Oscar Daly

Mock Tricuspid Valve for Right Heart Simulator

The thesis is submitted to University College Dublin
in part fulfilment of the requirements for the degree
of Master Of Biomedical Engineering

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Todo list

Abstract

Oh my god scene analysis aims at retrieving useful information from microphone recordings. Examples of these problems are sound source separation and sound source localization, where we are interested in estimating the content and location

THIS THESIS highlights the difficulty of getting beeches bashbdkbadp fsdffsodihddfdgsgaa

Keywords:
Mo money mo problems yak yak fuckin yak mo foka

Contents

List of Acronyms

Notation	Description	Page List
TV	Tricuspid Valve	3
CT	Computed Tomography	18
FSI	Fluid Structure Interaction	14
BHV	Bioprosthetic Heart Valve	16
PU	Polyurethane	17
PET	Polyethylene Terephthalate	18
TTVR	Transcatheter Tricuspid Valve Replacement	18
TAVR	Transcatheter Aortic Valve Replacement	18
CAD	Computer Aided Design	14
PLA	Polylactic Acid	34
MRI	Magnetic Resonance Imaging	18

Part I

PROLOGUE

1

Introduction

1.1 Background

1.1.1 *Understanding the Need for Heart Valve Simulators*

- Cardiovascular Diseases Prevalence

  Cardiovascular diseases (CVDs), 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]

Roth et al., "Global Burden of Cardiovascular Diseases and Risk Factors, 1990–2019: Update From the GBD 2019 Study"

- 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. [Nkomo et al. 2006]

Nkomo et al., "Burden of Valvular Heart Diseases: A Population-Based Study"

- 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]

Musumeci et al., "Prosthetic Aortic Valves: Challenges and Solutions"

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]

Sanders and Pluchinotta, "Tricuspid Valve: Embryology and Anatomy"

▸ 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]

Buzzatti et al., "Anatomy of the Tricuspid Valve, Pathophysiology of Functional Tricuspid Regurgitation, and Implications for Percutaneous Therapies"

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, Masuzawa, and Fukui (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. [Takashina et al. 1990]

Takashina et al., "A New Cardiac Auscultation Simulator"

Advancements continued with the introduction of tissue-based simulators for surgical training. Ramphal 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. [Ramphal et al. 2005] Current State of TV Simulators

Ramphal et al., "A High Fidelity Tissue-Based Cardiac Surgical Simulator"

Today, 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]

Baillargeon et al., "The Living Heart Project: A Robust and Integrative Simulator for Human Heart Function"

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]

Chatterjee, "Neurohormonal Activation in Congestive Heart Failure and the Role of Vasopressin"

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

Not entirely happy with this

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]

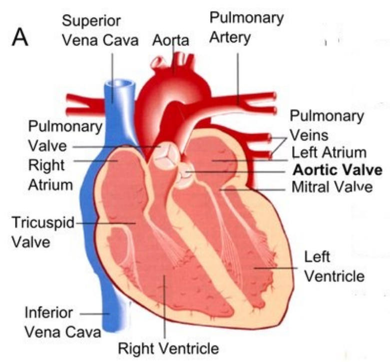


Figure 2.1: Heart Valve System [Rock et al. 2014]

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]

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

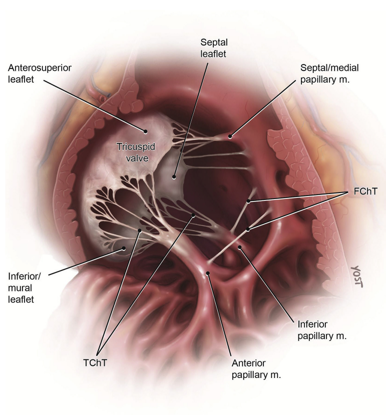


FIGURE 2.2: Sub-System of Tricuspid Valve [*Yost - Drawing Detailed View of Tricuspid Valve - English Labels | AnatomyTOOL* 2024]

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.

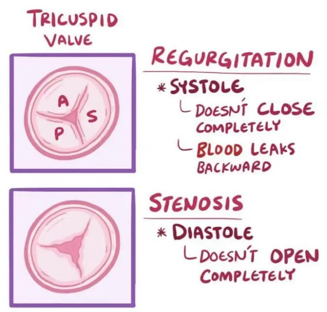


FIGURE 2.3: Illustration of Regurgitation vs Stenosis [*Tricuspid Valve Disease* 2024]

▸ 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

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].

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]

▸ 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.

- 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]

- Replacement: Transcatheter TV 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]

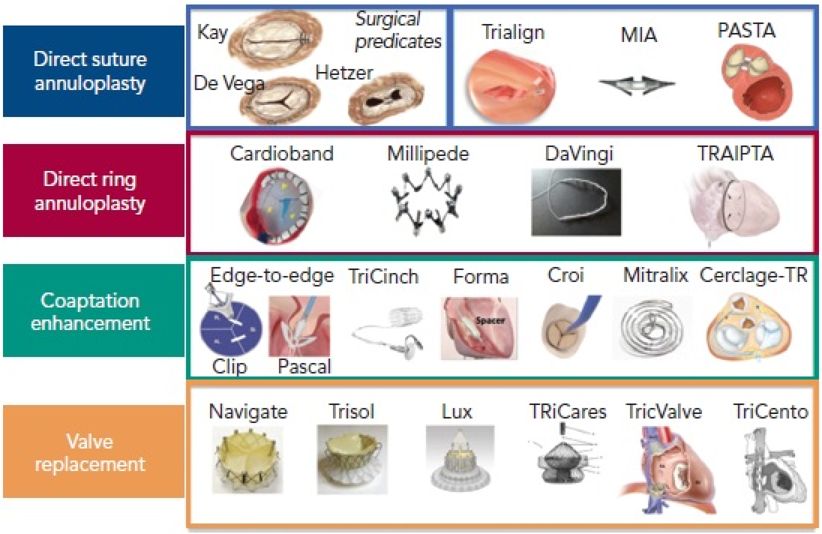


FIGURE 2.4: Current landscape of TTVR products being used surgically [Curio et al. 2019]

▸ IMPACT OF VALVE MODELING 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 Evolutation of Physcial 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. Tangental 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.

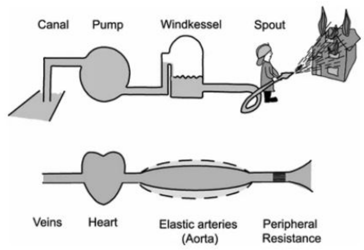


Figure 2.5: Concept of the WindKessel Model [Westerhof et al. 2009]

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

- 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]

High-Fidelity Tissue-Based Simulators: These offer 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. [Ramphal et al. 2005]

- Surgical Planning and Research Models:

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 Computational and Physical 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]

▸ 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 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.

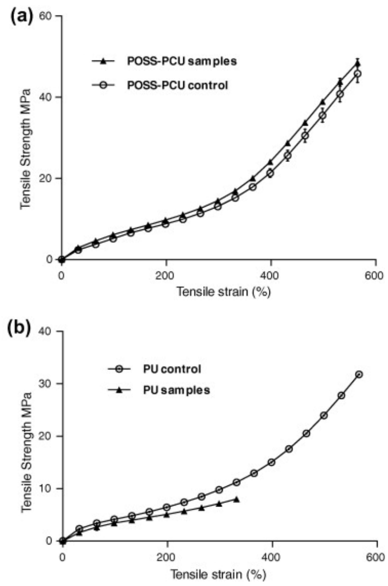


Figure 2.6: Comparison of PU and poly(carbonate-urea)urethane for heart valve performance [Ghanbari et al. 2010]

▸ 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 how-

ever porcine and bovinepericaridium remains commonplace in current TTVR and TAVR respectively. [Filová et al. 2009]

- 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] [1]

- EMERGING MATERIALS AND TECHNOLOGIES:[2]
  Recent advancements have led to the exploration of nanocomposite polymers 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.

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.

  [Ionasec et al. 2010] introduced one of the first automatic computational systems for patient-specific modeling and quantification of the left

[1] In 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

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

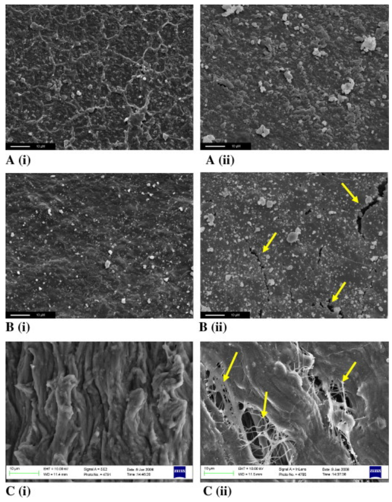


FIGURE 2.7: Comparison surfaces in fatigued (a) PU (b) poly(carbonate-urea)urethane (c) valve leaflets showing tissue failure and fibre dehiscence marked by the yellow arrows in each [Ghanbari et al. 2010]

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.

▸ 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.

  - [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.

Resources:

– Revised ISO Overview

- 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 disected 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 succesfully 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

▸ Synopsis In this chapter the mock valve modelling and prototyping is discussed from conception to completion. Different approaches are disccused 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 represenatively 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's a cyclical journey of conception, experimentation, evaluation, and refinement. This iterative cycle is fundamental to translating abstract ideas into tangible solutions that meet specific functional and operational goals.

At the heart of the design process lies the concept of trial and error—a methodical yet flexible approach that takes the discovery of unexpected challenges and leverages them as opportunities for learning. 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, 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 anatomical insights.

The initial vision of the mock 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 adapt as the project moves forward and harder boundaries are discovered.

The approach taken was to start prototyping from the start 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 and there was a minimal amount of investment in preliminary modelling so the prototyping process could be refined in tandem.

This iterative nature of the design process was essential in finishing with a refined the final model, balancing anatomical fidelity with practical considerations such as fabrication feasibility and functional performance.

3.1.1 *Design Criteria*

After this initial conceptualization, the design criteria were established to guide the development of the mock TV. These criteria were informed by the project's objectives, the anatomical requirements of the TV with respect to 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 account for the variations.

  - Justification: To maintain a realistic simulator every effort must be made to ensure represenative simulation and to provide a realistic evaluation environment 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 and stenosis 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 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.

- 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 depenedent on biological factors that are difficult to replicate such as collagen fiber allignment. 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 progesses past this thesis the valve should be easily replicated and improved upon again so that future goals can be met.

3.2 Modelling and Design Iterations

3.2.1 *Simplified Valve Designs*

- Flat Valve: As discussed above the flat valve was the first to be developed with the idea being to use it as a canvas for developing the complexity. The shape of the leaflets were designed by overlaying images of regurgitant valves 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 design the valve to not have them or include and then how. There was two schools of thought for this method:

cref

  - 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 wasnt until outcomes in the prototyping phase that the second option was fully decided on.

cref

- Ballooned Valve: As this basic model was being developed the current thought process was to keep adding complexity until the valve visually replicated an anatomical valve. The research showed how in reguritant valves with the annulus dilating and tendineae weakening the valve begins to develop a partially prolapsed appearance, this was reflection in later iterations by creating a revolve feature in SolidWorks of a 'U' shape which was centered within the leaflets as opposed to the annulus and then the same cut as the flat valve was set after. It was hoped with the added depth to the leaflets in this iteration that the valve would be able to coapt as the cusps began to have more overlap with adjacent leaflets

reference

3.2.2 *Represenative Valve Designs*

- ANATOMICAL VALVE MODEL: While development on the hand-modelled valve was progressing the idea for a more anatomically accurate valve began to look favourable for reaches the aims of the project. The idea was to use a CT scan of a TV and then convert this into a 3D model. While this could be done manually by meticulously slicing layers of a CT scan with lots of refinement it was alternatively decided that a pre-existing model from an online STL repository could be used as a base and then refined to fit the project's needs.

  With this approach the tracability of the model is lost but with confirmation from the author that is was a human valve it was deemed appropriate so time could be prioritized more on prototyping.

  Harnessing the scanned 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:

  - Vast amount of self-intersecting faces and non-manifold edges
  - Formatting issues
  - Inaccuracies in the model
  - Widely varying leaflet thickness

- MODEL REFINEMENT In tackling these issues and getting the repository model to a usable state there was a number of softwares tried and tested to see which could 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-level[3], 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 replacment as mentioned in many only forums discussing MeshLab's drawbacks. Originally designed for additive manufacturing processed it also contained a diverse suite of usefuls tools to repair the model, personalized repair kits could

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

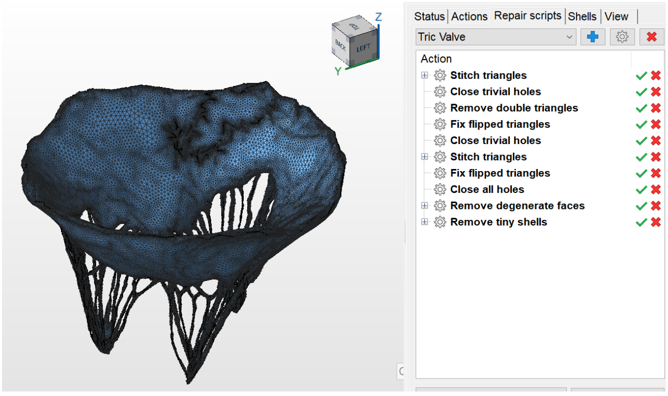


FIGURE 3.1: Netfabb Repair Scripts

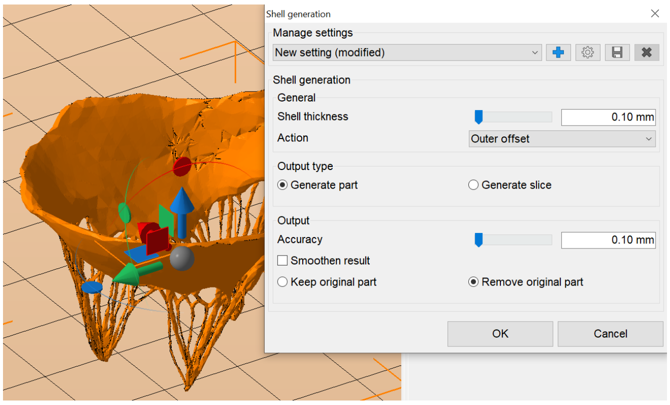


FIGURE 3.2: Netfabb Shell

be designed to fix specific issues for the TV and most importantly had been developed for higher-level applications.

- Repair Scripts
- Shell

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.

3.3 PROTOTYPING

3.3.1 *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 balloon valve models and then using a silicone mould to capture its likeness, through feasability testing it was found this method was not suitable for reasons;

- 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 ventilation would still have air bubbles and not fill out to the edges of the part.

acronym or sidenotes

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 SolidWorks 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 ontop with a C-clamp to create a tight seal.

acronym

Some key considerations developed over trial and error for this method were:

- Embossing and debossing key slots to ensure the moulds could be aligned correctly.
- Sanding down the PLA prints to a smooth finish so in combination with a tailored mould release the casted part could be separated easily.
- Utilizing a vacuum chamber to remove air bubbles from the resin before curing.

3.4 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:

  - 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 werent 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 miniscule amount for a good hold so the very thin thickness of the leaflets wasnt negated.

3.5 FIXTURING

The ideal 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 fixed anchors which are fully adjustable axially and angularly.

- The valve should be able to be mounted in a way that the leaflets are not obstructed and the valve can be viewed from all angles for through 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.

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.

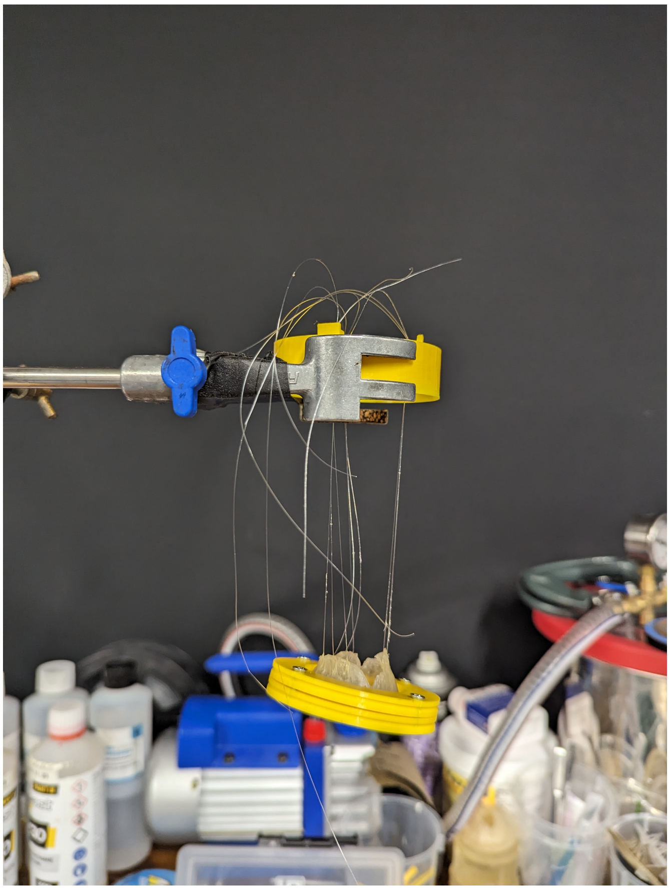


FIGURE 4.1: Tensioning of chordae tendineae

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 pumped was opened so the system could fill with fluid. The system was then

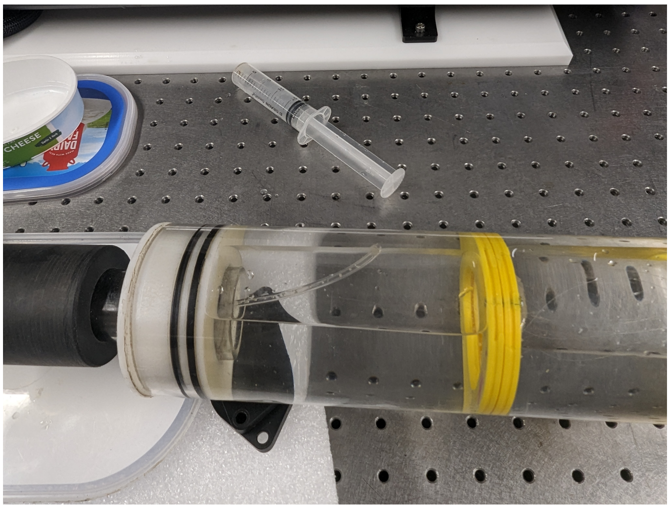


FIGURE 4.2: Removing air bubbles from the system

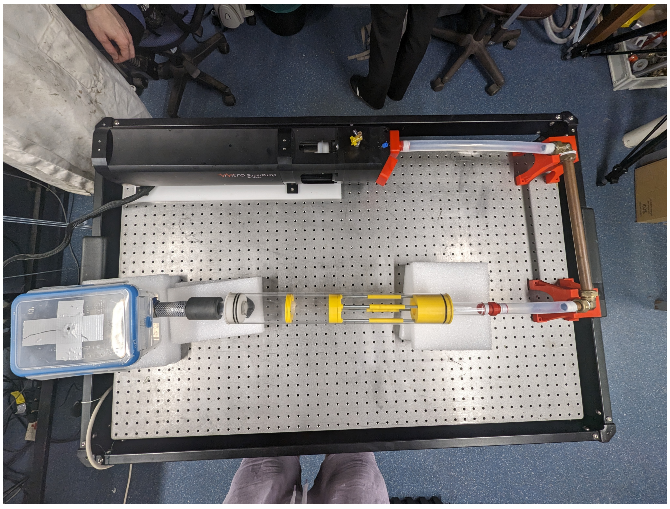


FIGURE 4.3: Birds eye view of the test rig

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.

Part III

RESULTS, ANALYSIS, AND DISCUSSION

5

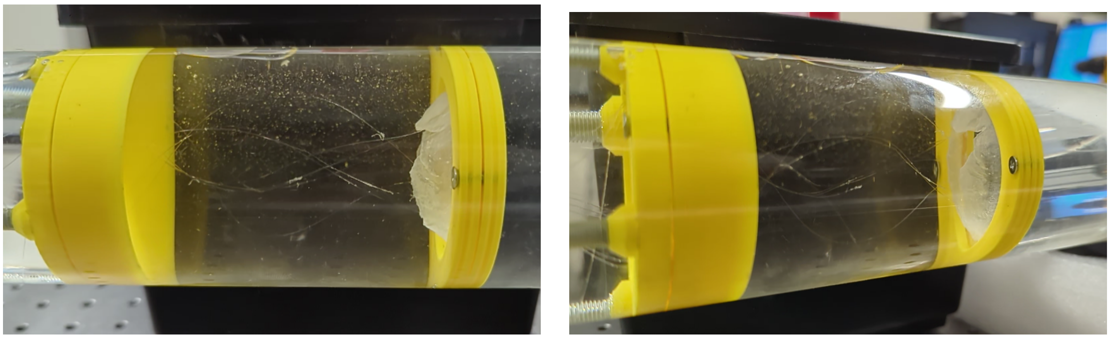
Results

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 Pilot Tests

5.2 Coaptation Test

A number of photographs and videos were taken as the testing was conducted.



(a) Head-On View (b) Oblique View

FIGURE 5.1: Frame from video of valve coapting during testing **(click to view video)**

6

Discussion

6.1 Contextualizing Findings

Discuss how your results relate to previous studies and theoretical frameworks. Are your findings consistent with other studies, or do they diverge?

Analyze the significance of any discrepancies and explore possible reasons.

6.2 Implications of the Findings

6.2.1 *Theoretical Implications*

Discuss the implications of your findings for the theoretical aspects of your field.

6.2.2 *Practical Implications*

Consider the real-world implications of your results. How do they impact the field, industry practices, or policy?

6.3 Reflecting on Limitations

Acknowledge the limitations of your study and how they might affect the interpretation of your results.

6.4 Future Research Directions

Based on your findings and the limitations identified, suggest areas for future investigation.

Part IV

EPILOGUE

7

Conclusions and Future Work

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8

Appendix

▸ SYNOPSIS This appendix briefly describes the Sliding Franck-Wolfe Algorithm used to solve the Non-negativ The main author of this work is Clement Elvira, to whom I extend my greatest thanks, and I will report it for sake of completeness.

Resources:

- Code
- Open-access paper with supplementary material

▸ NON-NEGATIVE BLASSO
To take into account the non-negative constraint on the coefficients, the authors ofhave proposed to slightly modify the SFW algorithm by *i)* removing the absolute value iand The reader is referred to for more details.

In particular, using the real part in the implementation allows to remove the imaginary part that may appear due to the imprecision.

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