEASES PREVALENCE

CVD's, including heart valve diseases, are the leading cause of global mortality and a significant contributor to disability. The Global Burden of Disease Study 2019 revealed that prevalent cases of total **CVD** nearly doubled from 271 million in 1990 to 523 million in 2019, with the number of **CVD** deaths increasing from 12.1 million to 18.6 million over the same period. The study highlights the continuing rise in **CVD** burden, especially in low- and middle-income countries, and a concerning trend of increasing age-standardized rates of **CVD** in some high-income countries where rates were previously declining.[Roth et al. 2020]

► VALVULAR HEART DISEASES PREVALENCE

Valvular heart diseases, a subset of **CVDs**, are characterized by abnormalities in the heart's valves, affecting blood flow within the heart chambers. These diseases encompass a wide range of conditions, including valvular stenosis, regurgitation, and prolapse, with the most common types affecting the aortic and mitral valves. Another study by [Nkomo et al. 2006] emphasizes the substantial prevalence of valvular heart diseases in the general population, affecting approximately 2.5% of the US population, with the prevalence increasing with age. This underscores valvular heart diseases as an important public health problem.

► CHALLENGES IN HEART VALVE TREATMENT

The treatment of heart valve diseases involves complex surgical and non-surgical interventions, facing several limitations that highlight the

need for innovative solutions. The challenges include the invasive nature of current treatments, the requirement for high precision in surgery to avoid complications, and the limited availability of treatment options for certain patient groups. [Musumeci et al. 2018]

1.1.2 *The Role of the Tricuspid Valve in Cardiac Function*

- ▶ ANATOMICAL AND PHYSIOLOGICAL OVERVIEW

The **TV**, an essential component of the heart's right side, plays a vital role in cardiac physiology. It is located between the right atrium and the right ventricle, acting as a one-way gate that ensures unidirectional blood flow. Structurally, the **TV** is complex, comprising an annulus, usually three leaflets (anterior, posterior, and septal), the supporting chordae tendineae, and the papillary muscles. This valve is crucial for electrically isolating the two cardiac chambers and maintaining efficient blood flow, with the variability in the number, length, and shape of the chordae tendineae and papillary muscles having significant clinical implications for valve function. [Sanders and Pluchinotta 2014]

- ▶ PATHOLOGIES AFFECTING THE **TV**:

TV diseases, such as tricuspid regurgitation or stenosis, significantly impact heart function. Tricuspid regurgitation, where the valve fails to close properly, allows blood to flow back into the right atrium during systole, while stenosis restricts blood flow from the atrium to the ventricle. These conditions can lead to heart failure if left untreated. In these diseases the annulus dilates and leaflet tethering is disrupted due to right ventricular remodeling, which are the main mechanisms responsible for most cases of tricuspid regurgitation. [Buzzatti et al. 2018]

These conditions underscore the need for accurate simulation models to improve diagnostic and treatment strategies. The complexity of the **TV**'s anatomy and the prevalence of its pathologies highlight the necessity for innovative solutions that can provide precise and personalized treatments, making the development of realistic simulation models critical for advancing cardiac care.

1.1.3 *Technological Advances in Heart Valve Simulation*

- ▶ EVOLUTION OF HEART VALVE SIMULATORS

The journey of heart valve simulators from early mechanical models to today's advanced computer simulations marks a significant evolution in

cardiovascular medicine. Initially, simulators were simplistic, focusing on the basic mechanical functions of heart valves. [Takashina et al. 1990] developed one of the early cardiac auscultation simulators that digitally recorded, modified, and played back heart sounds characteristic of various heart diseases, marking a pivotal moment in the simulation technology for educational purposes.

Advancements continued with the introduction of tissue-based simulators for surgical training. [Rampal et al. 2005] described a high-fidelity, tissue-based cardiac surgical simulator that significantly enhanced the realism of training, enabling surgical residents to practice a variety of cardiac procedures in a risk-free environment.

► CURRENT STATE OF **TV** SIMULATORS:

The focus has shifted towards creating highly realistic and patient-specific models. The Living Heart Project represents a groundbreaking step towards integrative simulators for human heart function. This simulator for a four-chamber human heart model created from imaging data illustrates the electrical and mechanical response of the heart, including its valves, throughout the cardiac cycle, offering a sophisticated tool for exploring heart function under various conditions. [Baillargeon et al. 2014]

Despite these advancements, current **TV** simulators still face gaps in realism, accessibility, or functionality. These limitations include the challenge of accurately replicating the intricate biomechanics of the **TV** and its interaction with the right heart dynamics under physiological and pathological conditions.

1.1.4 *The Importance of Realistic Simulation Models*

► BENEFITS FOR MEDICAL TRAINING AND SURGICAL PLANNING

Realistic heart valve simulators have emerged as critical tools for medical education and surgical planning. These simulators allow practitioners to gain hands-on experience without any risk to patients, bridging the gap between theoretical learning and practical application. They serve an essential role in pre-surgical planning, enabling surgeons to explore intervention strategies and anticipate challenges in a controlled environment. This aspect is crucial for complex procedures like heart valve surgery, where understanding the intricate details of the valve's anatomy and predicting the outcomes of surgical interventions can significantly affect patient outcomes.

▶ **CONTRIBUTION TO PROSTHETIC VALVE DEVELOPMENT**

Accurate simulation models contribute immensely to the design and testing of prosthetic valves. They enable the identification of design considerations that affect performance and longevity, such as the impact of geometric variations on valve mechanics. By simulating the dynamic behavior of valve leaflets and the surrounding blood flow, engineers and surgeons can refine prosthetic designs to enhance their functionality durability, and ultimately lead to improved patient outcomes.

1.2 AIMS, SCOPE AND LIMITATIONS

▶ **PRIMARY OBJECTIVE**

- To develop a mock **TV** that accurately replicates the anatomical structure and physiological function of the human **TV** for use in a heart simulator.

▶ **SECONDARY OBJECTIVES**

- To evaluate the realism and functionality of the developed valve model in comparison to existing simulators.
- To assess the potential of the valve model for enhancing surgical training and planning.
- To explore the model's utility in testing and improving prosthetic valve designs.

Achieving these objectives will not only fill the current technological void but also potentially revolutionize the way heart valve diseases, especially those affecting the **TV**, are understood, taught, and treated.

1.2.1 *Scope*

The primary focus of this research is the design, development, and testing of a mock **TV** intended for integration within a specifically designed right heart simulator. This project aims to utilize advanced biomedical engineering principles and methodologies to create a valve that closely mimics the physiological behaviors and properties of a natural human **TV**. The research will leverage materials known for their biocompatibility and mechanical resilience, ensuring the mock valve's functionality.

Additionally, the project will employ state-of-the-art **CAD** technologies to optimize the valve's performance under various physiological conditions and to refine the design in terms of anatomical accuracy. This scope encompasses the iterative design process, fabrication techniques potentially involving 3D printing with biocompatible materials, and a series of validation tests within the simulator environment to evaluate hemodynamic performance, durability, and response to simulated physiological variations.

make sound better

1.2.2 *Limitations*

There are inherent limitations associated with studies replicating biological function, this impacts the results and their applicability. Firstly, the complexity of replicating the exact physiological environment and dynamic conditions of the heart poses a significant challenge. The material selected for the mock **TV**, while similar, may not perfectly mimic the viscoelastic properties of natural heart valve tissue, potentially leading to differences in hemodynamic/hydrodynamic performance when compared to a biological valve. Additionally, the scale and scope of the study are focused exclusively on the **TV**, excluding other cardiac structures and valves, which may limit the understanding of the valve's interaction within the complete cardiac system. The research is also conducted within a simulator environment, which, despite its advanced design, cannot replicate every aspect of human physiology or the potential effects of systemic factors such as neurohormonal feedback. [Chatterjee 2005]

These limitations underscore the importance of interpreting the findings within the context of the study's controlled conditions, with an understanding that further research and testing are necessary to bridge the gap between simulation and real-world application.

1.3 RESEARCH QUESTIONS AND HYPOTHESES

Based on the outlined objectives, the following research questions and hypotheses are formulated to guide the study and provide a clear framework for investigation:

1. Research Question: How accurately can the developed mock **TV** replicate the anatomical and physiological characteristics of the human **TV**?
 - Hypothesis: The developed mock **TV** will significantly replicate the anatomical structure and physiological function of

the human TV, as evidenced by comparative analyses with clinical data(video).

2. Research Question: In what sense does the new valve model improve upon existing heart valve simulators?

- Hypothesis: The new valve model will demonstrate superior realism and experimental adaptability compared to existing heart valve simulators, providing a more effective and versatile tool for medical training and surgical planning.

3. Research Question: What is the potential impact of the developed valve model on surgical training, planning, and the design of prosthetic valves?

- Hypothesis: The integration of the developed valve model into surgical training and planning processes will lead to enhanced learning outcomes, more accurate surgical interventions, and informed prosthetic valve design, contributing to improved patient care and treatment outcomes.

1.4 PROBLEM STATEMENT

Current simulators for heart valve diseases, particularly those affecting the TV, fall short in accurately replicating the valve's intricate anatomy and physiology. This gap limits their utility in characterizing prosthetic valves, a critical step in the development and evaluation process. Despite advancements in simulation technologies, there's a distinct need for a TV simulator that closely models the real-world behavior of valves under various physiological conditions. This research aims to address this by developing a TV simulator that enhances anatomical and physiological realism while maintaining accessibility of measurement systems like particle image velocimetry.

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- ▶ IN SUMMARY, the research embodies a significant stride towards enhancing medical training, advancing prosthetic valve development, and filling a vital research gap in cardiovascular simulation technology, with the potential to impact broadly across the fields of medical education, biomedical engineering, and patient care.

2

Literature Review

2.1 HEART VALVE ANATOMY AND PHYSIOLOGY

2.1.1 Introduction to the Heart Valve System

The heart valve system plays a pivotal role in the circulatory system, ensuring the unidirectional flow of blood through the heart and maintaining cardiovascular health. The cardiovascular system, as a closed circulatory network, is divided into two primary circuits: one that pumps blood from the heart to the lungs for oxygenation, the right, and another that distributes this oxygenated blood to the body's organs, the left. The heart is composed of four chambers: two atria for receiving blood and two ventricles for pumping blood to the body. To maintain the blood's unidirectional flow, the heart has a valve in each chamber each of which are unique to the geometry of the chamber and have their own unique pathologies, they're strategically located between the atria and ventricles and between the ventricles and the arteries that emerge from the heart. [Frater 1962]

The functionality and integrity of heart valves are essential for cardiovascular health. Heart valves open and close with each heartbeat, totaling over 3 billion times in a lifetime. This continuous operation occurs under significant pressure and within flowing blood, a viscous fluid rich in minerals, proteins, lipids, and cells. When valves become defective, they critically affect heart performance, leading to valve diseases that necessitate surgical intervention in the absence of curative drug treatments. Currently, diseased valves are replaced with artificial devices designed to emulate the valves' mechanical functions and restore heart functionality. However, these artificial valves can fail due to design flaws, material imperfections, or biocompatibility issues, often requiring risky reoperations. [Simionescu 2006]

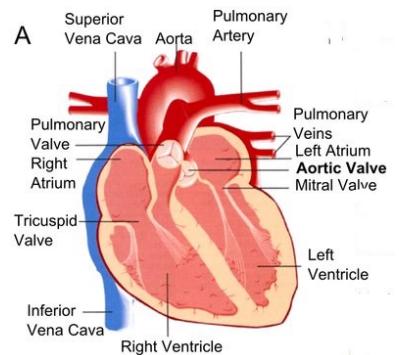


FIGURE 2.1: Heart Valve System [Rock et al. 2014]

Biomedical engineering strives to enhance treatments for valvular diseases, potentially impacting millions worldwide. This interdisciplinary field combines efforts from medicine, biology, engineering, and mechanics to improve device biocompatibility and explore tissue-engineering approaches that could enable the complete regeneration of valve tissues.

[Simionescu 2006]

2.1.2 Anatomy of the tricuspid valve

The **TV**, an integral component of the heart's valve system, is located between the right atrium and right ventricle. It plays a crucial role in ensuring unidirectional blood flow from the atrium to the ventricle, thus maintaining the efficiency of the cardiac cycle. The **TV**'s anatomy is complex and consists of several key structures: the annulus, leaflets, chordae tendineae, and papillary muscles.

- **Annulus:** The annulus is a fibrous ring that anchors the valve leaflets and maintains their spatial configuration. It is the foundation to which the leaflets are attached, providing structural support for the entire valve apparatus.
- **Leaflets:** Typically, the **TV** has three leaflets named according to their position: the anterior, posterior, and septal leaflets. These leaflets act as one-way doors that open to allow blood flow from the atrium to the ventricle and close to prevent backflow.
- **Chordae Tendineae:** These are thin, string-like structures that connect the valve leaflets to the papillary muscles. The chordae tendineae ensure the leaflets close securely and prevent them from inverting when the ventricle contracts.
- **Papillary Muscles:** These muscles extend from the inner walls of the right ventricle and attach to the valve leaflets via the chordae tendineae. During ventricular contraction, the papillary muscles contract, pulling the chordae tendineae taut and ensuring the valve leaflets close properly.

The **TV**'s structure is characterized by its adaptability and variability. The number, length, and shape of the chordae tendineae and the papillary muscles can vary significantly among individuals, which can be of clinical significance. Dysfunctional papillary muscles or dysplastic chordae can lead to valve dysfunction, emphasizing the importance

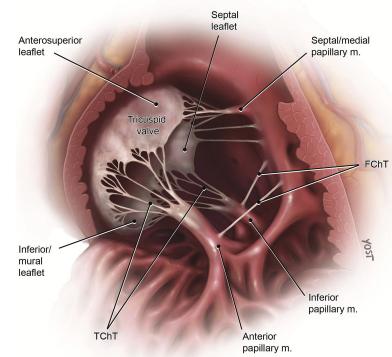


FIGURE 2.2: Sub-System of Tricuspid Valve
[Yost - Drawing Detailed View of Tricuspid Valve - English Labels | AnatomyTOOL n.d.]

of understanding this complex anatomy for clinical assessment and intervention [Sanders and Pluchinotta 2014]

Furthermore, the TV is part of a dynamic apparatus that includes closely linked structures such as the annulus, leaflets, chordae, papillary muscles, and the right ventricle itself. Understanding the precise anatomy and function of these components is crucial for the success of percutaneous and surgical interventions aimed at addressing TV pathologies [Buzzatti et al. 2018]

2.1.3 Physiological Functioning

The human heart contains four main valves: the mitral, tricuspid, aortic, and pulmonary valves. These valves play a critical role in ensuring unidirectional blood flow through the heart's four chambers, contributing to the efficiency of the cardiovascular system. The opening and closing of these valves are tightly regulated by pressure changes in the heart chambers during the cardiac cycle.

► MECHANISM OF VALVE FUNCTIONING:

- During diastole, the mitral and TVs open in response to pressure differences, allowing blood to flow from the atria to the ventricles.
- As the ventricles contract in systole, the mitral and TVs close to prevent backflow of blood into the atria. Concurrently, the aortic and pulmonary valves open, allowing blood to be ejected from the ventricles to the aorta and pulmonary artery, respectively.
- When ventricular pressure falls below that in the aorta and pulmonary artery at the end of systole, the aortic and pulmonary valves close to prevent the backflow of blood into the ventricles.

► IMPLICATIONS OF VALVE MALFUNCTION:

- Valvular Stenosis: Stenosis of a valve leads to a narrowing of the valve opening, restricting blood flow. This results in increased workload for the heart chambers upstream of the affected valve, potentially causing hypertrophy and, ultimately, heart failure.
- Valvular Regurgitation: Valve regurgitation occurs when a valve does not close properly, allowing blood to flow backward. This leads to volume overload in the affected chambers, requiring the

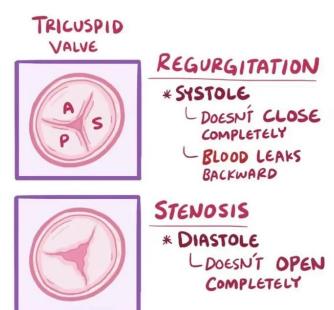


FIGURE 2.3: Illustration of Regurgitation vs Stenosis [Tricuspid Valve Disease n.d.]

heart to work harder to pump the additional volume, which can also lead to heart failure over time.

Both conditions, if severe, can significantly impair cardiac function and may require surgical intervention, such as valve repair or replacement, to restore normal blood flow dynamics and prevent further cardiac damage. For instance, afterload mismatch in valvular heart disease, particularly in aortic stenosis, occurs when the left ventricle is unable to generate sufficient pressure to overcome the increased afterload caused by the stenosed valve, leading to a decrease in cardiac output. Surgical therapy, like aortic valve replacement, can relieve this mismatch and improve cardiac function, underscoring the importance of timely intervention in patients with valvular heart disease [Ross 1985].

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2.1.4 Variability and Pathologies

The **TV** is an essential component of the heart's right side and plays a critical role in the unidirectional blood flow from the right atrium to the right ventricle. Its anatomy and functioning can be affected by various factors, highlighting the importance of understanding its variability and pathologies;

► **ANATOMICAL VARIABILITY:**

The **TV** typically features three leaflets (anterior, septal, and posterior), supported by chordae tendineae and papillary muscles. However, there can be considerable anatomical variability, including the number and size of leaflets, the structure of the subvalvular apparatus(papillary muscles, chordae tendineae and free wall), and the annular size. Such variations can impact valve function and are crucial for distinguishing between normal anatomical diversity and pathological alterations. In some instances, additional leaflets or unusual leaflet sizes are observed, affecting the valve's competence and flow dynamics. Understanding these variations is essential for accurate diagnosis and treatment planning, especially in surgical repairs and replacements . [Tretter et al. 2016]

► **PATHOLOGIES AFFECTING VALVE FUNCTION:**

TV pathologies can be classified into primary, involving intrinsic valve anatomy alterations, and secondary, resulting from functional modifications due to other cardiac or systemic conditions.

- Primary **TV** disease encompasses congenital abnormalities, infective endocarditis, rheumatic disease, and degenerative changes.

- Secondary **TV** disease is often related to left heart diseases or pulmonary hypertension, leading to tricuspid annular dilation and right ventricular remodeling. These changes can result in tricuspid regurgitation or, less commonly, tricuspid stenosis, significantly impacting cardiac function and patient prognosis.

Advanced imaging techniques are crucial for the detailed evaluation of **TV** anatomy and pathology, aiding in the accurate assessment and management of these conditions. [Shah and Raney 2008] One key aspect of tricuspid regurgitation that this study is looking to capture is the remodelling affects that tricuspid regurgitation has on the right ventricle and the valvular apparatus, some key variables that changes are the annular dilation, annular height, and circularity, which have been shown to increase in [Nam et al. 2023] and chordal/papillary muscle lengths in [Obase et al. 2016]. All of these parameters are hoped to be captured over the study.

► NEED FOR EFFECTIVE SIMULATION MODELS:

Given the complex anatomy of the **TV** and the wide range of pathologies that can affect it, there is a growing need for effective simulation models. These models, computational and experimental can help in understanding the functional impacts of anatomical variability and pathological changes on the **TV**, facilitating the development of more precise diagnostic tools and treatment strategies. Such models are particularly valuable in planning surgical interventions and predicting their outcomes.

2.2 ADVANCES IN HEART VALVE DISEASE TREATMENT

The landscape of treatments for **TV** disease has been evolving, incorporating both surgical interventions and transcatheter approaches to offer alternatives for patients with varied risk profiles. Surgery remains the standard treatment for **TV** disease, with techniques such as annuloplasty, leaflet repair, or valve replacement being common. However, surgical intervention is often reserved for patients without significant comorbidities due to the invasive nature of the procedures and the associated recovery times.

► TRANSCATHETER DEVELOPMENTS:

Transcatheter techniques have emerged as a forefront innovation for treating **TV** disease, especially for high-risk patients for whom traditional surgery is not viable. Transcatheter **TV** repair and replacement therapies

have shown promise in reducing tricuspid regurgitation and improving patient outcomes with less invasiveness than traditional surgery.

- In transcatheter tricuspid valve repair various devices and techniques are being developed and tested, including coaptation devices, annuloplasty systems, and heterotopic caval valve implantation. These approaches aim to reduce tricuspid regurgitation by improving leaflet coaptation or reducing annular dilatation, offering symptomatic relief and functional improvement to patients with severe tricuspid regurgitation. [Hell et al. 2021]
- Transcatheter tricuspid valve replacement involves the percutaneous placement of a new valve within the native tricuspid annulus or a previously implanted surgical valve. This method has been advantageous for patients with severe **TV** disease who are ineligible for surgical repair or replacement, demonstrating comparable safety and short-term outcomes. [Gales et al. 2018]

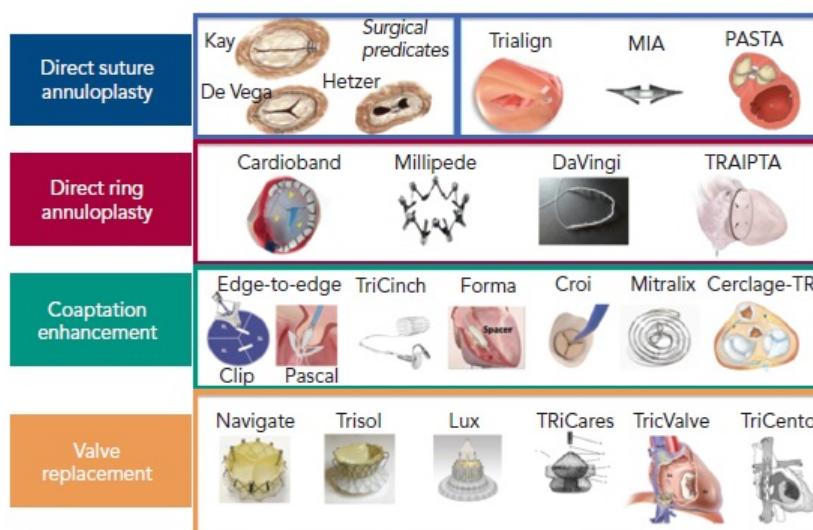


FIGURE 2.4: Current landscape of **TTVR** products being used surgically [Curio et al. 2019]

► IMPACT OF VALVE MODELLING AND SIMULATION:

Advancements in valve modeling and simulation have significantly impacted the development of new therapeutic techniques for **TV** disease. High-fidelity models created from patient-specific anatomical data have been instrumental in the design and testing of transcatheter devices, allowing for the precise customization of treatments. Computational simulations have also been crucial in understanding the biomechanical properties of the **TV** under various physiological conditions, aiding in

the optimization of device designs for improved durability and performance. These innovations in modelling and simulation hold the potential to enhance treatment outcomes for **TV** disease, paving the way for the development of more effective and less invasive therapeutic options.

2.3 CURRENT MODELS AND SIMULATORS

2.3.1 Early Developments and Evolution of Physical Simulators

The development of simulators in the field of cardiac care has a rich history, tracing back to the mid-20th century when the first conceptual models of blood flow dynamics and heart mechanics were introduced. These early models were primarily analog systems that used electrical circuits to mimic the hydraulic and hemodynamic properties of the heart. A pivotal innovation during this period was the development of the Windkessel model [Westerhof et al. 2009], which was crucial in understanding arterial load and its effects on cardiac function, it described the haemodynamics of the arterial system in terms of resistance and compliance. It explained aortic pressure decay in diastole, but fell short in systole. The development of physical simulators has come hand in hand with clinical, computational and biological research advancements. Increases in computational power have allowed for the development of more advanced finite element models of the heart, which can simulate complex interactions between blood flow and heart valve mechanics. Software advancements have also played a critical role, with tools capable of simulating **FSI** in the heart. Tangential clinical and biological studies have given more reason to develop physical simulators as now new hypotheses can be drawn from their learnings and then tested in a physical model.

The advent of 3D printing and **CAD** technologies has revolutionized the fabrication of physical heart valve simulators. These technologies allow for high precision and customization of simulator components, enabling the production of complex valve geometries that accurately represent diverse anatomical variations seen in the population. This capability is vital for developing simulators that can be used for specialized surgical training and pre-surgical planning.

2.3.2 Current State of the Art Simulators

Heart valve models and simulators have significantly advanced, providing diverse tools for educational purposes, surgical planning, and research. These models range from low-fidelity simulators for basic

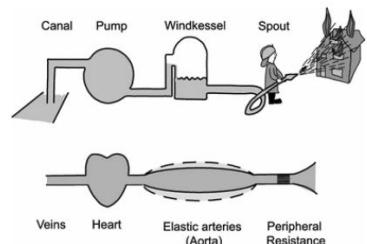


FIGURE 2.5: Concept of the WindKessel Model [Westerhof et al. 2009]

educational use to high-fidelity, patient-specific models for complex surgical planning and research on prosthetics or interventions.

► **SURGICAL PLANNING AND EDUCATIONAL MODELS:**

Low-fidelity models, often made from commonly available materials, are used primarily for educational purposes. They provide an accessible and cost-effective means for trainees to develop surgical skills and understand valve anatomy and function. For instance, novel simulators made from components like baby bottles, combined with dental dam, offer simulation training in mitral and TV surgical techniques, almost anywhere, at minimal cost. These models have been evaluated positively for their ability to replicate anatomy and surgical handling, proving very useful as training tools for cardiac surgery [Verberkmoes and Verberkmoes-Broeders 2013]

One attempt at such an educational simulator took an entirely tissue-based approach. [Ramphal et al. 2005] This offered a realistic environment for training cardiac surgical residents, replicating a variety of cardiac surgical procedures. They are instrumental in low-volume cardiothoracic surgery units, providing trainees with pre-clinical experience and helping them respond to clinical situations associated with heart-lung bypass machine operation and changes in patient clinical parameters.

Advanced, high-fidelity models are developed for surgical planning and research, employing technologies like 3D printing and silicone casting to create patient-specific valve models. These models enable simulation under dynamic physiologic conditions, allowing for the testing of surgical repairs and interventions with considerable accuracy. For example, dynamic ventricular simulators, capable of testing the quality of simulated heart valve procedures, utilize 3D printed valve suspension chambers and model pulsatile pumps to provide close-to-physiologic hemodynamic conditions for education and training in cardiac surgery [Zilinskas et al. 2022]

Simulation models for valve surgery, like those for mitral valve repair, offer detailed physiological simulation, including real-time feedback mechanisms. These models incorporate integrated sensors to generate, record, and display quantitative data on trainee performance, significantly enhancing the learning experience [Tozzi et al. 2022]

Utilizing 3D printed valve suspension chambers and model pulsatile pumps, these simulators offer close to physiologic hemodynamic conditions. They have been validated for testing aortic valve leaflet repairs and replacements, demonstrating the potential for extensive educational use in cardiac surgery. [Zilinskas et al. 2022]

Computational models are developed based on patient-specific data to predict clinical outcomes, aiding in planning medical procedures such as percutaneous pulmonary valve implantation and surgical repair of congenital heart diseases. These simulations have shown good agreement with clinical decisions, demonstrating their utility in personalized cardiovascular treatments. [Capelli et al. 2017]

► RESEARCH-FOCUSED MODELS:

For research, especially in developing prosthetics and testing interventions, simulators that can replicate the heart's mechanical and hemodynamic environment under various conditions are utilized. These include both native heart valve simulations and artificial heart valve simulations, categorized based on the prototype model. Such models are pivotal in studying valve biomechanics, facilitating predictive surgical planning, and aiding in the design and evaluation of repair devices and prostheses [Zhong et al. 2014]

Simulators designed to house an entire explanted heart subjected to pulsatile fluid-dynamic conditions enable the hemodynamic analysis of simulated surgical procedures. These setups are beneficial for device testing, offering a platform for in-depth investigation of valvular surgeries and interventions. [Leopaldi et al. 2012]

► FIDELITY TO HUMAN ANATOMY AND PHYSIOLOGY IN SIMULATORS:

- Some **BHV**'s, such as the Texas TriValve 1.0, have made significant strides in computationally capturing the kinematics and kinetics of the native **TV**. This model, reverse-engineered from a beating human heart, showcases how finite-element models can closely mimic the natural function of the **TV**, including disease-induced and repair-induced changes. This level of detail offers a promising

platform for simulating surgical and transcatheter interventions, aiming to improve patient outcomes. [Mathur et al. 2022]

- Advanced simulators and models, especially those using 3D printing and computational simulations, have demonstrated a high degree of anatomical and physiological accuracy. These models can replicate complex heart valve geometries and dynamics, providing realistic conditions for training, surgical planning, and device testing. [Rabbah et al. 2013]
- Anatomical and Mechanical Studies: Comparative studies have been crucial in understanding the mechanical, morphological, and microstructural differences between the mitral and tricuspid leaflets and chordae tendineae. These studies reveal that while there are no major differences in leaflet mechanics between the two valves, chordal mechanics can vary significantly, influenced by anatomical location and valve type. This information is vital for surgical and computational applications, especially considering the TV's unique stresses and strains. [Pokutta-Paskaleva et al. 2019]

► PAPER RELEASED MARCH 2024 - POST THESIS WORK CONDUCTED

- A research group in Heidelberg [Karl et al. 2024] developed a rig for mitral valve investigations in a manner similar to the aims of this project as they worked to investigate the effects of the MitraClip device. The rig was designed with less anatomical accuracy and not allowing PIV measurement however this allowed the group to implement fixturing for motorized chordae tendineae adjustment and a camera system very close up and head-on to the valve to capture the coaptation process. This study ran a few different experiments, one with a mitral valve prosthesis, one with a mechanical valve, two with ex-vivo valves that were sewn onto an oversized elliptical frame and one experiment most close to the nature of this thesis where an in-vitro valve was

► IMPACT ON UNDERSTANDING VALVE MECHANICS AND PATIENT OUTCOMES:

Simulators play a crucial role in understanding the intricate mechanics of heart valves under various physiological and pathological conditions. They provide a risk-free environment for exploring new surgical techniques and device interventions, which is critical for advancing cardiac

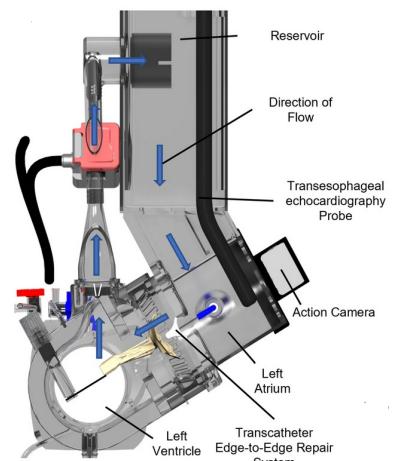


FIGURE 2.6: Side cross section of simulator with dynamic statecamera attachment [Karl et al. 2024]

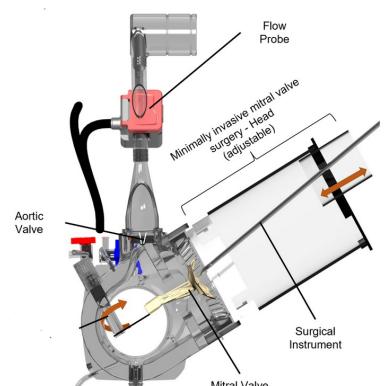


FIGURE 2.7: Side cross-section with static state surgery attachment [Karl et al. 2024]

care. By allowing for the simulation of complex cardiac procedures and the testing of prosthetic valves and annuloplasty rings, these tools help improve surgical precision and patient outcomes. The feedback and data generated from simulators enable continuous learning and adaptation of best practices in heart valve surgery and intervention.

2.4 MATERIALS AND METHODS IN VALVE MODELING

2.4.1 Materials Used in Valve Modeling

The development of heart valve models utilizes a range of materials, from biological tissues to synthetic polymers. These materials are selected based on their ability to simulate the natural behavior of heart valves, which is critical for ensuring the models' effectiveness in clinical training, pre-surgical planning, and device testing.

► BIOLOGICAL TISSUES:

Biological tissues have been a cornerstone in heart valve modeling, particularly for **BHV** constructs. These tissues, typically derived from porcine or bovine sources, undergo treatments to enhance durability and reduce immunogenicity. The inherent biological properties of these tissues, such as their biomechanical behavior and hemocompatibility, make them suitable for simulating natural heart valve function. Limitations such as potential calcification, immune reactions have been shown however porcine and bovine pericardium remains commonplace in current **TTVR** and **TAVR** respectively. [Filová et al. 2009]

► EMERGING MATERIALS AND TECHNOLOGIES:

Recent advancements have led to the exploration of nanocomposite polymers¹ and hydrogels for heart valve modeling. Nanocomposite polymers, such as poly(carbonate-urea)urethane integrated with polyhedral oligomeric silsesquioxanes, exhibit enhanced mechanical properties and biostability. These materials show reduced calcification potential under in vitro conditions, making them attractive for the development of synthetic leaflet heart valves [Ghanbari et al. 2010]

Hydrogels, derived from natural or synthetic sources, are being investigated for their potential in valve tissue engineering due to their biocompatibility and ability to support cell adhesion and proliferation. Challenges exist in balancing the bioactivity and mechanical durability of hydrogels to meet the demands of heart valve function. [Zhang et al. 2015]

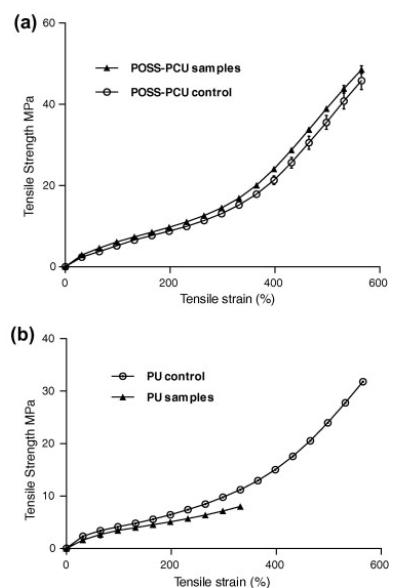


FIGURE 2.8: Comparison of PU and poly(carbonate-urea)urethane for heart valve performance [Ghanbari et al. 2010]

¹essentially adding nano-sized building blocks into the polymer matrix which enhances durability while maintaining flexibility and processability

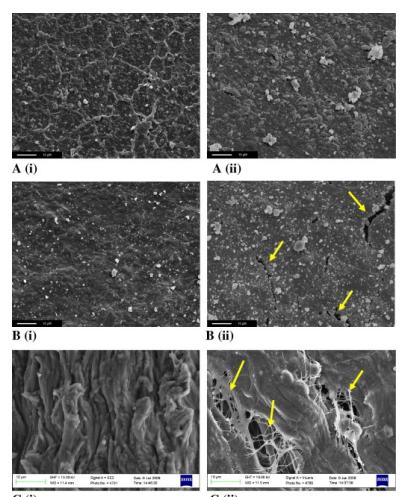


FIGURE 2.9: Comparison surfaces in fatigued (a) PU (b) poly(carbonate-urea)urethane (c) valve leaflets showing tissue failure and fibre dehiscence marked by the yellow arrows in each [Ghanbari et al. 2010]

Synthetic Polymers:

Synthetic polymers offer an alternative to biological tissues with advantages in consistency, durability, and the potential for customization. Polyurethane, silicone rubber, and PET are among the polymers explored for heart valve modeling. Polyurethane, in particular, has shown promise due to its excellent tear resistance and similarity to the mechanical properties of natural valve tissue. The flexibility and durability of PU make it an appealing choice for synthetic heart valve leaflets, though challenges remain in mimicking the viscoelastic properties of natural valves. [Baxter et al. 2006]²

- ▶ SILICONE MITRAL VALVE STUDY The Engelhardt group [Engelhardt et al. 2019]

²In the context of this project, choosing a synthetic material is desirable due to the intrinsic need of longevity so finding a PU similar to those in valve replacements that can mimic the TV's function is



FIGURE 2.10: Video of annuloplasty being performed on silicone mitral valve ([click to view video](#))

- ▶ [Ginty et al. 2018] finish this paper disc
- ▶ POLYURETHANE MITRAL VALVE STUDY [Luo et al. 2012] 0.125mm average thickness, chordae 0.7mm diam, modelled in systole, leaflet youngs modulus 5.4mpa chordae youngs 30mpa
small Youngs modulus (0.5 MPa) and high extensibility (900%) of the silicone alone. MV structures such as primary chordae tendineae have a higher Youngs modulus (85 MPa) and a lower extensibility (4.3%)[Liao and Vesely 2003]

2.4.2 From Anatomical Data to Model

► PRECEDENT OF LEFT HEART VALVE MODELS:

In the process of translating anatomical data from **CT** scans and **MRI** into functional heart valve models, researchers have developed sophisticated methods to accurately capture the complex geometry and dynamics of the heart's valvular apparatus. This transition from imaging data to practical, patient-specific models is pivotal in advancing cardiac care, offering insights for surgical planning, device testing, and personalized treatment strategies.

[Ionasescu et al. 2010] introduced one of the first automatic computational systems for patient-specific modeling and quantification of the left heart valves, operating on cardiac **CT** and transesophageal echocardiogram data. Their method, leverages discriminative learning and estimates parameters from volumetric slices, enabling a holistic representation of the aortic and mitral valves that accounts for anatomical variations.

In a similar vein, [Grbic et al. 2012] proposed a patient-specific model of cardiac valves from 4D cardiac **CT** data. Their model addresses the anatomical, functional, and hemodynamic aspects of the heart, utilizing a constrained Multi-linear Shape Model conditioned by anatomical measurements. This approach offers a more detailed representation of the heart's valvular structures and dynamics, facilitating the study of valvular pathologies and interventions.

[Finish this paper disc](#)

One research group has done multiple studies on making anatomical models for procedure planning and device testing. The group 3d printed semi flexible material to implant the MitraClip device[Vukicevic, Puperi, et al. 2017] and later did the same for the tricuspid valve [Vukicevic, Faza, et al. 2020]

► CHALLENGES WITH RIGHT HEART:

The challenges of the right heart stem primarily from the complex anatomical and functional nature of the **TV**, which can be more difficult to capture accurately due to several factors:

- The **TV**'s structure includes multiple leaflets (usually three) and a complex subvalvular apparatus, which are not symmetrically arranged. This complexity makes it harder to capture and model accurately using standard imaging techniques compared to the more symmetrically structured mitral valve.
- Both CT and MRI rely on good contrast resolution to differentiate between structures. The right heart's lower pressure and flow conditions can result in poorer contrast enhancement of the **TV**, further

complicating accurate imaging and subsequent modeling. [Ahn et al. 2021]

- The tricuspid valve is subject to significant motion during the cardiac cycle, and capturing its dynamic behavior accurately with CT and MRI is challenging due to potential motion artifacts. [Suh et al. 2017]

While these challenges have slowed progress, research on the right-heart is catching up and with techniques like CT motion-correction algorithms and wide-detector CT with low radiation doses [Ahn et al. 2021; Suh et al. 2017] so the benefits of patient specific modeling can be extended to the right heart as well.

2.4.3 *Evaluation and Testing Methods*

The evaluation and testing of heart valve models are crucial to ensure their functionality, mechanical properties, durability, and physiological accuracy. Several methodologies have been developed to assess these aspects, employing both in vitro and computational simulation techniques.

► MECHANICAL PROPERTIES AND DURABILITY TESTING:

- Bench Testing to ISO Standards: [Stasiak et al. 2020] reported on the design, development, and testing of a polymeric heart valve, including bench testing according to ISO 5840:2015 standards. Their study highlights the importance of rigorous bench testing in evaluating valve hydrodynamics, durability (tested to over 1.2 billion cycles), and preliminary biocompatibility in short-term animal models. This comprehensive approach ensures that new valve designs meet international safety and performance standards before clinical application.
- In Vitro Testing: [Walker 2010] developed a novel test chamber for an automated mock circulatory loop to evaluate the mechanical performance of heart valves. This method allows for the simulation of physiological flow conditions to assess valve functionality, durability, and potential thrombotic and hemolytic effects. Such setups are vital for understanding how artificial heart valves would perform under real-life conditions.

Resources:

- Revised ISO Overview

- [Thomas et al. 2019] implemented a multiscale modeling approach to predict extracellular matrix microstructural changes in response to tissue-level mechanical stimuli in the **TV**'s anterior leaflet. This study highlighted the importance of understanding microstructural alterations under mechanical loading for developing new tissue-engineered replacements.

► PHYSIOLOGICAL ACCURACY AND **FSI** MODELS:

- [Lee et al. 2020] developed dynamic computer models of **BHVs** in an experimental pulse duplicator, based on the immersed boundary method for **FSI**. These models simulate porcine tissue and bovine pericardial BHVs under conditions used to assess performance in commercial and custom pulse duplicators. The agreement between computational simulations and experimental data for bulk flow rates, pressures, and valve opening areas underscores the potential of **FSI** modeling in valve design and evaluation.
- [D'Amore et al. 2018] introduced double component deposition, an electrodeposition technique for fabricating valve scaffolds with controlled macro-scale morphology, mechanics, and micro-structure. This method allows for the creation of fully assembled stent-less multi-leaflet valves, demonstrating the capability of emerging fabrication techniques in producing scaffolds that closely mimic natural valve behavior.
- [Laurence et al. 2019] conducted an investigation into the regional variations in the biaxial mechanical properties and stress relaxation behaviors of porcine atrioventricular heart valve leaflets. Their findings underscored the significance of accounting for regional differences in valve biomechanics to refine computational models for predicting diseased or surgically altered valve function. This approach allows for a more accurate simulation of heart valve dynamics and mechanical behavior under varying physiological conditions.

2.5 REGULATORY AND ETHICAL CONSIDERATIONS

2.5.1 *Regulatory Standards for Valve Models and Simulators*

The development and use of heart valve models and simulators, particularly those intended for biomedical engineering or pre-surgical planning,

are governed by a comprehensive regulatory environment. This framework ensures that these tools meet stringent standards for accuracy, safety, and efficacy before being implemented in clinical settings.

► **EXPERIMENTAL VALIDATION AND ISO STANDARDS:**

The experimental validation of cardiac simulators, as described by [Bazan and Ortiz 2016-Mar-Apr], is a critical step in developing prosthetic heart valves. Their work underscores the importance of adhering to physiological conditions and meeting the requirements of ISO 5840 standards, which set global benchmarks for cardiovascular implants and cardiac valve prostheses. This ensures that simulators provide a suitable environment for testing valve performance in the mitral, aortic and tricuspid positions under varying heart rates.

► **SAFETY REGULATIONS:**

While physical simulators are not used within patients, they must still adhere to safety regulations to ensure they pose no hazard during use. This includes mechanical, chemical and electrical safety standards, especially for those simulators that involve interactive components or electronic devices. Regulators might require that these devices be certified safe for use in educational environments, involving regular maintenance and safety checks as well as proper training for users, personal protective equipment availability and general workplace safety.

► **LIVING HEART PROJECT AND INTEGRATIVE SIMULATORS:**

The Living Heart Project represents a significant advancement in simulating human heart function through a four-chamber heart model. This integrative simulator showcases the potential of computational models of the whole heart, including its valves. Such initiatives illustrate how regulatory standards can evolve to include advanced computational methods and integrative simulators for heart valve research and development [Baillargeon et al. 2014] and how other research work can contribute to new regulatory standards and set a precedent for how future heart valve simulators should be conducted.

2.5.2 *Ethical Implications*

The development and deployment of physical heart valve simulators involve significant ethical considerations, especially concerning patient safety, informed consent, and access to innovative technologies.

► PATIENT SAFETY:

The primary concern in the development of new heart valve simulators is to ensure patient safety. As these simulators are used in educational and pre-surgical planning, it is crucial that they accurately mimic human physiology to prevent potential errors during actual surgeries. Ensuring the safety and efficacy of these simulators involves rigorous testing and validation processes to avoid any adverse consequences during training sessions or surgical planning. [Rajab et al. 2013]

► INFORMED CONSENT:

Although physical simulators are not implanted in patients, obtaining informed consent is crucial when they are used in scenarios that involve patient interaction, such as educational demonstrations or pre-surgical planning. Patients and participants should be fully informed about the procedures being simulated, the use of their data (if applicable), and the nature of the demonstrations to uphold ethical standards of autonomy and consent. [Fletcher 1983]

► ACCESS TO INNOVATION:

Access to high-quality educational tools and advanced simulators should be equitable to ensure that all medical professionals, regardless of their institution's economic status, have the opportunity to train with the best available tools. This is essential for maintaining high standards of healthcare globally and ensuring that advancements in medical training are accessible to all healthcare providers, thus broadening the benefits of innovative educational simulators. [Aultman et al. 2018]

By addressing these ethical considerations, developers and users of heart valve simulators can ensure that their use in medical education and surgical planning is both effective and ethically sound, supporting the broader goals of improving patient care and surgical outcomes.

2.6 RESEARCH STRENGTHS AND GAPS

2.6.1 *Research Strengths*

► ADVANCEMENTS IN IMAGING AND COMPUTATIONAL SIMULATIONS:

Recent years have witnessed significant advancements in imaging techniques and computational simulations, which have enhanced the understanding and modeling of heart valve mechanics. High-resolution imaging modalities such as 4D CT and MRI have enabled detailed anatomical

and functional assessments of heart valves in real time. These advancements have facilitated the development of more accurate computational models that can predict how valves behave under various physiological and pathological conditions. Such models are invaluable for both pre-surgical planning and the design of prosthetic valves.

► INTEGRATION OF PATIENT-SPECIFIC DATA INTO VALVE DESIGN:

The incorporation of patient-specific anatomical data into the design and testing of heart valves is a major strength in current research which can significantly enhance the efficacy and safety of treatments as outcomes can be predicted. This approach has led to the development of customized prosthetic valves as opposed to one-size-fits-all valves where there is increased risk of failure. [Kidane et al. 2009]

► REGULATORY AND STANDARDIZATION ADVANCES:

The establishment of standardized testing protocols and regulatory guidelines for heart valve devices is another significant strength. This regulatory framework supports innovation while ensuring patient safety and the reliability of heart valve products on the market. By adhering to these standards, researchers and manufacturers can develop and test heart valve devices more effectively.

2.6.2 *Research Gaps*

► ANATOMICAL VARIABILITY:

The significant anatomical variability of the TV presents challenges in creating universally applicable models. For example, the presence of additional leaflets or variations in chordae tendineae and papillary muscles can significantly impact valve function and complicate the design of surgical interventions or prosthetic valves. Understanding and incorporating this variability into models remains a challenge. [Tretter et al. 2016]

Being able to, with the same piece of equipment, account for changes like these in real-time would be greatly beneficial to studies on the TV devices and interventions.

► MATERIAL PROPERTIES AND BIOMECHANICS:

Accurately simulating the material properties and biomechanical behavior of the TV leaflets and subvalvular apparatus is complex. Finite element modeling studies have attempted to address this by adjusting

material parameters and considering different collagen fiber distributions. However, these models still face limitations in accurately representing shear behavior and the complex interactions within the TV apparatus under various physiological and pathological conditions. [Stevanella et al. 2010]

Developing materials that can mimic the viscoelastic properties of natural valve tissues and withstand the mechanical stresses of long-term operational testing is a critical gap in the field. This would afford researchers the time to gather more data on the same specimens in testing, increasing the reliability and statistical significance of the results.

► DYNAMIC BENCH-TOP SIMULATION CAPABILITIES:

Enhancing the dynamic response of simulators to replicate real-time cardiac motions and valve mechanics accurately. This includes the ability to simulate different heart rates, pressures, and pathological conditions to understand their impacts on valve function and durability as well as materials that accurately mimic the biomechanical properties of natural heart tissues, which is challenging due to the complex nature of biological tissues. These materials need to withstand the mechanical stresses of long-term operation to be effective for training and testing.

Current simulators have often opted for integrating dissected porcine hearts into their setups rather than developing synthetic materials which can only withstand a very limited amount of testing before failure. This is a significant gap in the field as it limits the ability to perform long-term projects investigating aspects of valve design and function.

Authors & Year	Key Findings	Study Objective	Methodology	Relevance to Your Study	Key Learnings
Filová et al. 2009	Calcification of PU in vivo	Overview of tissue-engineered heart valves	Meta-Analysis	Material Choice	Limited sample size
Baxter et al. 2006	Flexibility and durability of PU	Overview of synthetic materials in heart valves	Tearing energy and crack growth rate tests	Material Choice	Performs even better at elevated temperatures
Aggarwal et al. 2013	Converting CT to 3D	To map patient-specific aortic valves	Spline-fitting with mathematic models using echocardiographic images	Modelling / Morphology	Maps microstructure of leaflets
Leopaldi et al. 2012	Comparative data for experimental and simulatory flow-loop	To develop a flow loop with a porcine heart	Endoscopic imaging and hemodynamic measured with ultrasound flowmeter and piezoelectric transducers	Simulator Development	Compares pressures and flow rates
Zilinskas et al. 2022	Simulator successfully used for performing valve replacement training	To develop a surgical training simulator using porcine aortic roots	Porcine aortic valve dissected and tether to chamber	Simulator Development	Demonstrates efficacy of bench-top simulators

TABLE 2.1: Comparison of key points in the literature review

Part II

METHODOLOGY

3 DESIGN AND PROTOTYPING	
3.1 Conceptualisation and Initial Design	29
3.2 Design Criteria	30
3.3 Modelling and Design Iterations	32
3.3.1 Simplified Valve Designs	32
3.3.2 Representative Valve Designs	33
3.3.3 Model Refinement	33
3.4 Prototyping	35
3.4.1 Valve Iterations	35
3.4.2 Chordae Tendineae	38
3.4.3 Fixturing	39
3.5 Design Validation	39
4 EXPERIMENTAL SETUP AND TESTING	
4.1 Fixturing Assembly	41
4.2 Rig Assembly	42
4.3 Testing Procedure	42
4.3.1 Pilot Checks	42
4.3.2 Coaptation Testing	43

3

Design and Prototyping

- ▶ SYNOPSIS In this chapter the mock valve modelling and prototyping is discussed from conception to completion. Different approaches are discussed in regards to the steps the core design went through;

- Flat Valve: The simplest approach involves creating a flat valve model with leaflets cut to proportion. This design is straightforward to fabricate and provides a basic representation of the TV form.
- Ballooned Valve: A more anatomically accurate design involves creating a balloon-shaped valve similar to regurgitant valves. This approach aimed to mimic the physiological behavior of the TV more closely in the diseased state.
- Ballooned Valve with Chordae Tendineae: Building upon the previous design, this approach incorporates chordae tendineae to simulate the TV's complex structure more accurately with practical considerations to how the valve would be modelled, fully representatively or a simple tri-leaflet valve.
- Anatomical Valve without Chordae Tendineae: This approach involved converting CT scans of an anatomical valve models, providing a highly realistic representation of the TV capturing the likeness very proportionally.

As well as the design of the other components such as the chordae tendineae and fixturing design.

3.1 CONCEPTUALISATION AND INITIAL DESIGN

The essence of a design process is inherently iterative and exploratory. It takes form of a cycle of conception, experimentation, evaluation, and

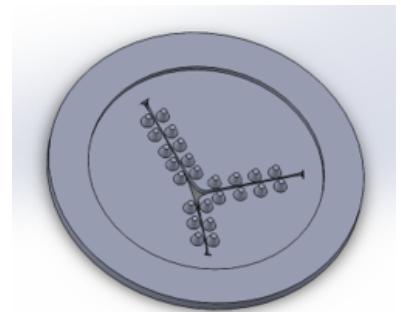


FIGURE 3.1: Flat Valve Model

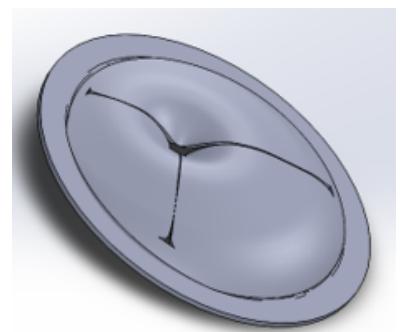


FIGURE 3.2: Billowed Valve Model

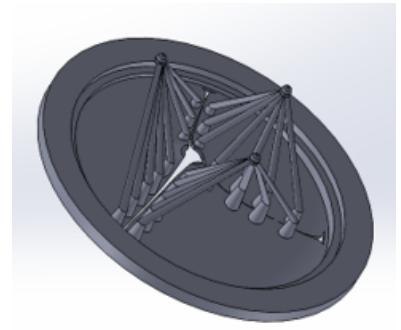


FIGURE 3.3: Billowed Valve with Chordae Tendineae Model

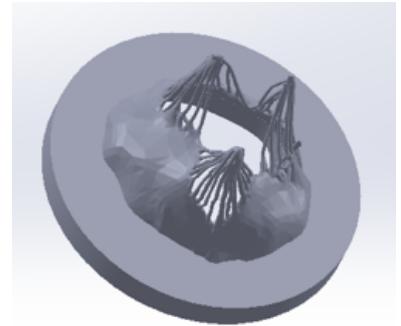


FIGURE 3.4: Anatomical Model

refinement. This iterative cycle is fundamental to translating abstract ideas into tangible solutions that meet set goals.

At the heart of the design process lies trial and error—a methodical yet flexible approach that takes discovery of unexpected challenges and leverages them as opportunities for learning and input. Initial ideas are transformed into preliminary models, serving as the first step in a series of continuous interactions between designing, testing, and iterating.

The dynamic nature of this process sets a strong base to pivot strategies, incorporate new technologies/materials, and adapt to findings in real-time. The design changes throughout this project were not merely reactions to setbacks but were driven by a pursuit of optimization whether in response to material limitations, fabrication challenges, or new modelling insights.

The initial vision of the in-vitro TV was formed on reflection of the literature review. It is crucial to consider both the anatomical fidelity required for effective simulation and the technical feasibility of creating a functional model when developing initial concepts which can then be adapted as the project moves forward and firmer boundaries are discovered.

The approach taken was to start prototyping with the simplest design and gradually increase complexity as the project progressed. This allowed for a more systematic exploration of the design, ensuring that each iteration built upon the insights gained from the previous one with respects to all stages of manufacturing and a minimal time investment in preliminary modelling so the prototyping process could be refined in tandem. This was essential to finishing with a refined final model, balancing anatomical fidelity with fabrication feasibility and functional performance.

3.2 DESIGN CRITERIA

The design criteria were established to guide the development of the mock TV. These criteria were informed by the project's objectives, the gaps in the literature, and the technical constraints of the fabrication process. The design criteria were as follows:

► CRITERION 1: ANATOMICAL FIDELITY

The mock **TV** should precisely resemble the anatomical structure of the **TV**, capturing the key features of the valve's leaflets, annulus, and chordae tendineae and where possible to account for the variations.

- Justification: To maintain a realistic simulator effort must be made to ensure representative geometry to provide a realistic evaluation tool for medical devices.

► CRITERION 2: FUNCTIONAL PERFORMANCE

The mock **TV** should exhibit the functional characteristics of the **TV**, including the ability to open and close in response to fluid flow, and the capacity to simulate regurgitation simulating the physiological and pathological conditions of a natural **TV**.

- Justification: Without these functional characteristics, the mock valve would be limited in applicability for integration and characterisation of a prosthetic valve device.

► CRITERION 3: MATERIAL COMPATIBILITY

The materials used in the fabrication of the mock **TV** should be flexible, durable, and suitable for the intended application, ensuring that the valve can withstand the fluid flow and mechanical stresses.

- Justification: The valve, once integrated into the right heart simulator, will be subjected to continuous fluid flow and mechanical forces over a long period of time, necessitating the use of materials that can withstand these conditions over a long period of time.

► CRITERION 4: FABRICATION FEASIBILITY

The design of the mock **TV** should be amenable to the fabrication process, considering the limitations of the 3D printing and moulding techniques used in the project.

- Justification: Some aspects of **TV** performance are dependent on biological factors that are difficult to replicate such as collagen fiber alignment. This design should be able to be fabricated in a way that can be easily replicated and improved upon in the future.

► CRITERION 5: SCALABILITY AND MODIFIABILITY

The design of the mock **TV** should be scalable, allowing for the creation of multiple valve moulds easily by hot-swapping the scanned and refined **CT** models with varying anatomical features and functional characteristics

- Justification: As the overarching project of the right heart simulator progresses past this thesis the valve should be easily replicated and improved upon again so that future goals can be met.

3.3 MODELLING AND DESIGN ITERATIONS

3.3.1 Simplified Valve Designs

- ▶ FLAT VALVE: As illustrated in [Figure 3.1](#) the flat valve was the first to be developed with the idea being to use it as a basis for developing the complexity. The shape of the leaflets were designed by overlaying images of regurgitant valves from a study which modelled the [TV](#) at different stage of regurgitation [Nam et al. 2023] in systole normal to the annulus of the valve over a disc in SolidWorks and then drawing a spline aligned with the leaflet shapes. In later iterations of this basic structure considerations started to be made for the chordae tendineae, whether to include them or not and then how. There was two schools of thought for this method:
 - Having the tendineae attached within the mould and casting the part all of the same material.
 - Casting the valve part without tendineae and then attaching tendineae after made from another material.

It wasn't until outcomes in the prototyping phase, section:[§ 3.4.2](#), that this was fully decided on based off of experimental results.

- ▶ BILLLOWED VALVE:

The next layer of complexity for the valve to visually replicated an anatomical valve was adding the billowed effect. The literature review section:[§ 2.1.4](#) showed how in reguritant valves the annulus dilates, tendineae weaken and valve develops a partial prolapse, this was reflected in later iterations by creating a revolve feature in SolidWorks in a 'U' shape which was centered within the leaflets (as opposed to the annulus) to overlay the cusp cut on top of. Later iterations of this model included the chordae tendineae, and added extrusions on the leaflet cusps to allow the leaflets to coapt properly however as prototyping progressed

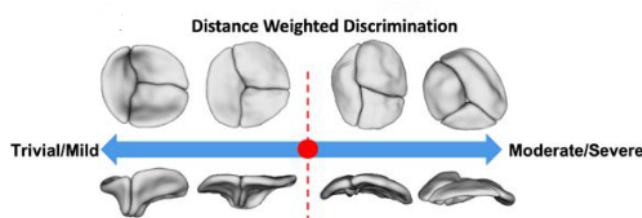


FIGURE 3.5: Visual representation of regurgitant valve morphological progression [Nam et al. 2023]

and the possibility for using a model converted from a **CT** scan grew brighter, the work on the representative models was put on hold.

3.3.2 Representative Valve Designs

► **ANATOMICAL VALVE MODEL:**

While development on the mock valve was progressing the idea for a more anatomically accurate valve began to look favourable for it aligned more closely to the aims of the project. The idea was to use a **CT** scan of a **TV** and then convert this into a 3D model. There was a few options on how to do this, a software package like Mimics can be used to do it easily however this package is very expensive or open source programs like Osirix. Due to the difficulties in capturing the geometry of tricuspid valves in **CT** and the less user friendly interface of Osirix it was decided that a pre-existing model from an online STL repository would be used as a base instead and then refined to fit the project's needs.

With this approach the traceability of the model is lost but with confirmation from the designer that it was developed off of imaging from a human it was deemed fit for purpose.

Harnessing the converted model presented many unexpected challenges, this was discovered when initially trying to import the STL model into SolidWorks a large amount of zero thickness geometries were present. The main technical issues with this model were:

- Self-intersecting faces,
- Non-manifold edges
- Holes throughout the surface
- Inaccuracies in the model
- Widely varying leaflet thickness

The development of it had been originally intended to provide educational illustrations of the anatomy not to be produced physically so work began to refine it.

3.3.3 Model Refinement

In tackling these issues and getting the converted model to a usable state there was a number of softwares tried and tested to see which could

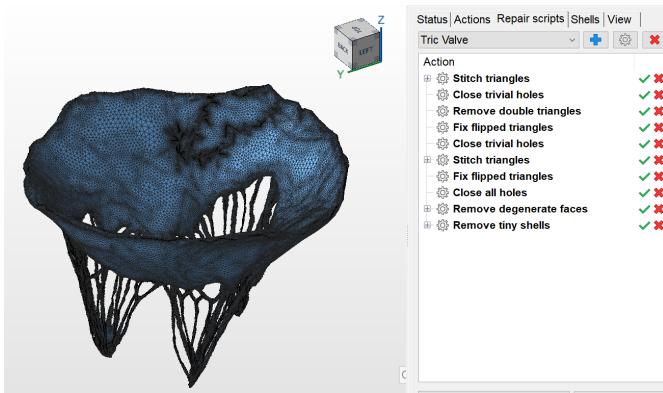


FIGURE 3.6: Netfabb Repair Scripts

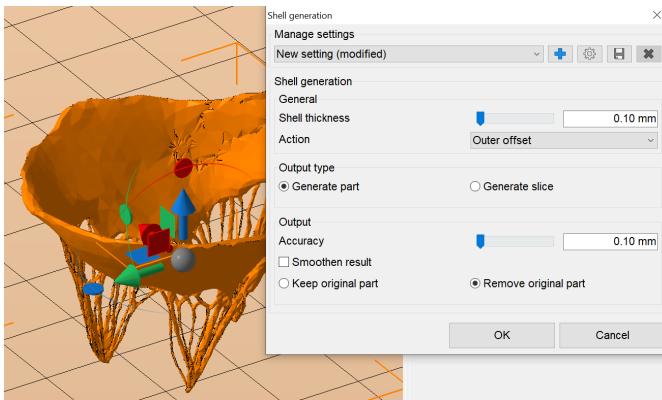


FIGURE 3.7: Netfabb Shell

effectively resolve the issues. The main softwares used were Meshlab, Meshmixer, Blender and AutoCAD NetFabb.

Meshlab is an open-source software that is used for processing and editing unstructured 3D triangular meshes. In nature mesh-lab is very low-level³, it was used to try and remove the non-manifold edges, however the methods to do so require knowledge of advanced mathematical equations and how to manipulate them. With initial attempts resulting in the model being distorted and unusable, the decision was made to find a more user-friendly software.

AutoCAD NetFabb seemed a fitting replacement as mentioned in many only forums discussing MeshLab's drawbacks. Originally designed for additive manufacturing processed it also contained a diverse suite of useful tools to repair the model, personalized repair kits could be designed to fix specific issues for the TV and most importantly had been developed for higher-level applications.

- Repair Scripts
- Shell

³Low-level programming involves direct manipulation of hardware resources, offering granular control but requiring detailed hardware knowledge.

After the repairing and hollow shell process was completed the model was imported into Blender, here

Meshmixer was used in tandem with blender as it contained a very useful thickness analysis tool which could be used to see the varying thicknesses of the leaflets in the imported model, then Blender was used to manually edit the model using its sculpting tools to either thicken or thin the surface where appropriate.

Once the final valve model was finalised the decision was made to flatten the saddle-shape of the geometry to simplify the moulding and mounting processes, some surgical studies like [Mahmood et al. 2010] showed that for mitral valves it does have a structural disadvantage however this did not reduce the ability to coapt properly.

3.4 PROTOTYPING

3.4.1 Valve Iterations

- ▶ PRELIMINARY PROTOTYPING METHODS The prototyping method went through a few key stages, throughout the simplified valve modelling stage the running methods were creating PLA prints of the flat and billowed valve models and then using a silicone mould to capture its likeness, through feasibility testing it was found this method was not suitable for as;
 - Silicone moulds could not hold firm enough in casting to maintain sub 1mm thicknesses.
 - The mould release agent was less effective on PU-Silicone interfaces than expected.
 - The moulds even with appropriate vent holes and degassing would still have large air bubbles and not fill out to the edges of the part.



FIGURE 3.8: Silicone Mould Design



FIGURE 3.9: Press Mould Design and casted part for Flat Valve

As it seemed no amount of optimization of this method would improve results further work was done to find a more suitable method.

- ▶ **PRESS MOULDING** This new method involved designing blocks in Solid-Works as a separate body to the valve part and using the 'Combine' tool to subtract the valve part. This hollowed block could then be split in the middle to create a two-part mould.

The **PU** resin could then be poured into the cavity part and the lid part pressed onto with a C-clamp to create a tight seal.

This method was trialed on the simplest flat valve model to seek learnings for my complicated designs, some such learning were;

- To measure the volume of the 2-part casting fluid with a precision scales as opposed to doing by eye, having the mixture slightly off resulted in gross discolouring and an extremely sticky surface.
- To come up with a new chordal attachment method as the trialed insertion buds were ineffective.

As the modelling stages evolved in complexity so did the prototyping, in trialing preliminary anatomical valves for press moulds it was discovered that due to STL interaction issues with solid **CAD** geometries the valve could not be moulded directly and so a mould die was designed and prototyped of the valve part mould die, making it a two step process to work around this modelling issue.

A deep-cast epoxy was used to pour into these die so form the moulds for the valve, key learnings from this process were;

- Thin, easily breakable walls for the mould die were imperative as the epoxy parts were difficult to remove, this had a downside



FIGURE 3.10: Iterations of epoxy mould die method

of making the die single use. This was hoped to be avoided with notches to pry the epoxy part out but ultimately wasn't effective.

- A split mould was trialed as it was thought to make demoulding the casted part easier however this resulted in significant lines being apparent and didn't help significantly in demoulding so it was abandoned.
- Embossing and debossing key slots in the die ensured the moulds could be aligned correctly with ease.
- Sanding down the **PLA** prints to a smooth finish so in combination with a mould release grease greatly eased the demoulding of the die.
- Initial drafts of mould die joined the cusps of leaflets directly however it was found that extruding the cusps axially stopped excess material from curing past the cusp of the leaflet and also acted as a central large key slot for pressing the moulds into each other.

3.4.2 Chordae Tendineae

Initial conceptualization of the chordae tendineae involved having the valve as one homogenous material with the tendineae attached within the mould. However, as the project progressed and the complexity of the valve increased, it was decided that the tendineae should be a separate part that could be attached after the valve was cast. This was decided on as the elastic modulus of the tendineae was vastly different as they function to be pulled taught to stop the leaflets from prolapsing.

- ▶ DESIGN OF CHOICE: A 0.1mm nylon fishing wire was chosen to represent the tendineae as it was thin enough to be completely collapsible and not interfere with the opening in the diastolic phase. The attachment to the valve was the more challenging aspect, a few methods were considered and tested:



FIGURE 3.11: Testing the methods for attaching the chordae tendineae to leaflets

- Suture patterns along the cusp of the leaflets.
 - A short continuous suture was used to attach a few tendineae to the leaflets on a sample piece of PU how on a gentle tensile test the suture ripped out as the PU wasn't strong enough to hold.
- Using a small hole in the leaflet to thread the tendineae through and then knotting it on the other side.
 - This method also failed as the elasticity of the PU made it so the knot would have to be PU would rip anyway.
- Embedding the wire in the PU leaflets.
 - While hopeful the embedding technique proved not feasible as the wire just slipped out, there was an attempt made with thick and thin layers of additional PU but to no avail.

- Gluing the tendineae to the leaflets with a cyanoacrylate adhesive.
 - While this method showed initial promise as the adhesive was strong enough to hold the tendineae after seconds of curing, when 24 hours passed the adhesive would harden much stiffer and deform the leaflets making them very rigid.
- Gluing with B7000 adhesive.
 - The B7000 adhesive was chosen as it was a flexible adhesive, initial tests weren't fruitful but if left to set fully over 24 hours the bond became very strong and the leaflets retained their flexibility while also only needing a minuscule amount for a good hold so the very thin thickness of the leaflets wasn't negated.

3.4.3 Fixturing

The design criterion was considered carefully before modelling the test fixturing. The main desired outcomes from the testing that the fixturing should facilitate were:

- The chordae tendineae should have anchors which are fully adjustable axially and angularly to allow for a range of testing positions.
 - The valve should be mounted in a way that the leaflets are not obstructed so the valve can be viewed from multiple angles for thorough evaluation.
- DESIGN OF CHOICE: A combination of 3D printed parts, off-the-shelf components and hand-cut threaded rods were used to emulate the initial sketch of the rig
- The threaded rods allowed for the anchoring points of the tendineae to be adjusted axially.
- Attached to the rods was the ring system with notches that could be adjusted angularly which the mock tendineae were passed through and fastened to with a rubber wedge.

3.5 DESIGN VALIDATION

To investigate the experimental thickness of the valve model and compare to the theoretical thickness from the **CAD** model a series of micrometer



(a) Testing the thickness with the chordae tendineae attached



(b) Testing the thickness without the chordae tendineae attached

FIGURE 3.12: Thickness investigation for experimental model of the valve

measurements were taken on the leaflets. This was done for both model with chordae tendineae attached and without to also get a measured estimate of how much thickness the adhesive adds to the leaflets.

4

Experimental Setup and Testing

After completing the literature review I decided to go down two main paths: developing a representative valve and a anatomical valve. The representative valve would be a simple model that could be used to test the simulator and the anatomical valve would be a more complex model that could be used to test the simulator and also be used for educational purposes.

4.1 FIXTURING ASSEMBLY

The assembly process began with seating the valve in it's ring holder and passing the chordae tendineae through the evenly spaced notches of the ring fixture.

The chordae tendineae were tensioned evenly by hanging the two part fixture in a retort stand and manually pulling the wires through the notch fixture until visibly evenly tensioned, at which point Buna-N rubber wedges were inserted to hold the tension in place.

The assembly fixturing being all one piece was inserted through the distal end of the polycarbonate tubing, once the end cap was press fit into the tubing a hook tool was used to manuver the seated valve into place further down the tube.

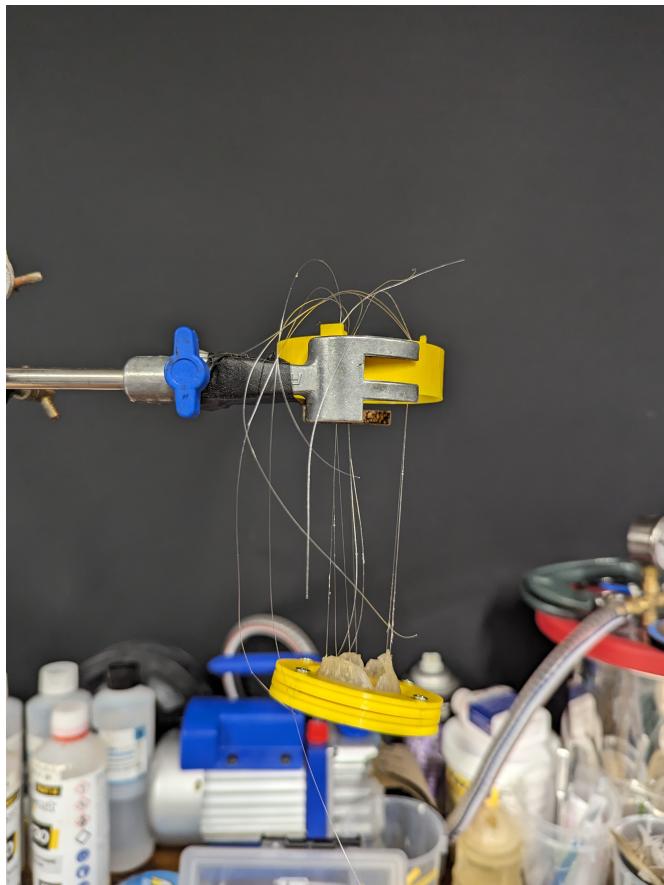


FIGURE 4.1: Tensioning of chordae tendineae

4.2 RIG ASSEMBLY

Once the core testing apparatus was assembled, the various adapters for routing the pulsatile flow loop to the valve and valve to reservoir were wrapped in teflon tape to secure the connections from leaks.

When all connections were securely tightened, the components were levelled to eye with pads of styrofoam.

4.3 TESTING PROCEDURE

4.3.1 *Pilot Checks*

Prior to the main testing a series of system leakage checks were performed to ensure minimal leaking throughout the main tests. Leakage in coaptation testing results in a great loss in the differential pressure across the valve resulting in a reduced coaptation for the same pump displacement.

The reservoir was filled and leur lock valve on the pulsatile pump was opened so the system could fill with fluid. The system was then

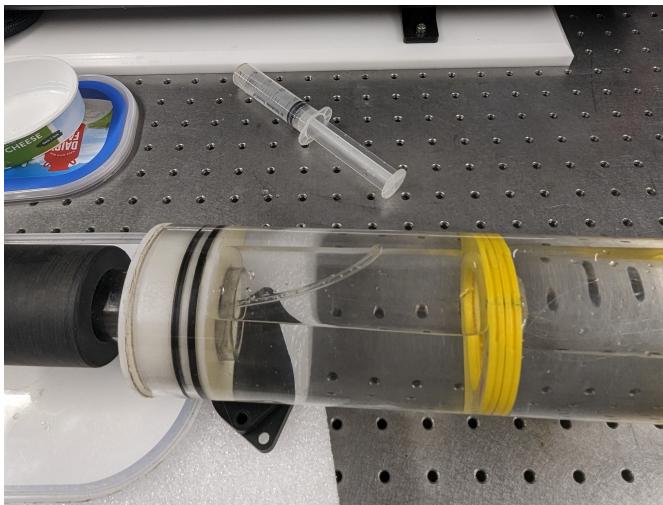


FIGURE 4.2: Removing air bubbles from the system

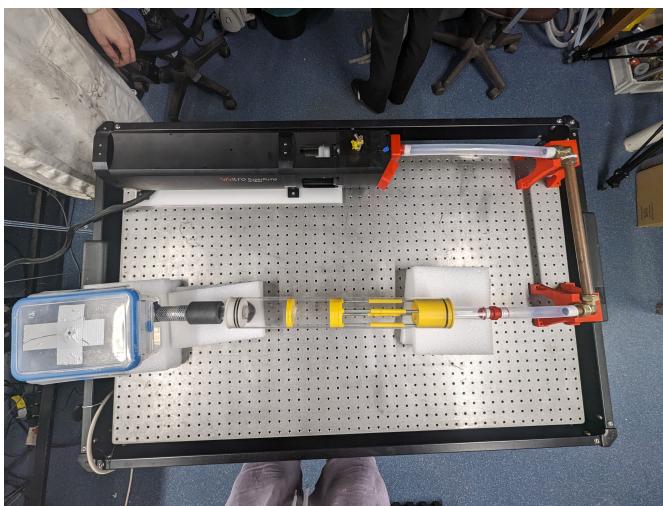


FIGURE 4.3: Birds eye view of the test rig

purged of air bubbles by using a guide wire and syringe to pull the air out. As leakage spots were observed they were sealed with blue tack.

4.3.2 Coaptation Testing

Once leaks were adequately sealed and air bubbles removed, the pulsatile flow loop was started. The pulsatile pump had a set displacement and frequency. This was sequenced to remove new bubbles which the system leaks introduced as the testing progressed which obscured the visual and performance of the valve. The valve was observed and recorded for coaptation at multiple angles. To see if the valve presented failure from cyclic stress at the chordae tendineae attachments the test was let to run for 10 minutes.

change to subfloats

Part III

RESULTS, ANALYSIS, AND DISCUSSION

5 RESULTS

5.1 Design evaluation and thickness investigaton	46
5.2 Pilot Tests	46
5.3 Coaptation Test	46

6 DISCUSSION

6.1 Challenges and the Various Explored Approaches	48
6.1.1 Modelling Challenges	48
6.1.2 Manufacturing Challenges	49
6.2 Contextualizing Results	52

5

Results

The results of the testing of the proof of concept rig are presented in this chapter. The results are presented in a qualitative manner as the rig was not designed to provide quantitative results. The goal of the testing was to determine if the proof of concept rig was able to simulate the coaptation of the tricuspid valve and the flow of blood through the valve, if the valve leaflets and chordae tendineae could sustain the systolic pressure developed from coaptation, verifying the functionality of the valve for use in the right-heart simulator and later integration of CroiValve DUO.

5.1 DESIGN EVALUATION AND THICKNESS INVESTIGATON

Differences in cast parts with and without tendineae (Table of thickness results)

flesh out section, populate table

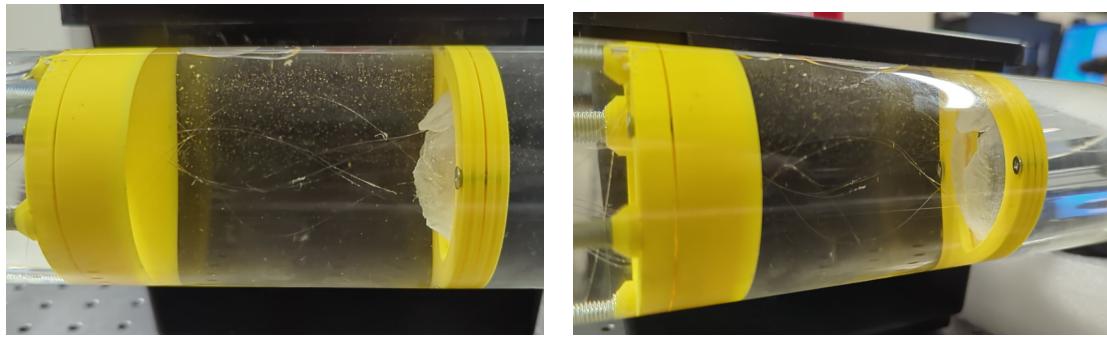
5.2 PILOT TESTS

The teflon tape worked very well where applied however the 3D-printed end cap of the core testing chamber leaked a lot even after an attempt to seal with tack. This was due to a mis-fitting of the O-ring used on the part.

5.3 COAPTION TEST

The valve part coapted well, septal and posterior leaflets in particular, the cusp of the anterior leaflet however didnt coapt with either of the adjacent two creating a larger regurgitant orifice than expected. This is likely due to;

- The material properties of the PU used not being elastic enough.



(a) Head-On View

(b) Oblique View

FIGURE 5.1: Frame from video of valve coaptation during testing ([click to view video](#))

- The thickness of the leaflets being too thick making them less flexible.
- The overlapping length of nylon wire on the leaflets making them stiffer.
- The natural saddle shape of the valve annulus being flattened off to fit in the seating fixture.
- Leaflets length loss from the processing of the valve model.

The chordae tendineae held up well under the pressure and prevented the valve from prolapsing. They were tensioned to a point where they were allowed to partially prolapse similar to how native TV's do in regurgitant cases and an expected degree of prolapse occurred as a result.

During assembly one of the chordae on the posterior leaflet broke leaving just two although this didn't majorly effect test results.

6

Discussion

- ▶ **SYNOPSIS** In this discussion, the good and bad of the methodology and the results obtained from the testing of a tricuspid valve rig are discussed. The focus is on the challenges encountered and the insights gained from the design and manufacturing processes, particularly in the areas of mold die design and valve prototyping. The successful coaptation and functional testing of the valve, the challenges in achieving anatomical accuracy due to material properties and design limitations, and the durability and functionality of the chordae tendineae.

6.1 CHALLENGES AND THE VARIOUS EXPLORED APPROACHES

6.1.1 *Modelling Challenges*

- ▶ **MOULD DIE DESIGN**

The challenges in the early stages after deciding to work off of an pre-constructed anatomic valve geometry spawned many issues, it didn't allow for feature interaction in SolidWorks which prompted some very suboptimal prototyping choices that ended in a huge amount of time investment for an avenue that was eventually made obsolete upon later findings. The series of 2-stage epoxy moulds developed as discussed in [Figure 3.10](#) had a 72 hour curing time, which made the turnaround for learnings much slower to implement.

This process became obsolete when the SolidWorks package being used was arbitrarily updated. It was discovered that the 'Segment Mesh' tool previously attempted to use to convert the STL to mesh body and then to a solid part had been overhauled to allow more complex geometries to be segmented. On this discovery the part was successfully converted to a solid body which allowed for it to be subtracted from an

encompassing cylindrical body as originally theorised which was then split into the what were the foundations of the final design press mould pieces.

From this point further iterations of the press mould were much quicker, taking only 4-5 hours, reducing the print-to-casting time by 95%. 20 hours for finalised designed where the layer lines were much smoother, being almost invisible on the casted part.



FIGURE 6.1: Final cast of anatomical valve

► VALVE DESIGN

Another area that caused an excess of time used was the post processing of the anatomical valve geometry, in becoming acquainted with STL modelling⁴ on the various programs trialed throughout the study the model was transferred across systems a lot to utilize the different tools each had, for example, how blender had great sculpting tools but lacked simple geometry analysis which was required for monitoring the surface as the thickness was homogenised.

While blender has capabilities to manipulate shaders to render this kind of information however due to it being an open source program the process of developing a custom shader for this purpose was deemed too resource intensive however if further work was conducted with many patient-specific models being developed it would be quite likely the most efficient option.

⁴Software packages like Blender use mainly sculpting tools that are used to modify the surface as opposed traditional CAD programs like SolidWorks where parts are built up from a tree of features

6.1.2 *Manufacturing Challenges*

► CHORDAE TENDINEAE PROTOTYPING

The tendineae attachment to the leaflets was another highly contested and thought out factor of the design. Balancing the rigidity that is added

to the leaflets by some methods in attaching the nylon wire and the adhesion to the leaflet is very difficult, for the scope of this study it was found that B7000 adhesive worked well as the tendineae could be effectively attached with minimal disruption to the mechanics of the valve however this did add thickness to the leaflets which not only adds rigidity that hinders coaptation in experimental use but also brings many issues for potential computational simulations that could be conducted in tandem to a study of this nature.

Studies like [Karl et al. 2024] which had been examined in the later stages of the study use a method of embedding their chordae tendineae within the leaflets, containing a medical gauze matrix, so that the tendineae do not detach under tensile forces. An approach like this could prove very effective in application to this study as it would simplify the manufacturing process in that with a the tendineae can be attached to the gauze matrix prior to PU casting ensuring accurate and replicable placement.

► VALVE PROTOTYPING

The prototyping conducted through the study for the mould parts, fixturing and experimental rig revealed a few key insights into the rapid-prototyping landscape. For each print the configuration of the printer was tailored to the purpose of the parts being produced, parts being made in early iterations were set to a faster infill and layer height setting, whereas finalised ideas were set to slower, higher resolution settings.

It was found these dense high definition settings needed for accurate and rigid mould die had issues of their which took many iterations and failed prints to perfect. They often resulted in a large amount of stringing, a printing defect, which in many cases was not solvable via post processing. To circumnavigate this the researchers in the UCD print lab were consulted. Tailored settings in Prusa Slicer were then programmed for the geometry where the resulting gcode would stop the nozzle from crossing the perimeter of the valve moulds, retraction settings would stop the printer from leaving blobs of plastic on the interior of the mould and z-axis seams were aligned to not interfere with the geometry.

In earlier stages of the study a resin SLA printer was used to manufacture an anatomic model for the silicone mould method discussed in Figure 3.8 which however it was not feasible to develop further iterations from resin

due to the printer being in a separate lab and having a much higher cost of with proprietary resins. Two major benefits to **SLA** printing are;



FIGURE 6.2: Early revision **SLA** print of anatomical valve

Resources:

- The vastly increased tolerance of resin printing
Prusa **FDM**:0.3mm
FormLabs **SLA**:0.01mm
- The reduced layer height that resin printing is capable of
Prusa **FDM**:0.05mm
FormLabs **SLA**:0.025mm
- Prusa TDS
- FormLabs TDS

This has two main benefits regarding this study;

- Minimizing layer height results in mould parts reduces surface affects
- Reducing adhesion of cast part to mould, this is minimized on **PLA** parts with mould release and sanding however with casted parts on this degree of thickness there can still be an increased risk of breakage in the demoulding process.

Another option worth considering is machining from either steel or a performance plastic like delrin [Li et al. 2022], this would be more expensive however it could be worth the cost for moulds that need to be used for a larger number of castings as well as increasing the precision over multiple casts since you the 3D printed parts can warp under the pressure of the clamping. The transparency of the part was a consideration for further work on the valve as the proposed integration into the right heart simulator would involve **PIV** measurement where maintaining

transparency would allow for an measured flow field uninterrupted by the valve, this was an issue in studies like [Rabbah et al. 2013] and the efficacy on dynamic transparent parts in PIV rigs has been shown in studies like [Büsen et al. 2017]

6.2 CONTEXTUALIZING RESULTS

The results of this study have shown how development of imitative synthetic heart valves can be a valuable tool in cardiac simulators. The coaptation tests on the valve show great promise for technology of this nature, previously in simulational studies such as [Rabbah et al. 2013] dissected porcine valves, [Ginty et al. 2018] used rigid valves and [Raghav et al. 2018] non-anatomically representative valves which each have major limitations in their ability for a wider range of experiments. Some such limitations of these valves which the work of this study has surpassed are;

- The longevity of porcine for repeated experiments. While it can be stored in the likes of formalin the tissue degrades over time which leads to an irrepeatability in testing and eventual need for replacement.
- Semi-rigid valves can't be used in flow studies as they can't deform to coapt.
- Non-anatomical valves can coapt but don't represent true geometry which won't yield accurate results.

► CHORDAE TENDINEAE PERFORMANCE:

The coaptation test illustrated how the chordae tendineae can be used in a synthetic part to prevent prolapse and aid coaptation. This aligns well with how it had been done before such as in [Rabbah et al. 2013] and [Karl et al. 2024] where native and synthetic tendineae were used respectively. Such works also show how this part of the model can be manipulated with motors to simulate the contraction of papillary muscles which while not applicable to the current design of the right heart simulator, could be developed for future iterations or simpler rig design like that of the tube-based coaptation test [Figure 5.1](#)

► LEAFLET PERFORMANCE:

The area with most room for improvement is likely the leaflets. The final

iteration from this study came very far relative to the initial iterations in term of rigity, transparency and geometrical precision, it also performed better than similar attempts from other studies like [Ginty et al. 2018] although in regards to the initial design criteria from section:§ 3.2 it is lacking in functional performance and scalability

Not all the leaflets coapted together which was the objective however it was supposed to occur from annular dilation and chordal loosening not from just the geometry, this is most likely due to the model of the valve being based off a valve in the diastolic phase so the full length of the leaflets was malformed in CT conversion as they weren't not being under load from the presure. This can be seen in Figure 5.1:B where the leaflets do move back but are not long enough to meet eachother. The work of [Karl et al. 2024] capture this well in their mitral valve design, they did well with leaflet length however theyre design was not anatomically representative, building off this to capture both physiological replicity and functional performance would be a first of it's kind for in-vitro tricuspid valve testing.

Part IV

EPILOGUE

7

Conclusions and Future Work

In conclusion, this study shows how the design process can be fraught with many more obstacles of many more varieties than expected. It resulted more in learnings of the iterative process of design and prototyping compared to test method development than expected.

The study resulted in a manufacturing process that is consistent and effective in producing anatomically accurate valve models, developed over many different approaches with the strengths taken from each and weaknesses phased out. It also resulted in a test method that was able to effectively test the basic efficacy of the produced valves in a controlled environment and potential to very easily be adapted to introduce a variety tricuspid valve medical devices with simple fixturing and also account for variables like; pressure, flow rate, flow field, and regurgitant characteristics like orifice and volume, once integrated with the right heart simulator.

The implications this type of testing could have on the development of **TTVR** devices is significant. The ability to test the efficacy of these devices in a controlled environment can provide important data that can influence design choices and potentially mitigate against the risk of device failure in the clinical investigations.

7.1 FUTURE RESEARCH DIRECTIONS

Pressure monitoring during test, 36% glycerin for blood viscosity - rabbah

In vitro micro ct scanning

The next steps in this research would primarily be to fully integrate this valve into the right heart simulator. From there the rig would be enhanced so that fully representative simulations could be conducted where the flow field could be measured with and without **TTVR** devices

in place to characterize their efficacy on regurgitant valves. The main prospective device to integrate is the CroiValve DUO device which partially occludes the annulus of the valve reducing the regurgitant flow.

At the moment the CroiValve team don't have the means to conduct work of this nature so the data collected in this study could be used to inform the design inputs of later interations.

Appendix

Solidworks drawings

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