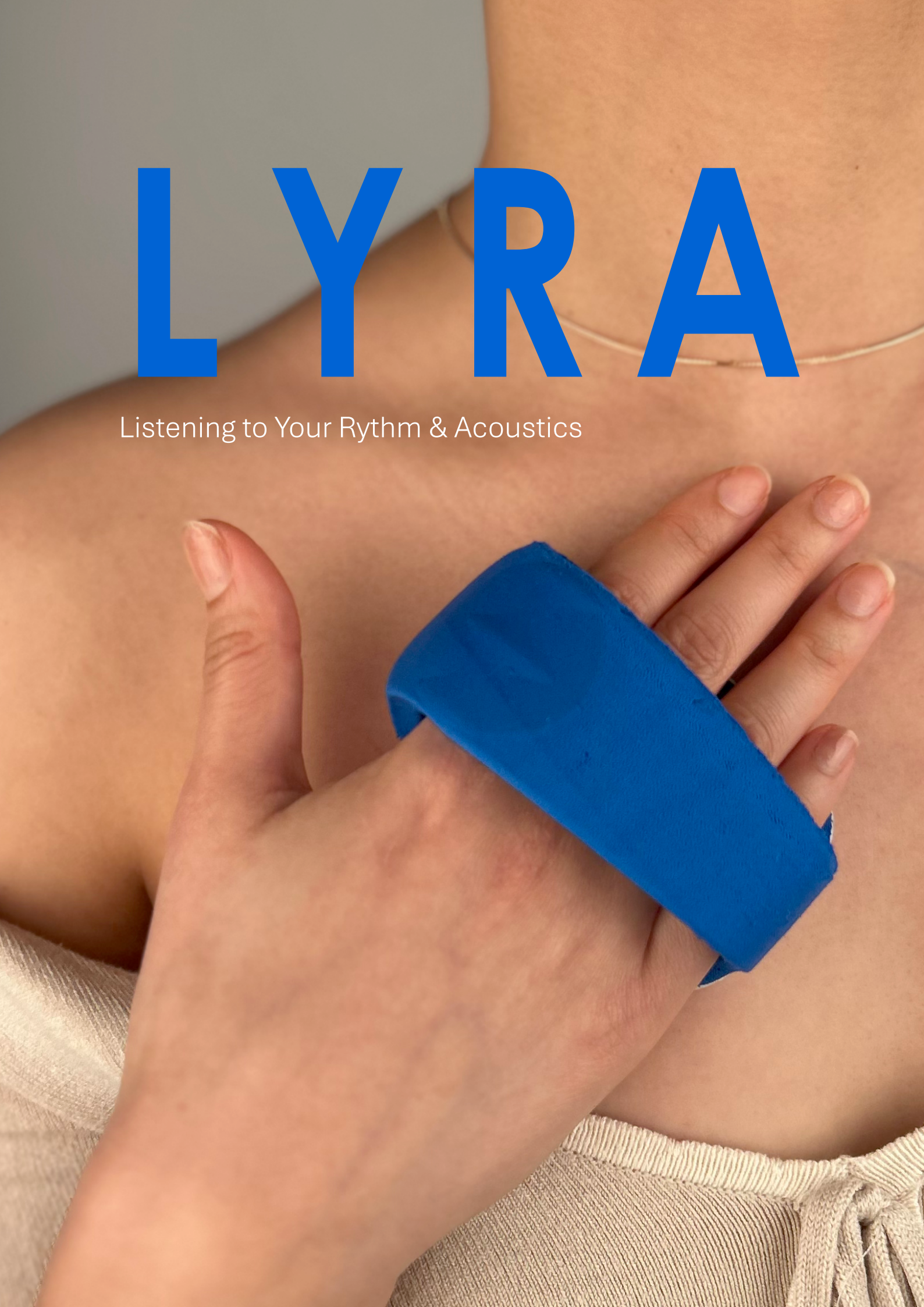
LYRA

Listening to Your Rythm & Acoustics



Master Thesis | Integrated Product Design

Designing a home monitoring tool for patients with degenerative heart disease

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Delft University of Technology

February 2026

Delft, The Netherlands

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Preface

I am happy and above all proud to share my graduation thesis with you. This thesis was written from a personal conviction that healthcare should be designed around the patient experience, not only around clinical outcomes. When people feel supported, understood, and confident during treatment and recovery, they are more likely to cope better, engage more, and heal faster. With that belief in mind, this project explores how design can reduce uncertainty and support people in their everyday health journey.

When I look back on my years in Industrial Design Engineering, I think of the many memories created, the people I had the chance to learn from and truly engage with, and the countless moments of making. I have been able to turn ideas into real things with my hands, from early sketches to prototypes that you can hold and test, and that has been one of the most meaningful parts of this journey. Since I was little, I wanted to become an inventor. Now that I am graduating from the master's program in Integrated Product Design, with the Medisign specialization, I feel proud to say that I can call myself an inventor.

One of the biggest challenges during this thesis was deciding when to settle on an idea. There were many possible directions, and learning to make choices, commit, and move forward was an important part of my process. At the same time, I am proud of the level of engagement this project received from patients. Collecting 105 questionnaire responses in only one month showed me how strongly people want improvements, and how willing they are to contribute to design that aims to serve them.

I was also genuinely moved by how open and generous doctors were with their time and feedback. Their willingness to reflect, critique, and share perspectives strengthened the work more than I expected.

I am grateful for the guidance of my supervisors at TU Delft and at Sonion, whose feedback shaped the project throughout these months. I also want to thank the Sonion prototyping lab team for their hands on support with material selection and prototype development.

With this, I wish you a pleasant reading experience.

February 13th, 2026

Delft, The Netherlands

Abstract

Cardiovascular diseases remain the leading cause of death worldwide, yet patient monitoring between medical check-ups is still limited. After diagnosis, follow-up care for conditions such as valvular heart disease, specifically primary heart disease (degenerative heart disease) relies mainly on episodic echocardiography, leaving long intervals with little visibility into patients' day-to-day cardiac status. This lack of continuous insight creates uncertainty for both patients and clinicians.

This project explores to what extent can Sonion's acoustic sensor technology enable continuous at-home heart sound monitoring. The goal is to design and validate a patient-centered system capable of recording and analyzing phonocardiographic signals in everyday settings. The concept combines high-fidelity sensing, data processing, and user-friendly interfaces to support both early anomaly detection and patient reassurance.

The thesis investigates three key aspects: technical feasibility in real-world use, patient usability and adherence, and the potential clinical value of continuous heart sound data. Through an iterative design process integrating expert input, prototyping, and user insights, the project aims to deliver a proof-of-concept system and evidence for its future application in digital cardiac follow-up care. Ultimately, the work seeks to transform heart sounds from a one-time diagnostic cue into a continuous health indicator that connects patients and clinicians between visits.

The new device and system enables patients to perform guided cardiac sound recordings at home, following measurement routines defined by their cardiologist, while allowing additional use when extra reassurance is needed. Acoustic data is captured using Sonion's sensor technology and processed within a mobile application, where signals are analyzed and visualized locally on the user's smartphone. This approach supports repeated measurements in everyday contexts without adding clinical burden, while preserving a clear separation between patient self use and medical decision making.

In conclusion, LYRA offers a patient focused proof of concept for at home heart sound monitoring that supports telemonitoring scenarios while strengthening patient empowerment. By combining accessible acoustic measurements, local signal analysis, and a human centered design approach, the system demonstrates how heart sounds can support reassurance, awareness, early recognition of change, and sustained engagement for people living with degenerative heart disease.

Key Words

Cardiovascular disease, Cardiac sounds, Phonocardiography, At-home monitoring, Telecardiology, Acoustic sensing, Patient-centered design, Medical device design.

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Abbreviations

AS	Aortic Stenosis
AR	Aortic Regurgitation
CAD	Coronary Artery Disease
CHD	Coronary Heart Disease
CVD	Cardiovascular Disease
EKG	Electrocardiogram
GP	General Practitioner
Hz	Hertz (Frequency)
MR	Mitral Regurgitation
MVP	Mitral valve Prolapse
PCG	Phonocardiography
PPG	Photoplethysmogram
S1	First heart sound (Lub)
S2	Second heart sound (Dub)
TAVI	Transcatheter Aortic Valve Implantation
TAVR	Transcatheter Aortic Valve Replacement
TVT	Transcatheter Valve Therapy
VHD	Valvular Heart Disease
VPU	Voice Pick-up Unit

01 INTRODUCTION

1.1 Problem context

Since the COVID-19 pandemic, the use of telehealth has increased in the Netherlands. In response, the Ministry of Health, Welfare and Sport (2021) has examined how healthcare is becoming more digital and what this means for patients and care providers. For this reason, the Ministry commissioned the Digital Healthcare Monitor, which provides yearly insight into the use of digital care, the experiences of users and providers, and the conditions needed for wider and safer implementation (Digitale Zorg | RIVM, n.d.) (Nivel, 2025).

This shift matters because it offers a practical way to keep care accessible while demand grows and capacity remains limited. Digital care is expanding quickly, with growing uptake among care users and healthcare organizations through remote contact tools and home monitoring systems. It also indicates that digital solutions can support access to care, strengthen self-management, and reduce pressure on the healthcare system (Nivel, 2024).

These advantages are especially relevant for chronic diseases, where health status can change gradually between appointments. Today, clinical follow up for valvular heart disease (VHD) relies mainly on periodic echocardiographic examinations. Between these scheduled checkups, patients are instructed to take prescribed medication and maintain lifestyle changes, but no continuous or patient accessible monitoring exists. As a result, subtle physiological changes can remain undetected for long periods, which can increase uncertainty for patients and leave clinicians making decisions based on infrequent snapshot data.

This gap is important because cardiovascular disease (CVD) remains the leading cause of death worldwide, responsible for nearly 20 million deaths annually (World Health Organization: WHO, 2025), and that burden is projected to rise steeply due to population aging and chronic disease progression. For that reason, CVD and related conditions such as VHD are a clear focus area where telehealth and home monitoring can help connect the time between clinic visits with more timely, usable information for both patients and clinicians.

1.2 Involved parties

The project is carried out within the Faculty of Industrial Design Engineering at TU Delft, under the Medisign track. It has been supported by the supervisory team consisting of Prof. Richard Goossens and Dr. Wilfred van der Vegte, who have provided academic guidance, methodological input, and feedback throughout the research and design process. Their expertise in human factors, healthcare design, intelligence design, and product development has been essential for aligning the project with both academic standards and user-centered design principles.

Sonion is a global leader in the development and manufacture of advanced microacoustic and micromechanical components for the hearing care and medical industries. As the client and initiator of the project, Sonion has provided essential context, technical expertise, and continuous support. Ashesh Shah, mentor at Sonion, has guided the project from the company's side, sharing valuable insights into the application domain, user needs, and signal processing. Sonion's involvement ensured that the research remained relevant and aligned with industrial and technological realities.

1.3 Stakeholders

Stakeholders for LYRA were mapped using Mendelow's Matrix, grouping actors by their power and interest to guide how each group should be engaged.

Given the six month thesis scope, the project focused on high power, high interest key players who could directly influence a patient focused design and near term validation. This included TU Delft, Sonion, and clinical stakeholders such as hospitals and cardiology leaders, alongside patients with degenerative valvular disease and home care services as the primary end users and support network. Policy and standardization bodies were treated as context setters that shape future requirements, but were not central to active engagement during this thesis.

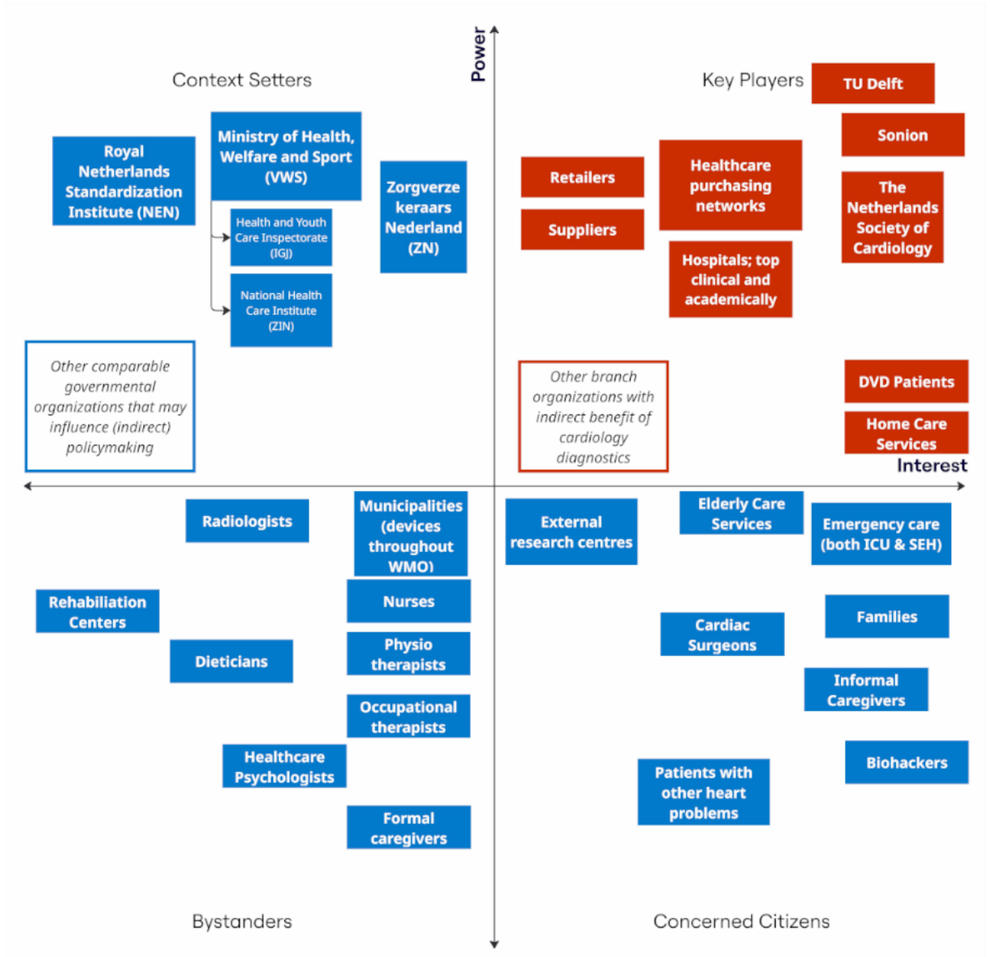


Figure 1. Stakeholder map

1.4 Scope

This thesis defines and evaluates a prototype system intended to support at home cardiac sound monitoring for people living with degenerative valvular heart disease. The scope is set to match the project timeframe and resources, while still producing a coherent outcome that can be built upon. The work focuses on enabling repeatable recordings in a realistic use flow and translating the resulting signals into basic, interpretable outputs that support future clinical validation.

The intended target group within this scope is adults aged 60 years and older living with degenerative valvular heart disease, since this is the age range in which degenerative conditions commonly emerge and routine follow up becomes relevant. The system is designed for patients whose chest wall characteristics allow reliable acoustic capture using an auscultation style approach. Patients with severe obesity are excluded at this stage, because increased soft tissue thickness can attenuate cardiac sounds and reduce recording quality, a limitation that clinicians also face during standard stethoscope auscultation.

Within scope, the project covers the design and integration of a physical recording device, placement support, and a guided app flow. The device and placement support are developed through iterative prototyping with the aim of achieving stable contact, practical handling, and consistent positioning across recordings. The app experience is designed to guide users through preparation and recording, reduce common user errors, and communicate outcomes in plain language. The digital flow is treated as part of the measurement system because guidance, interaction, and user behavior directly influence recording quality.

Technical feasibility within scope is defined as data acquisition and initial analysis. The thesis therefore evaluates whether the system can capture heart sounds with sufficient signal quality to allow visualization, basic quality checks, and exploratory processing. Analysis is limited to prototype level methods that help determine whether recordings are usable and how signal characteristics can be summarized for quality control and future development. The work does not aim to provide diagnosis, quantify disease severity, or claim sensitivity to progression.

Several activities are intentionally out of scope. The project does not collect longitudinal patient datasets to evaluate change over time, since meaningful progression in degenerative valvular disease typically requires extended observation. Within a six month graduation project, there is insufficient time to obtain repeated recordings across a period long enough to observe multiple progression events, and generating such evidence would require a formal clinical study with appropriate infrastructure and approvals. For the same reasons, large clinical trials are out of scope, including statistically powered validation, clinical performance metrics for detection or progression, and the definition of clinical decision thresholds. As a result, the thesis delivers evidence of recording feasibility and early analysis potential, while positioning longitudinal validation and clinical efficacy as future work.

1.5 Goal

The national shift toward digital care creates an opportunity to rethink how patients manage long term cardiac conditions. The Digital Care Monitor shows that remote contact tools and home monitoring systems are becoming more common, giving patients more oversight of their health and helping care teams notice changes sooner. These developments align with the Dutch healthcare strategy, where **patient control** and **prevention** are key themes (Monitor Digitale Zorg, n.d.). In this thesis, those themes guide what a cardiac monitoring solution should enable in everyday life.

Yet the period between consultations remains a major blind spot in the care pathway. This gap can contribute to delayed recognition of disease progression, unplanned hospital visits, and increased anxiety when patients have little feedback about how they are doing. Evidence based home tools already support parts of cardiac care, such as blood pressure monitoring, symptom tracking, and wearable measurements including ECG features. However, these tools do not directly reflect valve related change, and they do not provide longitudinal acoustic information that could complement episodic clinical assessment. As a result, there is still no practical solution that helps patients follow valve related status in daily life while also offering clinicians interpretable trends between visits.

This motivates a patient centered monitoring approach that bridges episodic assessments, supports earlier recognition of meaningful change, and strengthens engagement in long term cardiovascular care.

The goal is to design a solution that supports patients during uncertain periods, giving clearer guidance and a stronger sense of control, while complementing clinical follow up rather than trying to replace it. As shown in Figure 2, the support system is the part of the processes of care and evaluation pathway that sits closest to the patient. If this support layer is designed well, it can improve the patient experience directly and strengthen the downstream steps that follow in the pathway.

The Digital Care Monitor focuses on seven themes (Monitor Digitale Zorg, n.d.):

1. Organizability of care (Organiseerbaarheid van zorg)
2. Quality of care (Kwaliteit van zorg)
3. **Patient control** (Regie van de patient)
4. **Prevention** (Preventie)
5. Labor market challenges (Arbeidsmarktuitdagingen)
6. Preconditions for digitalization (Randvoorwaarden)
7. Environmental factors (Omgevingsfactoren)

Figure 2. Patient-processes of care relationship. From Hawkey, M., Lauck, S., & Straiton, N. (2021). Valvular heart disease. In Processes of Care and Evaluation Pathway for Patients with Valvular Heart Disease (pp. 75–85). https://doi.org/10.1007/978-3-030-86233-6

1.6 Problem and Vision Statement

This project brings together insights from literature, expert discussions, and early user feedback to refine a complex and extensive issue into a precise and workable problem statement. Below is the refined problem statement that anchors this project, followed by the vision that points toward the intended future impact.

Problem Statement

“People living with degenerative valve disease move through long periods without reliable feedback about their condition once they leave the clinic. In this setting, patients struggle to understand what their symptoms mean, which raises worry and reduces confidence in their care. The absence of clear information outside the hospital affects daily life in several ways. It increases stress, limits adherence to medication routines, and reduces trust in recovery progress.

This issue matters because patients want control, clarity, and support in the moments between appointments, and healthcare systems need approaches that reduce avoidable visits and improve communication during reviews. Addressing this gap is essential to improve quality of life for individuals, guide them toward calmer routines, and give clinicians a clearer picture of each patient’s condition.”

Vision Statement

“I aim for a patient centered tool that offers clear guidance, simple use, and steady support. By giving people an accessible way to understand their heart sounds and track their condition, it helps them feel more confident and informed in their daily lives. I want people to experience their daily health routines with medications, lifestyle choices, and self-care as moments that guide them toward reassurance, knowledge, and better conversations with clinicians. With a design that adapts to different situations and abilities, it supports autonomy, encourages engagement, and strengthens the connection between patients and their ongoing care.”

1.7 Research Questions

The following research questions guided the analysis part of the project to reach the initial project goal.

1. Degenerative Valve Disease

    1.1 What is degenerative valve disease?

    1.2 What are the types of degenerative heart disease?

    1.3 How are degenerative valve diseases currently detected?

    1.4 How are degenerative valve diseases currently monitored?

    1.5 How does the disease progress over time?

    1.6 What complications are most sensitive to delayed detection?

2. Heart Murmurs

    2.1 How are murmurs generated, classified, and linked to specific valve lesions and severity?

    2.2 What is the role of heart sounds and murmurs in diagnostics?

    2.3 How are murmurs monitored throughout the patient's disease?

    2.4 What are the roles, strengths, and limitations of these approaches?

3. Patient Pathways

    3.1 What factors influence adherence to follow-up visits and to treatment?

    3.2 What are current patient experiences from these pathways?

    3.3 What are the current patient pathways?

4. At home monitoring for cardiovascular diseases

    4.1 What are the attributes of monitoring that matter to clinicians? (interviews)

    4.2 What are the attributes of monitoring that matter to patients? (survey)

    4.3What barriers/enablers would shape adoption in cardiology clinics and at home?

1.8 Approach and Methodology

Cardiovascular health, particularly degenerative valve disease, presents complex physiological, psychological, and technological challenges. To develop a meaningful telemonitoring solution, this thesis combines multiple research methods aimed at building a holistic understanding of patient needs, clinical requirements, and technological feasibility.

The project builds upon three main pillars: an extensive literature review, a quantitative questionnaire study targeting individuals with cardiovascular conditions, and qualitative interviews with medical experts. Together, these methods form the foundation for the conceptualization and design of the telemonitoring device, ensuring that both user experience and clinical utility are grounded in evidence.

1.8.1 Exploratory Literature Review

The literature review was conducted in an exploratory and iterative manner, gradually refining the focus as new insights emerged. It was structured into several thematic stages, each addressing a key area of knowledge required for the development of the new telemonitoring device.

The (1) first stage established a **broad understanding of cardiovascular diseases**, followed by a focused exploration of degenerative heart diseases, examining their causes, progression, diagnostic challenges, and current clinical interventions. This included an overview of the main diagnostic methods, treatment pathways, and long-term management strategies used today.

The (2) second stage addressed heart murmurs, due to their close association with degenerative heart conditions. Since, in this project, heart sounds will serve as a primary data input for phonocardiography monitoring, this section **examined the acoustic signatures of murmurs, their clinical interpretation, and the technologies used to detect them.**

Subsequently, (3) the review **explored patient pathways and the emotional, behavioral, and experiential aspects of living with cardiovascular disease.** This included how patients feel between consultations, their levels of confidence and uncertainty, and how these psychological factors influence adherence and perceived safety, an understanding that was later expanded through the patient questionnaire.

The next stage (4) focused on **current at-home monitoring technologies.** A market-oriented review examined commercially available and research-stage devices, evaluating their functionalities and design limitations.

Relevant sources were retrieved from databases such as ScienceDirect (Elsevier), IEEE Xplore, SpringerLink, PubMed, and MDPI. The snowballing technique was used to identify additional studies from reference lists. This flexible and interdisciplinary approach enabled a broad mapping of the research landscape across medicine, behavioral science, engineering, and design.

The outcomes of this phase informed the questionnaire design, the interview framework, and the technological direction for the solution's conceptual development.

1.8.2 Quantitative Research - Online Questionnaire

To complement the literature findings and gain first-hand insight into patients lived experiences, a quantitative online questionnaire was conducted. Its objective was to **explore how individuals with cardiovascular conditions perceive the periods between medical consultations, what emotions and uncertainties they experience, and how they view the potential of telemonitoring solutions to support them.**

Data collection was done for a month (1st of November to 1st of December 2025). To mitigate selection bias, the survey was shared through a variety of platforms and networks beyond specific disease subgroups.

The final sample consisted of 105 valid responses. Although this project focuses on degenerative valve disease, the questionnaire was open to anyone with a cardiovascular condition. The largest respondent groups were people with heart valve disease and heart failure. These responses remain highly relevant, since both conditions involve chronic and progressive courses that require ongoing monitoring and decision making about treatment.

This approach was adopted because the uncertainty and emotional strain associated with heart conditions are common to all such patients, making their insights equally relevant. Furthermore, the survey was shared across multiple online communities and patient forums with two main goals: to reach a large number of participants and to capture diverse perspectives. To ensure inclusivity, it was offered in three languages (English, Dutch, and Spanish) and distributed across Latin America, Spain, the Netherlands, the United States, and Canada. The majority of respondents were over 45 years old. This is particularly relevant because most medical devices require approximately ten to fifteen years to progress through development, testing, and certification before reaching the market. For respondents who are currently around 45 years old, this implies that when a device such as the one proposed in this project becomes available, they will be approximately 55 to 60 years old and therefore fall within the intended target group.

The questionnaire contained 16 questions, structured in three sections:

1. General information: Two questions on heart condition type and age range.
2. Follow-up experience: Five questions addressing emotions and perceptions between check-ups, confidence in disease management, main sources of uncertainty, and current use of at-home monitoring devices.
3. Perception of a new device: The remaining questions explored initial impressions of the proposed telemonitoring concept, perceived usefulness, desired features, and potential barriers to use. Two open-ended questions invited participants to elaborate on what would make the device helpful between appointments and what factors might discourage its use.

The survey included multiple-choice, rating scale (0–10), and open-ended questions. Most closed questions featured an “Other” option, allowing respondents to provide personalized input. Approximately 87% of the survey focused on quantitative insights, while qualitative responses were analyzed thematically. A more comprehensive overview of the questionnaire and the results is available in the appendices (see Appendix A)

A pilot test ensured clarity and reliability before deployment. Data analysis included descriptive statistics, cross-tabulations, and thematic categorization of open-ended responses. The findings provided a grounded understanding of patient attitudes, emotional needs, and acceptance of telemonitoring technologies, which informed the design requirements.

1.8.3 Qualitative Research - Expert Interviews

To gain more insights from health experts and understand the organizational needs from doctors, semi-structured interviews were conducted. This qualitative phase was **designed to complement the literature research and gather clinical expertise on degenerative heart diseases and the practical realities of patient follow-up.** The goal of these interviews was to collect professional perspectives on current medical procedures, challenges faced during consultations, and expectations regarding the possible use of a telemonitoring device. Experts were also asked whether they considered such technology a useful addition to current care practices.

A total of five interviews were carried out. To minimize geographical and institutional bias, two cardiologists from Spain, two from the Netherlands and a rural GP from Spain were interviewed, each affiliated with a different hospital. A semi-structured approach was utilized, combining structured questions with open-ended prompts that encouraged elaboration. The interview guide was developed based on literature review and a pilot interview to ensure clarity and relevance. Sessions lasted between 20 and 45 minutes.

Interviews were recorded in audio format, and transcripts were produced only with the participants’ consent. In such cases, supplementary written notes were taken to complement the audio recordings. Conducted in English and Spanish, the transcripts were preserved in their original languages, and direct quotations used in the thesis were translated into English as required.

This study was approved by the Human Research Ethics Committee (HREC) of TU Delft. All participants provided informed consent prior to the interview. Data from experts who requested anonymity were anonymized, while those who agreed to be identified were referenced by name, professional role, and hospital affiliation.

The insights obtained from the expert interviews were merged with findings from the literature review and the online questionnaire. This combination of qualitative and quantitative data offered a comprehensive understanding of both patient and professional perspectives, which together informed the design and functional requirements of the device.

In appendix B, one can see a concise description of each interview participant, summarizing their qualifications and outlining the main topics discussed during the interviews.

02 FINDINGS

2.1 Introduction

Cardiovascular disease is the leading cause of death worldwide. In 2021, it accounted for an estimated 19.4 million deaths (World Health Organization: WHO, 2025). Chong et al. (2024) forecast that between 2025 and 2050, cardiovascular prevalence will increase by 90% and crude mortality by 73%. Annual cardiovascular deaths are expected to rise from 20.5 million in 2025 to 35.6 million in 2050. Although age-standardized rates are projected to remain stable or decline, the steep rise in crude mortality underscores the growing impact of global population aging. Beyond its human cost, the disease places immense strain on health systems and economies through hospitalizations, interventions, long-term treatment, and productivity loss.

This burden is reflected at the national level as well. In the Netherlands, cardiovascular disease leads to around 400,000 hospital admissions annually, including more than 80,000 cardiac interventions. Prevalence data indicates that 730,000 individuals live with coronary heart disease, 120,000 with heart failure, and 260,000 with atrial fibrillation (Leening et al., 2014). The incidence of heart failure rises steeply with age, from approximately 1 per 1,000 person-years before the age of 60 to nearly 50 per 1,000 among individuals over 90 years old.

Against this backdrop, heart murmurs acquire particular clinical importance. They are often among the earliest detectable indicators of valvular disease and structural abnormalities (Edder, et al., 2025). The Tromsø Study (Davidsen et al., 2025) found murmurs to be especially prevalent in women, older adults, and patients with comorbidities such as hypertension, diabetes, or a history of myocardial infarction or heart failure (Figure 3). Murmurs not only guide clinical decision-making but also serve as accessible markers of underlying cardiovascular risk in populations where disease burden continues to increase.

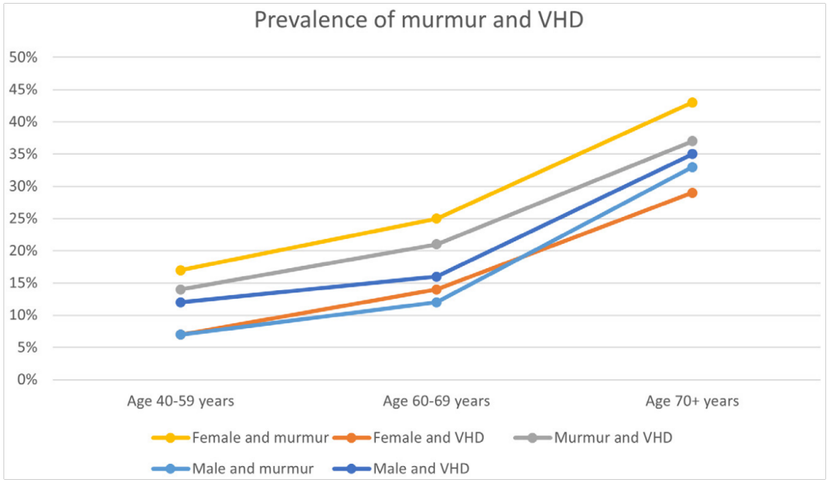


Figure 3. Prevalence of murmur and valvular heart disease (VHD) related to age and sex. Graph derived from the Seventh Tromsø Study (Davidsen et al., 2025).

** For readers who wish to explore the global burden of cardiovascular disease through interactive charts and graphs, data are available from the Institute for Health Metrics and Evaluation's visualization tool (CoD viz, n.d.): https://vizhub.healthdata.org/cod/*

2.2 Degenerative Valve Diseases

2.2.1 Introduction, Causes, and Diagnosis

RQ 1.1 What is degenerative heart disease?

Degenerative valvular heart disease is an age related condition where one or more heart valves gradually thicken, stiffen, or calcify, which reduces how well the valve opens or closes and can impair blood flow.

Degenerative valvular heart disease has become the dominant form of valvular pathology in industrialized nations. Iung and Vahanian (2011) observed that as rheumatic disease declines, degenerative pathologies have increased sharply, especially among aging populations. Goldbarg et al. (2007) noted that degenerative aortic valve disease is now the third most common cardiovascular condition, underlining its growing clinical and economic significance.

Moreover, the origin of degenerative valvular disease is multifactorial and it is not fully defined. Despite advances in pathophysiological understanding, no pharmacologic therapies have yet proven effective in halting or reversing degeneration (Sengupta et al., 2024).

Diagnosis of degenerative valve disease relies primarily on echocardiography, which enables visualization of valve anatomy, quantification of gradients, and evaluation of ventricular function (Mrsic et al., 2018), but physical examination, particularly auscultation, remains a key initial tool.

2.2.2 Degenerative Valve Disease and the Elderly

The aging population has changed both the presentation and management of degenerative valvular disease. In patients over 80 years, care often requires a multidisciplinary approach and explicit shared decision making to balance procedural risk, symptom burden, and patient priorities (Kodali et al., 2018). Diagnosis is frequently delayed because older patients may normalize symptoms as part of aging, while comorbidities such as chronic lung disease can mask cardiac causes. Although stress testing is recommended to uncover latent symptoms, limited mobility often restricts its use in this group.

On top of that, recent studies show that decision aids that support patient understanding and involvement have been shown to improve satisfaction and reduce decisional conflict, reinforcing the importance of early, structured conversations in this population (Kodali et al., 2018).

2.2.3 Types of Degenerative Valve Diseases

RQ 1.2 What are the types of degenerative heart disease?

In developed countries, degenerative heart disease most often refers to age related degenerative valvular disease, led by calcific aortic stenosis, followed by degenerative mitral regurgitation, then aortic regurgitation. Mitral stenosis is uncommon and is usually rheumatic rather than degenerative, although an age related calcific form linked to mitral annular calcification can occur.

Type	Frequency	Severity	Prognosis
Aortic stenosis (AS)	Most common degenerative valve disease in Europe	Severity correlates better with murmur timing than intensity	Once symptomatic, rapid deterioration; prompt intervention essential
Aortic regurgitation (AR)	1–5% of adults over 65, varies by region and method	Murmur duration correlates better with severity than intensity	Poor if untreated; requires surgery before irreversible ventricular dysfunction
Mitral regurgitation (MR)	Affects ~24 million people worldwide; MVP in 2–3% of population	Severity varies; linked to degree of leaflet prolapse and regurgitant volume	Untreated symptomatic severe MR: ~30% 5-year survival; early repair improves outcomes
Mitral Stenosis (MS)	Developed countries have an estimated incidence of 1 in 100,000	Diminishing murmur intensity may indicate disease progression with extensive valve calcification	Approximately 80% of patients will not survive ten years from symptomatic onset

Table 1. Explanations of the four most common DVDs, severity and prognosis. Information from Themes (2016) and Vahanian et al. (2012). Full table can be found in appendix C.

2.2.4 Diagnosis of Degenerative Valve Disease

RQ 1.3 How are degenerative valve diseases currently detected?

They are usually first suspected in primary care when symptoms or a heart murmur are noticed during a physical exam, which triggers referral to a cardiologist. It is then confirmed and graded mainly with echocardiography, before a multidisciplinary team decides on monitoring or intervention.

As seen in figure 4 in the next pages, the diagnostic pathway for degenerative valvular disease usually begins in primary care and progresses through several stages of clinical evaluation and imaging.

First, patients often first present to their general practitioner with symptoms such as exertional dyspnoea, fatigue, chest discomfort, or dizziness. During the initial consultation, the GP performs a physical examination to hear the heart sounds and conclude if the patient needs a referral. When a murmur is present or symptoms raise concern, patients are referred to a cardiologist for further assessment.

After that, cardiology evaluation generally starts with a repeat physical examination focused on cardiac auscultation to identify murmurs, characterizing said murmur and see other signs suggestive of structural valve abnormalities. Specific findings may suggest the underlying valve pathology. (Maganti et al., 2010).

Because physical examination alone cannot determine disease severity, cardiologists rely heavily on echocardiography. Transthoracic echocardiography provides a visualization of the heart structure and remains the cornerstone of diagnosis in degenerative valve disease (Hawkey et al., 2021). If the echocardiogram raises uncertainty or if additional information is required, supplementary tests may be used. These may include ECGs, chest radiographs, or more specialized imaging.

Furthermore, once diagnostic findings are available, the patient is usually discussed in a multidisciplinary context involving cardiologists, imaging specialists, heart failure physicians, and cardiac surgeons to determine disease severity, symptom attribution, and the optimal timing of intervention. Treatment planning can range from watchful monitoring to medical therapy, transcatheter intervention, or surgical valve replacement, depending on the individual's clinical profile.

2.2.5 Management of Degenerative Valve Disease

The chronic nature of degenerative valvular disease necessitates structured surveillance. Mrsic et al. (2018) recommend echocardiographic **follow-up every three to five years for mild disease, one to two years for moderate disease, and six to twelve months for severe lesions.** An annual cardiology review is appropriate for all patients with progressive disease.

In addition, Iung and Vahanian (2014) stress that contemporary management must consider both disease progression and patient frailty. They report that large surgical databases in Europe, the United States, and Canada show a steady increase in the proportion of valvular surgeries and in mean patient age, reflecting the dominance of degenerative etiologies. This trend underscores the appeal of less invasive techniques, particularly for older adults with comorbidities.

On the contrary, while physical examination remains useful for detecting new or changing murmurs, its diagnostic accuracy varies widely. Echocardiography thus continues to anchor monitoring strategies. However, authors increasingly emphasize the potential role of digital and wearable technologies to facilitate earlier detection and remote monitoring (DesJardin et al., 2022; Aluru et al., 2022). Such tools could reduce underdiagnosis, improve continuity of care, and allow for more frequent assessment between formal clinical visits.

RQ 1.4 How are degenerative heart diseases currently monitored?

Degenerative valve disease is monitored mainly through regular cardiology follow ups and scheduled echocardiography:

- 3 to 5 years for mild disease
- 1 to 2 years for moderate disease
- 6 to 12 months for severe disease

Degenerative Valve Disease Patient Pathway

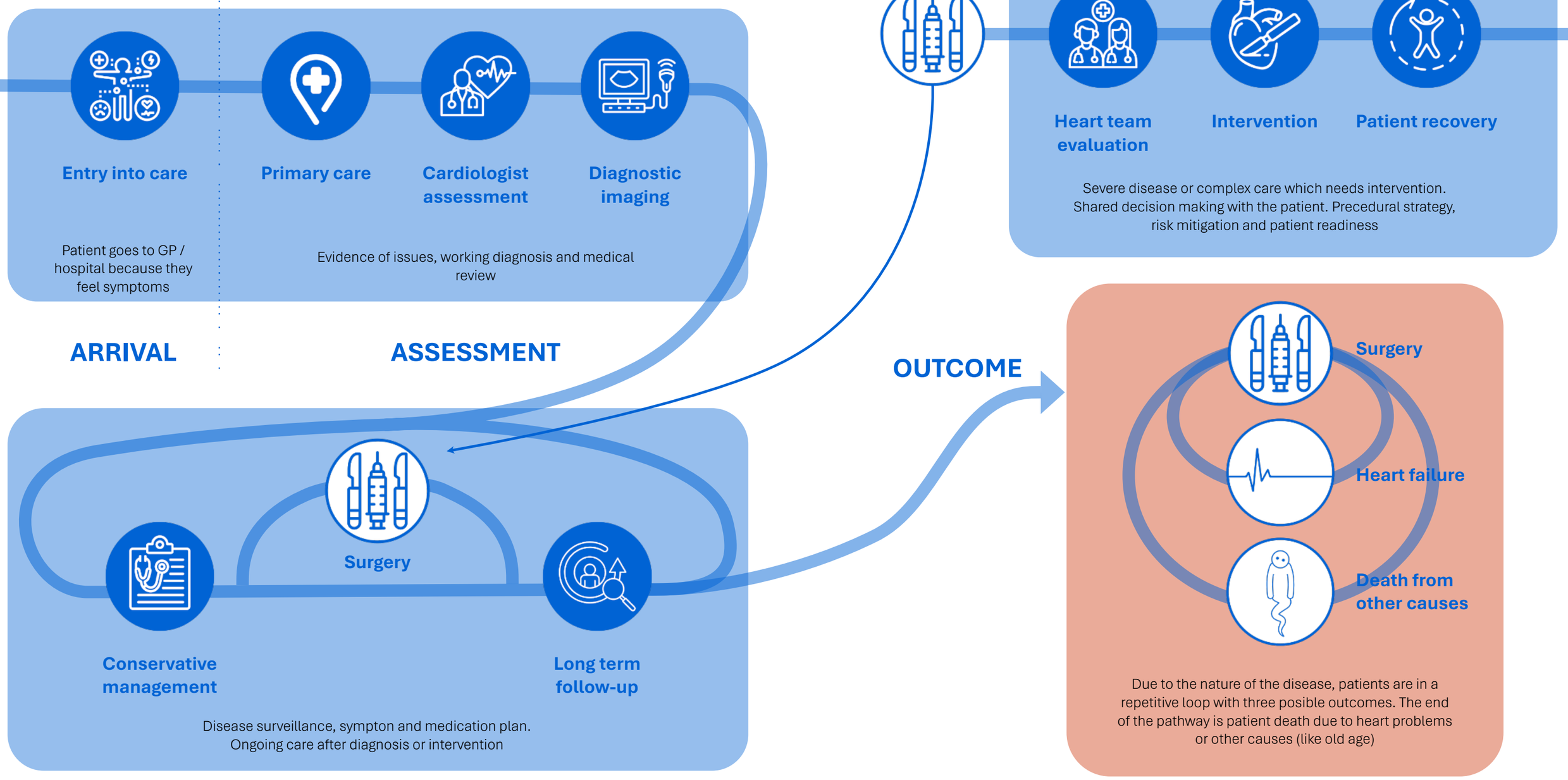


Figure 4. Pathway for degenerative valvular disease patients. Once diagnosed, patients enter a pathway loop of revisions and waiting for the revisions. The only outcome is eventual death (as the disease has no cure).

2.2.6 Current Interventions

2.2.6.1 Progression of Degenerative Valve Disease

RQ 1.5 *How does the disease progress over time?*

Degenerative aortic stenosis usually worsens slowly at first, then can speed up unpredictably as valve calcification increases, with faster decline once symptoms appear. Progression differs greatly between patients, which makes it harder to predict.

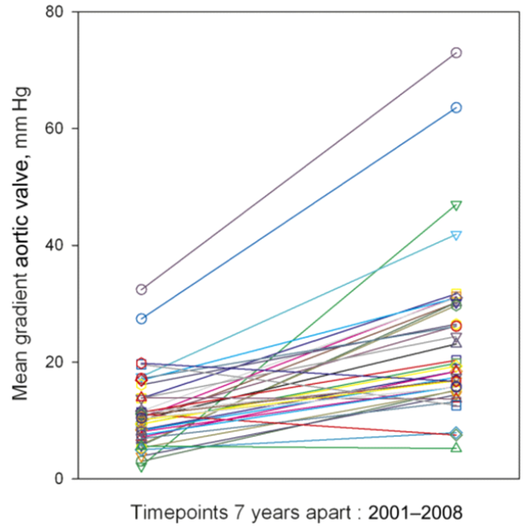


Figure 5. Progression of aortic stenosis. The figure shows the progression of the mean gradient (mm Hg) in a subgroup of 38 participants with measurements in both T5 and T6, delineating a large individual variability in disease progression and trend towards an increasing progression rate in the more advanced disease stages. Graph from Eveborn, et al. (2012)

The progression of degenerative valvular heart disease, particularly aortic stenosis (AS), is gradual yet highly variable among individuals. As seen in figure 5, longitudinal data from the Tromsø Study show that while there is a mean progression rate of AS, it is as a non-linear process, where deterioration accelerates as the valve becomes more calcified and restricted, underscoring that progression is not constant over time.

Supporting these conclusions, Davies et al. (1991) reported that mild or moderate AS can evolve rapidly and unpredictably, and that patients with coexisting cardiac conditions undergoing surgery (for example, coronary bypass or mitral procedures) should be considered for aortic valve replacement.

A consistent conclusion emerges: the course of degenerative AS is unpredictable and influenced by structural valve pathology and systemic cardiovascular factors. Once symptoms develop, deterioration accelerates and adverse outcomes become more likely. For this reason, longitudinal monitoring through echocardiography remains essential for all patients, even those with mild or moderate disease. Understanding individual progression rates is critical to determining appropriate follow-up intervals and the optimal timing for surgical or interventional therapy.

2.2.6.2 Timing Importance of Surgical Interventions

Surgical valve replacement remains the definitive treatment for severe degenerative valvular heart disease but determining when and how to intervene is complex. Historically, surgical aortic valve replacement (SAVR) has been considered the standard of care for severe aortic valve disease, improving both survival and quality of life, even among elderly patients (Rostagno, 2019). However, as the incidence of valvular disease rises sharply with age the decision to operate increasingly involves balancing procedural risk against expected benefit (figure 6). Older patients often present frailty, multimorbidity, and reduced physiological reserve, all of which heighten perioperative risk.

Even when surgery is technically feasible, approximately 30% of patients with severe aortic stenosis are considered inoperable due to prohibitive surgical risk (Rostagno, 2019). For these individuals, transcatheter valve interventions have become essential alternatives. Kodali et al. (2018) observe that minimally invasive procedures such as transcatheter aortic valve implantation (TAVI) and percutaneous mitral repair offer lower perioperative morbidity, shorter hospitalization, and faster recovery compared with open surgery.

In short, the timing of surgery remains a central challenge. Everett et al. (2018) argue that intervention should ideally occur when the risks of disease progression (such as heart failure, irreversible left ventricular dysfunction, or sudden cardiac death) begin to exceed those of the procedure itself (figure 7).

The authors note that waiting until advanced ventricular decompensation develops increases perioperative mortality (reported between 9% and 19%) and reduces long-term recovery due to irreversible myocardial fibrosis. Conversely, premature intervention may expose patients to unnecessary procedural risk.

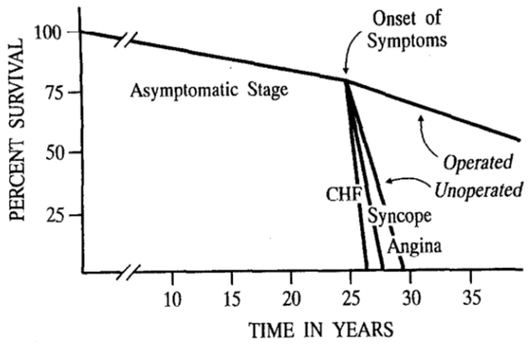
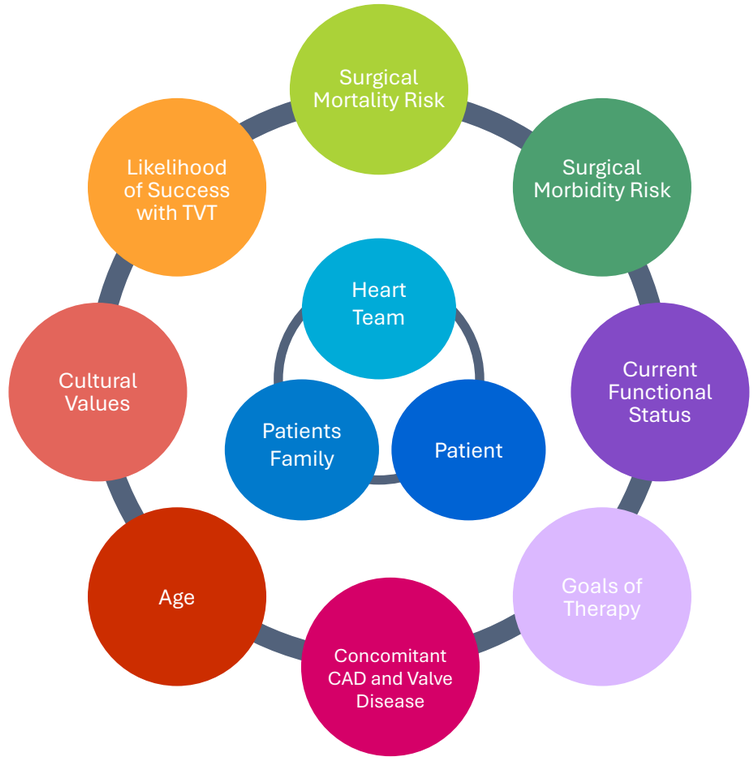


Figure 8. Survival rates in patients with aortic stenosis. During prolonged asymptomatic stage annual mortality rate is very low; after onset of symptoms prognosis is substantially worsened. In patients who do not undergo surgery, survival is closely related to the nature of symptoms. Graph taken from Faggiano (1992).

The risks of non-intervention are also significant. Patients with asymptomatic severe aortic stenosis have an annual risk of sudden cardiac death of approximately 1%, often without preceding symptoms (Everett et al., 2018). As seen in figure 8, once symptoms appear, deterioration can be rapid, with mortality reaching 12% within six months if left untreated.



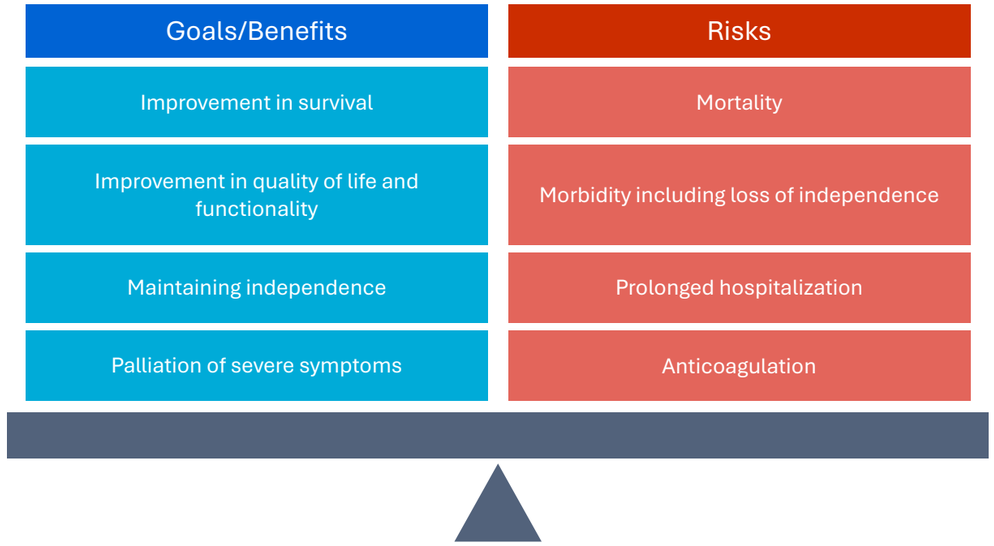


Figure 6. Successful management of valvular heart disease in the elderly involves shared decision making between the patient, patient's family, and heart team (top figure). Multiple factors must be taken into consideration, and the importance of each factor will vary among the different parties involved (bottom image). Image from Kodali, et al. (2018).

RQ 1.6 *What complications are most sensitive to delayed detection?*

Delayed detection of disease progression is most sensitive to death related outcomes, especially sudden cardiac death that can occur even without prior symptoms, and rapid mortality after symptoms appear if severe disease is left untreated. It also increases the chance that patients reach advanced heart failure or irreversible ventricular damage before intervention, which is linked to higher perioperative death risk and poorer long term survival.

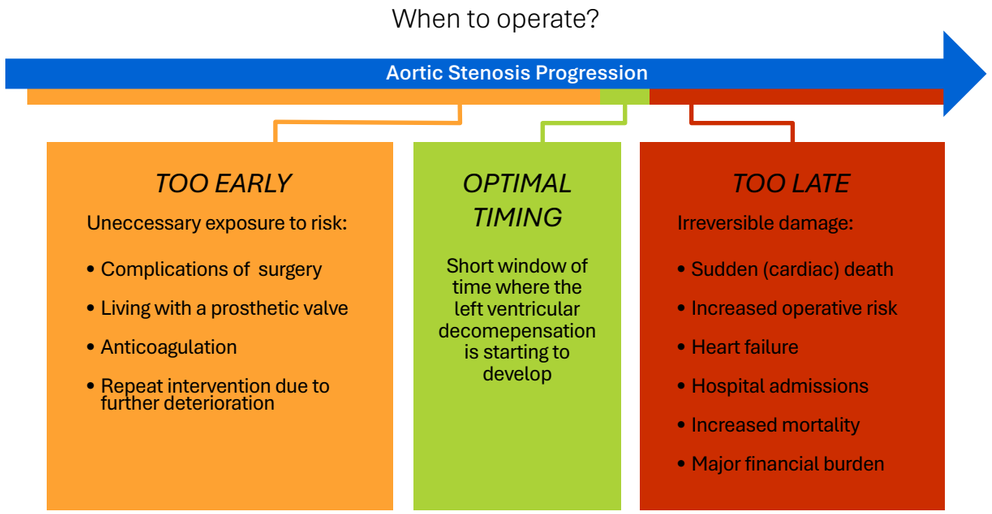


Figure 7. Optimization of surgery timing for Aortic Stenosis. Image based of the paper "Timing of intervention in aortic stenosis: A review of current and future strategies." by Everett, et al. (2018).

2.2.7 Conclusion Degenerative Valve Diseases

Degenerative valvular disease has become a common cardiovascular condition, especially among older adults. Since there are no therapies that can reverse the degeneration, treatment relies on surgical correction. Elderly patients tend to minimize or overlook their symptoms, which often delays the moment when they enter the care pathway. In these cases, heart murmurs play a central role during diagnosis because they provide the first clear indication that something may be wrong. Once identified, patients are monitored with echocardiography, which remains the main tool to track disease evolution.

Aortic stenosis is the most common degenerative heart disease (in developed countries). Due to the nature of the disease, it is difficult to estimate when a patient will worsen, as DVDs progress in a non-linear way. As a result, timing surgery becomes a complex decision. Since these are usually older patients, the procedure carries significant risk. Clinicians need to weigh the danger of operating against the danger of waiting. The priority is to intervene at the moment when the risk of disease progression becomes greater than the risk of surgery, especially when there is a threat of heart failure or sudden cardiac death.

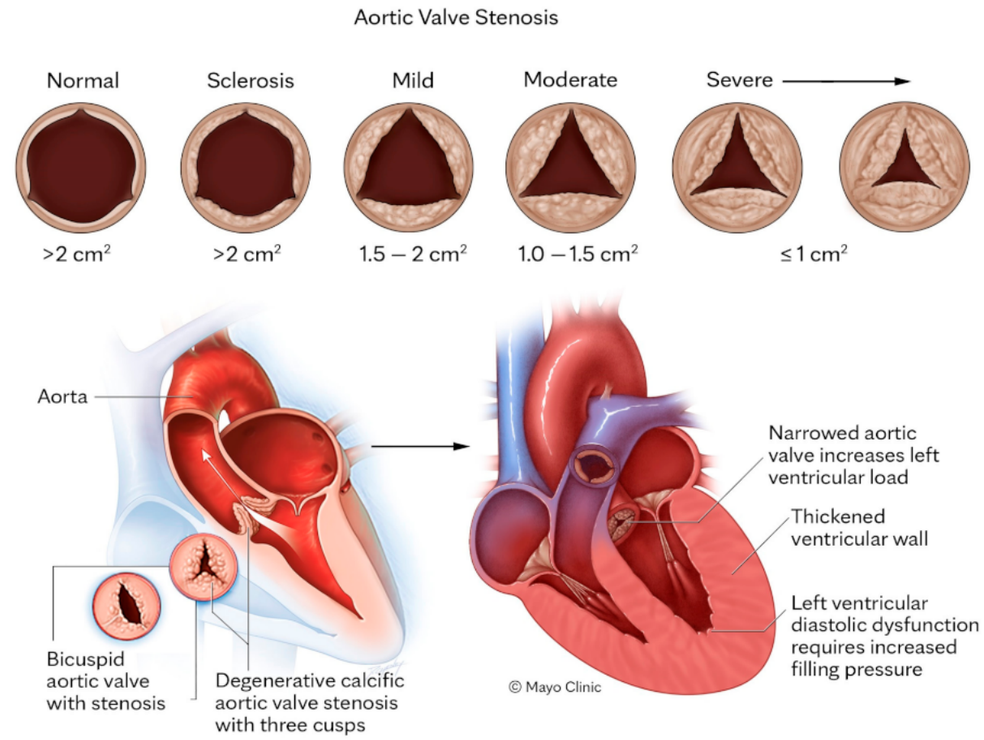


Figure 9. Progression of aortic stenosis in a three-cusp aortic valve. Image from Scalia et al. (2023)

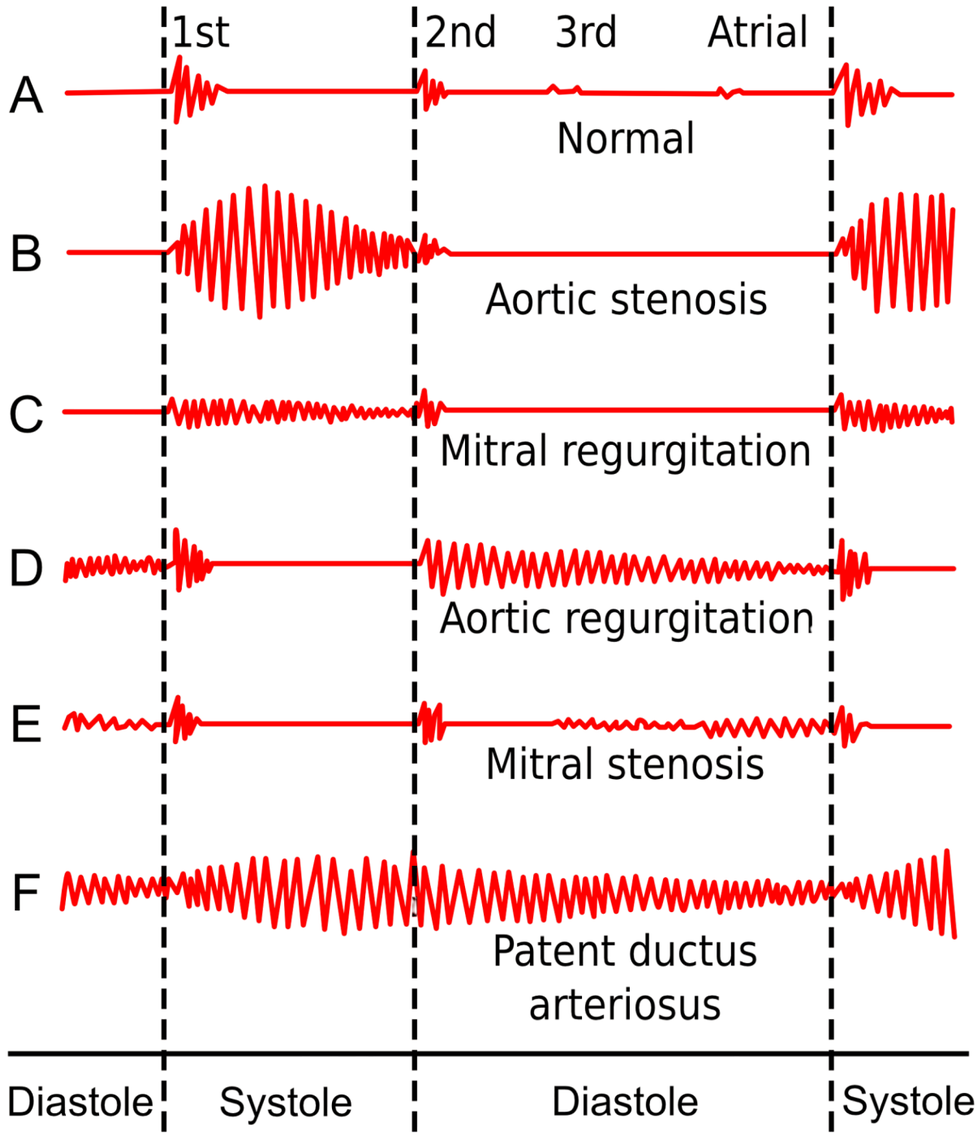


Figure 10. Recording A is an example of normal heart sounds, showing the vibrations of the first, second, and third heart sounds. Image from Physiology (2024).

2.3 Heart Murmurs

2.3.1 Definition and Classification

Heart sounds arise from the closing of the cardiac valves, producing the familiar S1 and S2 components of the cardiac cycle. When blood flow becomes irregular due to structural or functional abnormalities, additional sounds known as murmurs appear, shown in Figure 10. These may be innocent or pathological. Innocent murmurs occur without structural abnormalities, whereas pathological murmurs indicate congenital defects, valvular disease, or other acquired cardiac conditions (Ganguly and Sharma, 2017).

They are broadly grouped into systolic murmurs and diastolic murmurs. Each group corresponds to different structural or functional lesions of the heart.

RQ 2.1 *How are murmurs generated, classified, and linked to specific valve lesions and severity?*

Murmurs are generated by turbulent blood flow from structural or functional abnormalities. They are classified mainly by timing in the cardiac cycle, location, intensity, and radiation. Each murmur is linked to a specific valve disease and can be used to estimate severity.

From a diagnostic perspective, murmurs serve as one of the earliest detectable signs of underlying cardiac pathology. During routine clinical evaluations, the presence of a murmur often prompts further investigation. Findings from cardiologist interviews consistently showed that auscultation with the presence of murmurs is the primary trigger for referral to imaging. Without this initial acoustic cue, many early cases of degenerative valve disease would remain undetected.

RQ 2.2 *What is the role of heart sounds and murmurs in diagnostics?*

Heart sounds and, especially, murmurs act as an early acoustic warning sign that triggers referral to imaging. Their acustic signals help clinicians suspect which valve is affected before echocardiography confirms the diagnosis.

Clinical classification of murmurs relies on several features:

- Timing within the cardiac cycle
- Shape of the acoustic pattern over time
- Intensity on a standardized six-point scale
- Pitch and quality
- Anatomical location of maximal audibility

Consequently, auscultation provides early clues about which valve is affected, since each listening area corresponds to a specific valve and therefore to the degenerative conditions that

commonly involve it. Localization is particularly important because it supports identification of the affected valve (Figure 11). For example, a systolic sound heard best at the right upper sternal border is associated with aortic stenosis, while an apical blowing systolic sound is associated with mitral regurgitation. These observations guide clinicians toward an initial diagnostic impression before imaging confirms the underlying lesion.

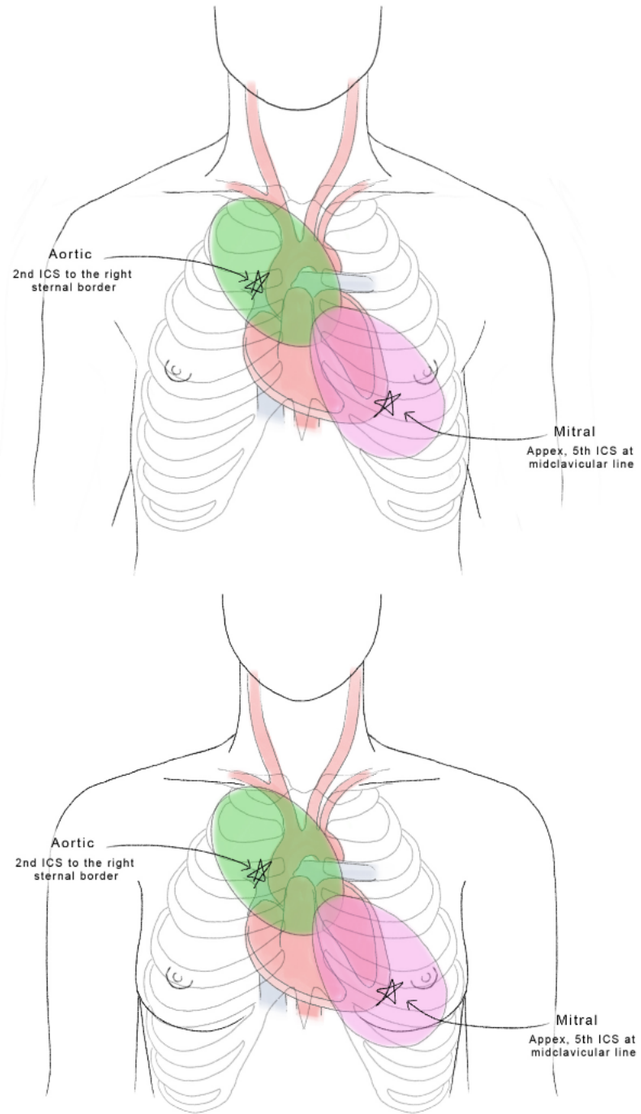


Figure 11. The image overlays the aortic listening region in green, at the second intercostal space along the right sternal border. The mitral listening region in pink, at the apex in the fifth intercostal space along the midclavicular line. Image rendered from multiple sources (main source: Shade, 2024).

It is important to note that the auscultation point are the same for men (top image) and women (bottom image).

2.3.1.1 Murmur intensity and Disease Classification

Cardiac murmurs are audible signs of turbulent blood flow, so when a valve lesion or shunt progresses, the murmur often changes because of the pressure change, the amount of flow, and chamber function change over time. These changes can show up as shifts in timing, longer or shorter duration and changes in where the murmur is loudest (Thomas et al., 2023), (Chatterjee, n.d.), (Beerman, 2023) & (Hirata et al., 2022).

A key caution is that intensity alone can mislead. In several conditions, murmur intensity has limited correlation with severity, and in advanced disease the murmur can actually become softer if forward flow falls or if pressures equalize across a defect (Themes, 2016).

Examples:

- Aortic stenosis often gets louder as it progresses, until late low output stages.
    - In typical progression from less severe to more severe aortic stenosis, the murmur generally grows louder, lasts longer, and peaks later in systole as obstruction increases. (Armstrong, 2025)
- Aortic stenosis can sound softer when it is critical.
    - As aortic stenosis becomes very severe and left ventricular contractility falls, the murmur can become softer and shorter because forward flow drops, so intensity can be misleading in low output states. (Armstrong, 2025)

Population-based evidence suggests that the presence of a heart murmur is strongly associated with increased mortality. Brown, Giles, and Croft (2009) reported that the crude coronary heart disease (CHD) mortality rate among individuals with a heart murmur was more than three times greater than among those without (82.5 vs. 25.2 per 10,000 person-years).

Moreover, the association was even more pronounced when examining mortality from all heart diseases. **Persons with murmurs had a crude mortality rate of 140.4 per 10,000 person-years compared with 34.9 per 10,000 person-years among those without.** Murmur intensity appeared to be a key factor: moderate-to-high intensity systolic murmurs were linked to more than a twofold increase in mortality, while moderate-to-high intensity diastolic murmurs conferred a more than fourfold increase. Importantly, individuals with murmurs were also more likely to present with other cardiovascular risk factors, such as diabetes, hypertension, and left ventricular hypertrophy, further amplifying their clinical relevance (Brown et al., 2009).

2.3.2 Monitoring of Murmurs

RQ 2.3 *How are murmurs monitored throughout the patient's disease?*

Murmurs are checked during periodic auscultation, the disease progression monitoring is done with echocardiography.

Findings from clinical interviews indicate that murmurs serve as the primary trigger for diagnostic evaluation. When a clinician hears an abnormal acoustic pattern during auscultation, this immediately initiates further testing, most commonly an echocardiogram. In this sense, murmurs represent the gateway into the diagnostic pathway. They reveal the first indication that valvular disease may be present, even before symptoms are prominent.

Although murmurs are central to early recognition of valvular disease, their role becomes limited once the diagnosis is confirmed. Cardiologists report that auscultation is unreliable for longitudinal assessment due to several factors: high variability across patients, dependence on examiner skill, and the absence of stored acoustic baselines for comparison. In routine practice, clinicians may hear a patient only once or twice per year, making it impossible to recall the exact characteristics of earlier examinations.

For this reason, echocardiography (figure 12) becomes the principal modality for monitoring disease progression. It offers visual and quantitative measurements that can be compared across time and across individuals, including valve area, jet velocity, regurgitant fraction, and chamber remodeling. These standardized measures allow clinicians to evaluate progression, plan treatment, and determine appropriate follow-up intervals. While murmurs continue to be assessed during physical examination, their role is supplementary rather than central once imaging has been performed.

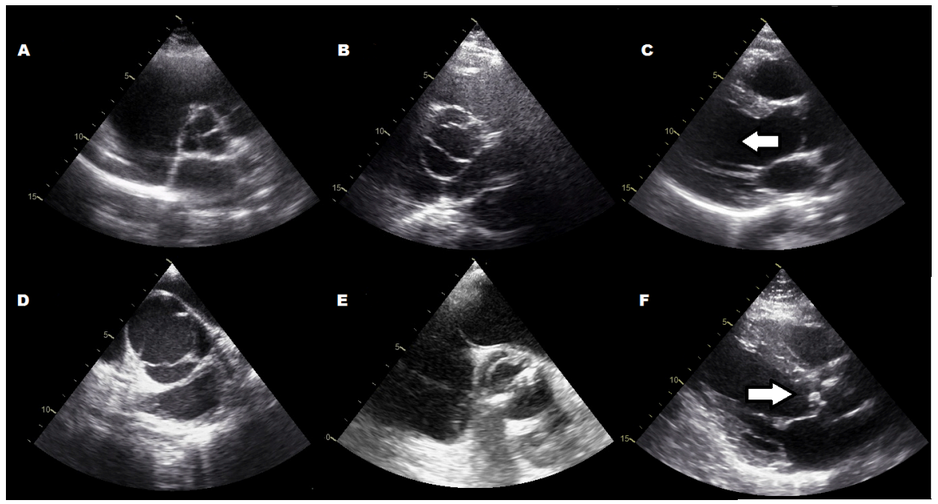


Figure 12. Ultrasound images show a normal three leaflet aortic valve, several bicuspid aortic valve patterns, an enlarged ascending aorta, and severe calcified bicuspid aortic valve disease. Image from Tokmaji et al. (2013)

2.3.3 Limitations of Physical Examination (Qualitative Interviews) – Knowledge Exploration

RQ 2.4 *What are the roles, strengths, and limitations of these approaches?*

Strengths: Auscultation is quick and accessible for early detection, while echocardiography provides objective, quantitative measures that establish a baseline and allow reliable severity grading and follow up over time.

Limitations: Auscultation is subjective with high patient to patient variability and no stored signal for comparison across visits, while echocardiography is intermittent and resource dependent, which can leave gaps where progression occurs between scans.

Although murmurs reflect underlying flow dynamics and evolve as valve disease progresses, they cannot be used reliably for longitudinal monitoring. Murmurs vary considerably across patients due to differences in anatomy, chest wall characteristics, and heart sounds. This variability makes cross-patient comparison impossible, and even within a single patient, a clinician cannot reliably recall the acoustic characteristics of a murmur heard many months earlier. In contrast, echocardiography provides visual and quantitative baselines that can be compared across time and across individuals. This standardization is one of the key reasons clinicians rely on imaging, rather than auscultation, for follow-up evaluations.

During routine review appointments, cardiologists perform a physical examination to listen to the murmur again, but the purpose is limited. The examiner is not attempting to compare the sound directly with the previous evaluation. Instead, the focus is on noticing whether any new characteristic stands out, such as a change in pitch, duration, or intensity. These changes can occur because progressive valve narrowing or increasing regurgitation alters flow turbulence. While these acoustic changes may be clinically meaningful, they remain difficult to interpret without a stored reference.

The diagnostic performance of auscultation has additional constraints. Physical examination alone cannot reliably distinguish between moderate and severe stenosis, and key auscultatory findings may be absent even in patients with significant structural lesions. For example, classic markers of aortic stenosis may not be audible in individuals with reduced cardiac output or complex hemodynamic patterns. As noted by McGee (2010), this limitation underscores the dependence on echocardiography and other imaging modalities to confirm diagnosis, determine severity, and guide management decisions.

Insights from clinical interviews highlight a consistent gap in current practice. Murmurs contain information that reflects disease progression, yet their utility is restricted to the initial diagnostic phase because there is no reliable method to capture, store, and compare them over time. This reliance on episodic imaging creates intervals of uncertainty for both clinicians and patients. Subtle acoustic changes between imaging appointments go undocumented, and opportunities for earlier detection of deterioration may be missed.

2.3.3.1 Positioning of the heart

The heart's position is relatively consistent across individuals. It is generally located behind the sternum, with its apex positioned at the left 5th intercostal space, approximately 9 cm from the midline.

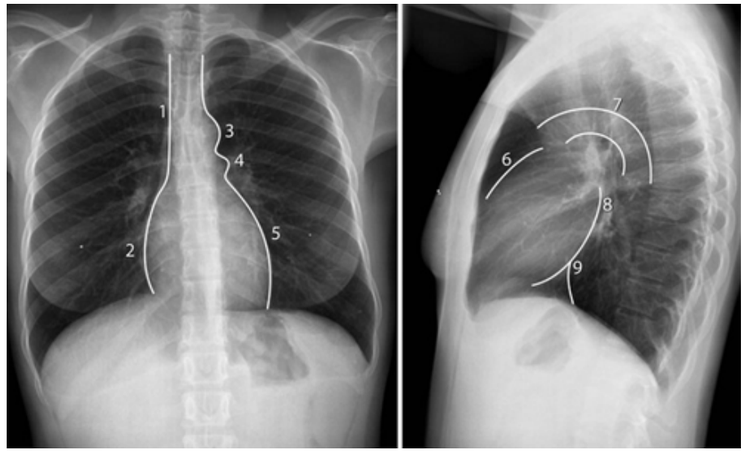


Figure 13. Normal postero-anterior (left) and lateral (right) chest radiographs. Image from Themes, U. (2016, March 2).

Across men and women, the anatomical position of the heart relative to external landmarks is essentially the same, so the standard auscultation points do not change by sex (figure 14). The heart sits in the mediastinum behind the sternum, where there is no breast tissue, so listening over the sternal border is unaffected. A common concern is that breasts block access, but in most cases this is not a practical barrier because heart sounds transmit through soft tissue, and breast tissue can be gently displaced to allow stable sensor contact when needed. The main overlap is at the mitral area, typically at the left fifth intercostal space near the midclavicular line, where breast tissue may cover the target spot, yet placement remains feasible with slight tissue displacement and consistent contact pressure. Only in cases of very large breasts, often associated with higher BMI, does positioning tend to require extra guidance or adjustment. The illustrations below reflect this, showing similar heart position in men and women, with most targets located behind the sternum and only limited overlap near the mitral area.

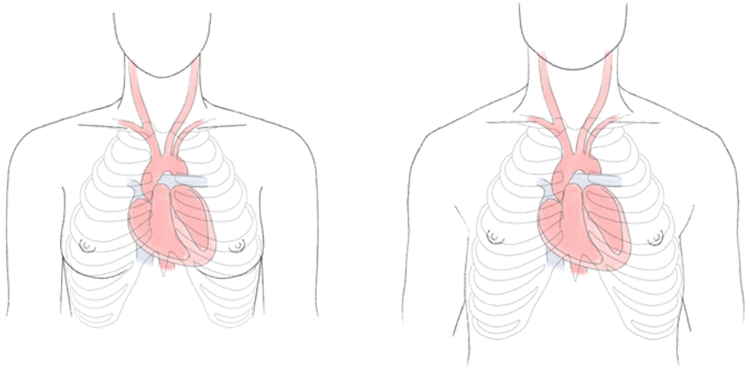


Figure 14. The heart and great vessels in relation to the rib cage and sternum. Left is the heart in womens body and right the heart on mens body.

2.3.4 Conclusion Heart Murmurs

Heart sounds arise from the closing of the cardiac valves, and pathological murmurs appear when turbulent flow is created by structural abnormalities such as congenital defects or degenerative valve disease. These murmurs differ in timing and pitch depending on the specific valve affected, and their presence serves as one of the earliest indications of underlying cardiac pathology. Clinicians rely on auscultation to identify which valve may be involved, since each listening area corresponds to a specific anatomical location. This early acoustic cue is crucial: interviews with cardiologists confirmed that the detection of a murmur is the primary reason patients are referred for echocardiography, and population data show that individuals with a murmur carry a markedly higher risk of mortality.

Despite this diagnostic value, the usefulness of murmurs diminishes after the initial assessment. Cardiologists noted that auscultation cannot be used reliably for long-term monitoring because murmurs vary widely across patients and cannot be recorded or compared over time. Since clinicians may hear a patient only once or twice per year, subtle changes in pitch or intensity are impossible to track. For follow-up and severity grading, echocardiography becomes essential because it provides visual and quantitative data that can be measured consistently. These insights reveal a clear gap in current practice: murmurs reflect disease progression, yet they remain clinically underused beyond the first diagnostic encounter due to the absence of a reliable method to monitor them longitudinally.

2.4 Patient Pathways

2.4.1 Treatment Team

The diagnostic and treatment pathway for heart disease, particularly degenerative valvular disease, increasingly relies on shared decision-making between clinicians and patients. Cardiologists interviewed for this study consistently emphasized that patient-reported symptoms are the primary indicator of clinical change and remain central to high-quality care. When symptoms evolve, this signals a need for reassessment, making patient communication an essential part of monitoring and management.

Shared decision-making challenges the traditional assumption that simply giving patients information automatically empowers them. Instead, it requires clinicians to actively invite patients into the conversation, ensuring that they understand their condition, expected disease course, and the risks and benefits of different treatment strategies (Matthias et al., 2013). In structural and valvular heart disease, this approach is particularly important. The progression of these conditions is no longer viewed as a slow path of passive observation; untreated valvular disease carries a clear and serious mortality risk (Hawkey et al., 2021).

Patients entering the care system do so with widely varying levels of knowledge, stress, expectations, and symptom awareness. Some arrive with misconceptions about the severity of activity restrictions, while others underestimate symptoms by attributing them to aging. Many also have unrealistic expectations shaped by outdated research or second-hand experiences. This variability makes early clinical conversations essential to align understanding, identify symptoms that patients may not recognize as pathological, and support informed decision-making that reflects individual goals, values, and preferences (Hawkey et al., 2021).

2.4.2 Adherence to treatment and medication, and the emotions tied to it

2.4.2.1 Information, partnership, and the work of self-management

Patients often feel unprepared for daily management. Mead et al. found that many lacked basic knowledge about diet, activity, and warning signs. As one said, *“I have no idea what to do. What can I eat. I do not know what to look for.”* Discharge teaching was described as overwhelming. *“I was given a stack of materials to read.”* Several wanted a more active role but felt dismissed. *“I want to tell my doctor this is how I feel and it is important to listen.”* These narratives indicate that clear, staged education and shared planning can support adherence.

Henriksen and Rosenqvist similarly describe a desire for guidance anchored in the whole life context. Patients wanted to talk about prognosis, side effects, work, finances, sexuality, and family roles. Many perceived time pressure in clinics and limited space for these topics. Telephone contact was welcomed and increased confidence. These authors argue that patients need to feel supported and heard. This can help connect treatment tasks to everyday roles which can then improve adherence, especially after an acute event that becomes a chronic condition (Henriksen & Rosenqvist, 2003).

2.4.2.2 Emotions, overload, and adherence

Psychosocial strain was common and closely linked to lapses. Focus group participants described depression, isolation, and worry. *“It is overwhelming because it is like a physical and mental thing. Sometimes I look around and I actually cry because I cannot handle it. I am losing control.”* Stress around lifestyle change and complex regimens led some to stop treatment. *“I would get so stressed I would not take my medicine.”* These accounts suggest that mood symptoms and treatment burden should be monitored and addressed as part of adherence support, not as an afterthought (Mead et al., 2009).

> ***RQ 3.1*** *What factors influence adherence to follow-up visits and to treatment?*
>
> Adherence improves when patients get clear, staged education and feel listened to through shared planning that connects diet, activity, medications, and warning signs to their daily lives.
>
> It worsens when patients feel overwhelmed, depressed, isolated, or stressed by complex regimens or information overload, which can lead to skipped medications and missed follow up.

2.4.3 Emotional experiences around cardiac surgery

2.4.3.1 Waiting for surgery

The waiting period between the decision to operate and the actual procedure is often marked by deep uncertainty and psychological strain. Ivarsson et al. (2004) describe this phase as “long, heavy, and dreary,” with most patients experiencing worry, insecurity, and an awareness of their own mortality. Thoughts of death, pain, and complications were common, particularly among those who had been told that surgery was essential for survival. Patients expressed fear that the operation might not take place in time, knowing that a prolonged wait could increase the risk of another cardiac event.

At the same time, many patients balanced this fear with hope for recovery and a longer life after surgery. This coexistence of anxiety and hope underscores the emotional ambivalence of the preoperative period. Positive internal factors (like finding inner strength) and external factors (receiving attention and feeling involved in care) helped patients cope. Conversely, poor communication and a lack of social support intensified distress. These studies reveal that reassurance and clear information during the waiting period are critical not only for emotional well-being but also for maintaining trust in the healthcare process (Ivarsson et al., 2004).

2.4.3.2 After surgery

Postoperative recovery introduces a new set of emotional challenges. Higgins et al. (2007) found that anxiety and depressive symptoms were highly prevalent after cardiac surgery. Practitioners identified fear of another heart attack or death as the most common source of distress. This fear often triggered hypervigilance toward bodily sensations, leading patients to misinterpret benign symptoms as signs of recurrence. Such anxiety created a self-reinforcing cycle: distress heightened physical discomfort, which in turn increased anxiety.

Patients also reported feeling vulnerable and insecure once discharged from hospital care. One practitioner described how “the event, treatment, and return to home can be so fast it is anxiety provoking for the patient.” Many feared “leaving the security of medical care,” highlighting how abrupt transitions from intensive monitoring to self-management can amplify anxiety. This lack of engagement limited recovery and increased the likelihood of ongoing anxiety or depression. These findings emphasize the importance of psychological support and gradual education throughout the recovery process to help patients integrate their experience and adapt to new routines (Higgins et al., 2007).

2.4.3.3 Emotional sequelae and adjustment

Even when surgery is successful, many patients experience long-term psychological effects. According to Henkel (2023), cardiac procedures can be traumatic both physically and mentally. The sudden nature of many interventions leaves little time for patients to process what is happening. Around one in five develop clinical depression, and roughly one in three experience significant anxiety after a cardiac event or procedure. These emotional reactions can persist for months or years, effectively becoming a “second diagnosis” alongside the cardiac condition itself (Henkel, 2023).

2.4.4 Conclusion Patient Pathways

Living with degenerative valvular disease places patients on a journey filled with emotional highs and lows. Many move between moments of reassurance, knowing their condition is being monitored, and moments of anxiety linked to having a heart condition that may worsen without warning. Patients awaiting or recovering from cardiac surgery describe a continuum of emotional strain: anxiety while waiting, fear and vulnerability after surgery, and sometimes depression in the long term. Central to these experiences is uncertainty. There is unpredictability about survival, the timing of the procedure, and the future quality of life.

Their ability to adhere to medication, adjust daily habits, and stay engaged in their own care is shaped by a mix of personal, clinical, and social factors. When patients understand what is happening in their bodies, their anxiety decreases, because uncertainty is one of the strongest emotional burdens they face. The introduction of new treatments, medicines, lifestyle changes, and long-term prognoses adds both physical and psychological stress that can be hard to manage on their own.

Support from family, friends, and structured programs plays a major role in helping patients cope. When they feel accompanied, they express themselves more openly, remain motivated, and are better able to navigate the challenges ahead. Surgery marks a major milestone in this path. It brings hope for symptom relief, yet it also brings fear, since open heart procedures carry clear risks and require a demanding recovery. Because the disease can progress quickly, decisions about surgery often have to be made with little time to absorb the news. This leaves patients with limited space to process a life-changing event that reshapes both their health and their future.

2.5 Perspectives on heart problems and experiences of patients - Questionnaire

RQ 3.1 *What are current patient experiences from these pathways?*

Many patients describe long periods of uncertainty between appointments, because they lack clear, understandable information about what is happening in their body, when to seek care, and how their condition is changing. This often drives anxiety before check ups and reduces confidence in self management.

2.5.1 Disease management perceptions

One of the key themes that emerged was uncertainty between follow up appointments. Many participants reported that they often do not know what is happening in their body, how their condition is evolving, or what might occur in the future. This sense of "not knowing" is closely linked to their reported lack of data and information. One respondent expressed this clearly: *"Very newly diagnosed, less than a year, so I just feel like I am learning my body but worry I could miss something."* In contrast, individuals who had lived with their condition for several years described feeling more able to recognize changes, interpret symptoms, and act accordingly.

To further explore how participants perceive the management of their cardiovascular condition, they were asked to rate the following statements on a Likert scale from strongly disagree to strongly agree:

1. I feel very confident in my management of my cardiovascular disease CVD.
2. I feel anxious before check up appointments.
3. I feel confident I know when to seek care for example in case of new symptoms.

Overall, responses tended to cluster on the agreeing side, with 197 answers in the agree or strongly agree categories and 112 in the disagree or strongly disagree categories.

Nonetheless, 36,25% of participants indicated that they did not feel confident in managing their condition, felt anxious before appointments, and did not know clearly when to seek care. This suggests that although a substantial proportion of patients feel relatively in control, a considerable share still experiences doubt and anxiety regarding their self-management and help seeking.

For many patients, receiving a diagnosis is a sudden and frightening experience, often described as overwhelming and difficult to process. Many participants felt they lacked clear information about their condition, treatment options, and prognosis. Some perceived that explanations from health professionals were incomplete or difficult to understand. Others expressed a wish for better coordination between different clinicians, easier access to appointments or shorter waiting times, tools that could help them track symptoms and progress at home, and stronger emotional support and reassurance.

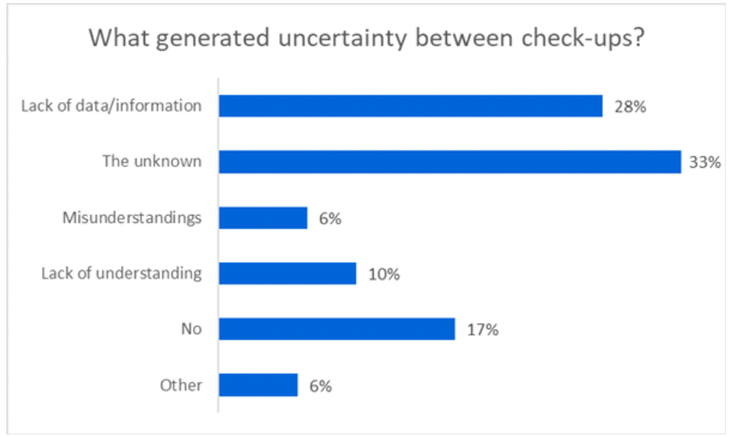


Figure 15. Quantitative Research (n=105); What patients lack in between appointments.

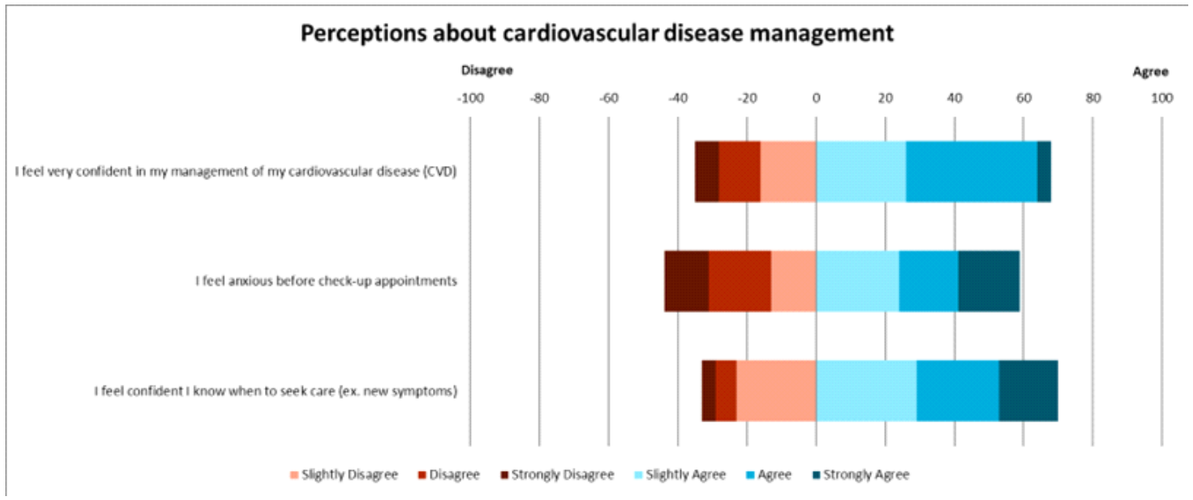


Figure 16. Quantitative Research (n=105); Thoughts on the management of CVD.

Based on these reported needs, this project aims to address several aspects directly:

1. Explanations (within the app)
2. Information about the condition (within the app)
3. Emotional support and reassurance (from the use of the device)
4. A tool to help track symptoms and progress at home (goal of this thesis)

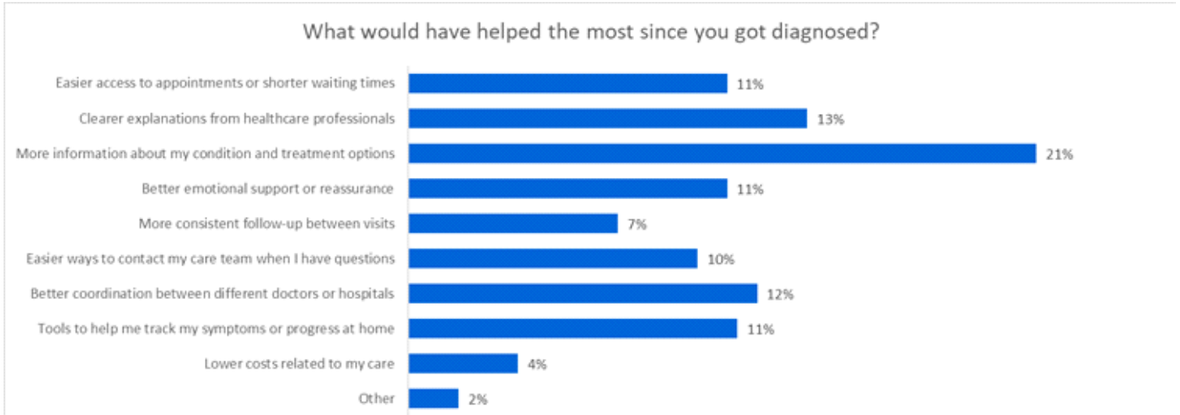


Figure 17. Quantitative Research (n=105); What patients lacked in support.

2.5.2 Home monitoring practices and likelihood of device adoption

To explore the likelihood that a new device would be adopted, participants were asked about the devices they currently use at home to monitor their health. As shown in Figure 16, 88% of respondents reported using some type of device for home monitoring, with blood pressure monitors being the most commonly used. This indicates that home based self monitoring is already a familiar practice for the majority of this population, and that many patients are accustomed to integrating measurement routines into their daily lives.

Blood pressure monitors in particular require users to be seated, calm, and relatively still for approximately thirty seconds to one minute while the measurement is taken. The widespread use of such devices suggests that patients are willing to follow short, structured procedures at home, provided that the device is easy to operate and that the perceived benefit is clear. It is therefore reasonable to assume that if a new cardiovascular monitoring device is introduced with a comparable level of complexity in terms of set up and measurement time, it would be well accepted by this target group. This finding supports the feasibility of the proposed solution and underscores the importance of designing the device and its companion application to align with routines and expectations that patients already have regarding home monitoring.

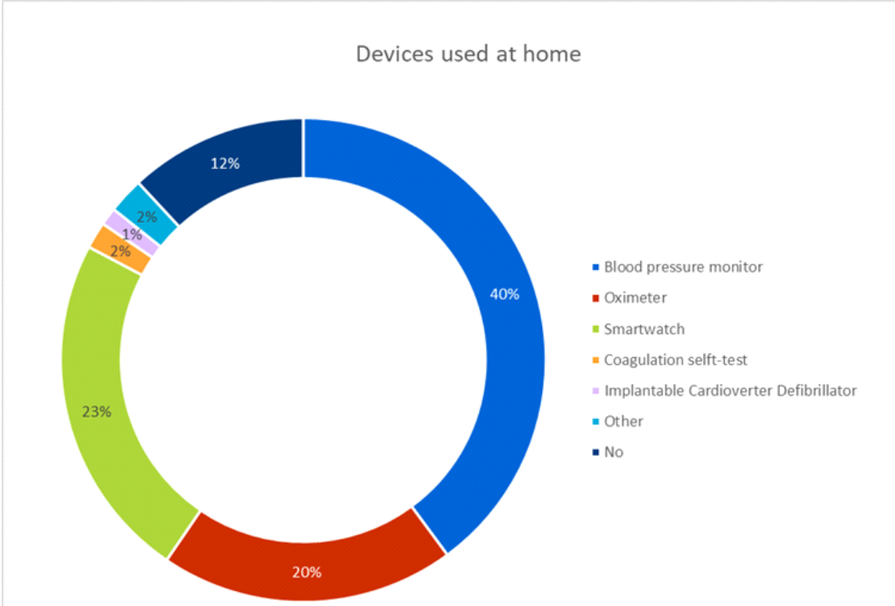


Figure 18. Quantitative Research (n=105); Current devices used.

2.5.3 Acceptance of the proposed device

Figure 19. Quantitative Research (n=105); Likelihood of use.

For the second part of the questionnaire, participants were asked to evaluate the proposed device based on a short description of its intended function and use. They were first asked to rate their general impression of the device on a scale from one to six. In addition, they indicated how likely they would be to use it if it were recommended by their cardiologist, on a scale from zero to ten.

The results support the earlier assumption that user adoption would be high. The average likelihood of use if recommended was equivalent to 83%, indicating that, on average, respondents expressed a strong intention to follow medical advice regarding this device. The overall evaluation score was also high, with a mean rating of 5,13 out of 6. Together, these findings suggest a generally positive attitude toward the proposed solution and a substantial willingness to integrate it into everyday care when guided by a trusted clinician.

Participants were then asked again about their perceptions of their cardiovascular disease management, this time imagining that they had access to the device. Similar items were used as in the earlier section, which allowed a direct comparison. With the device in place, responses shifted clearly toward the more positive, agreeing side. The proportion of respondents who reported low confidence, high anxiety, and or uncertainty about when to seek care decreased from 36,25% to 8,33%. This substantial change indicates that participants anticipate a notable improvement in their sense of control and reassurance if they could use such a device.

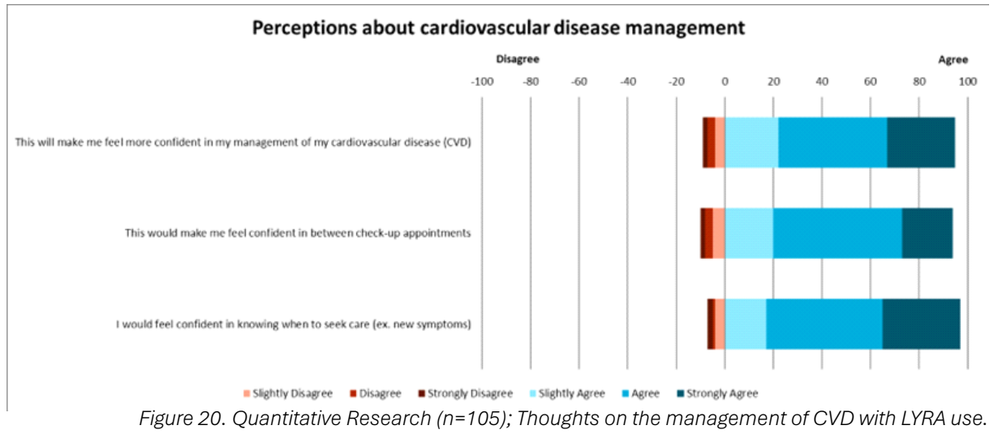


Figure 20. Quantitative Research (n=105); Thoughts on the management of CVD with LYRA use.

2.5.4 Intended usage behavior

To gain more insight into preferred patterns of use, participants were asked how they would like to use the device, how frequently they would record measurements, and what session duration they would perceive as acceptable. For the vast majority, the primary reference point was clinical guidance. Most respondents stated that they would follow their cardiologist's recommendation regarding frequency of use, which is consistent with the central role of the specialist in their care trajectory. The second most selected option, although with a much lower proportion of responses from about 50% down to 18%, was that they would use the device only when they noticed symptoms. This is an important finding as symptom triggered use could still offer value for detecting progression of degenerative heart disease through changes in heart sounds, but the system would function more effectively if it could rely on patterned, longitudinal data to compare measurements over time. It is also relevant to note that not all respondents had degenerative heart disease, which may explain why some would prefer to use the device only in response to symptom changes rather than on a regular schedule.

Preferences regarding session duration followed a similar pattern. Most participants indicated that they would accept whatever duration their cardiologist recommended. This can be interpreted as a sign that the target group is willing to invest time and effort to gain peace of mind and a better understanding of what is happening in their body. Among those who specified a preferred duration, the most desirable option was a session of less than five minutes. However, if this is not technically feasible, sessions of less than ten minutes were still considered acceptable by 25% of respondents, which is relatively close to the 30% who selected less than five minutes. These preferences provide a clear design guideline. Ideally, measurement sessions should be kept under five minutes, but durations of up to ten minutes appear acceptable for a substantial portion of the target group, particularly if the perceived benefit and clinical relevance are clearly communicated.

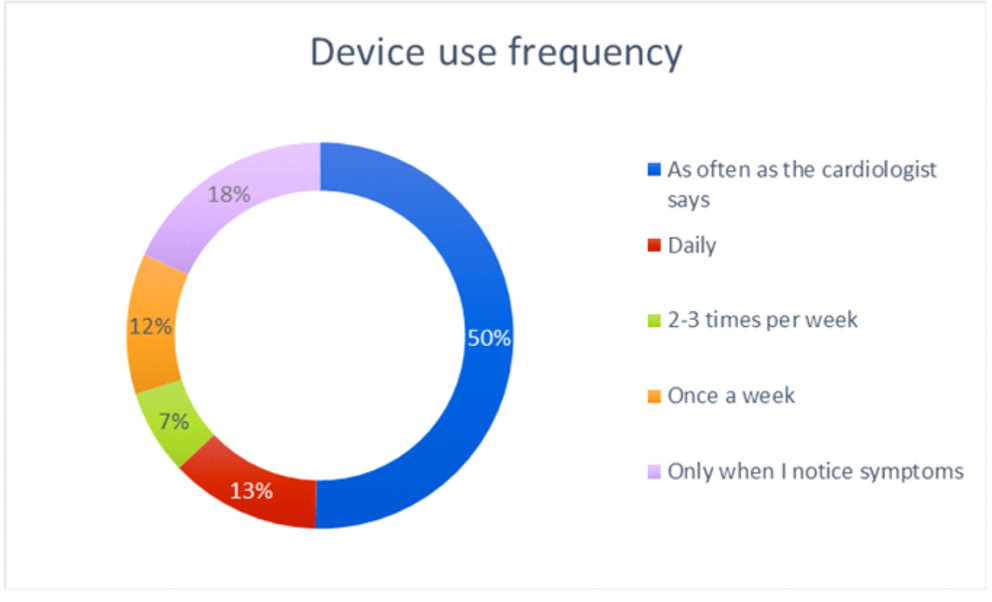


Figure 21. Quantitative Research (n=105); Device use frequency.

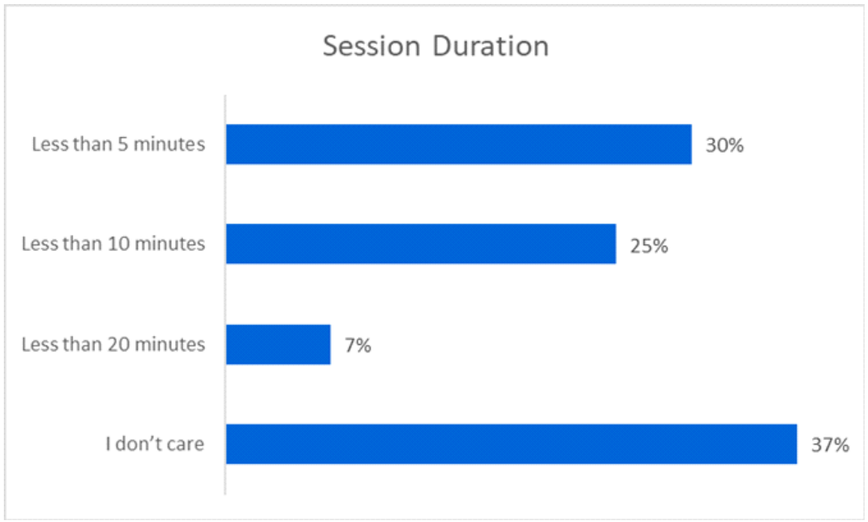


Figure 22. Quantitative Research (n=105); Session Duration.

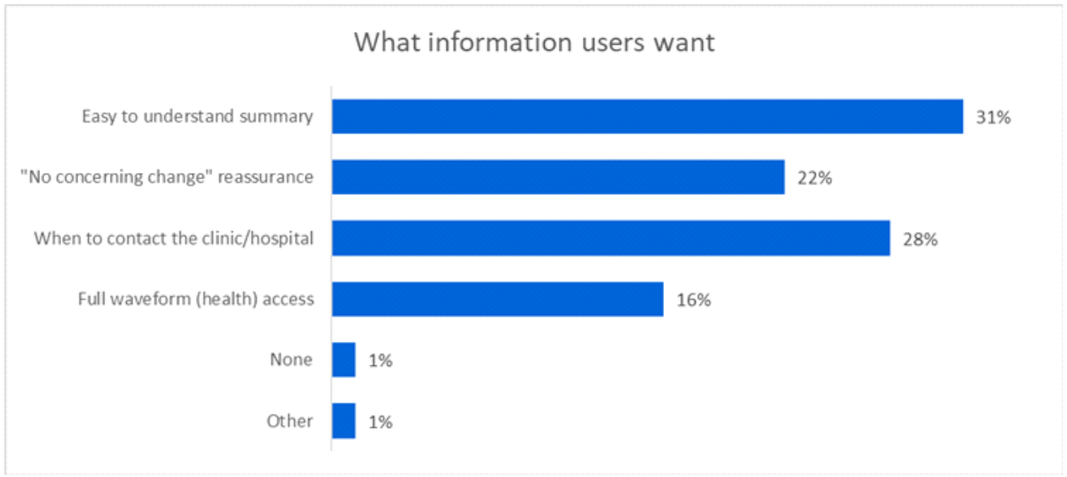


Figure 23. Quantitative Research (n=105); What information users want from LYRA.

2.5.5 Information needs and anticipated barriers of use

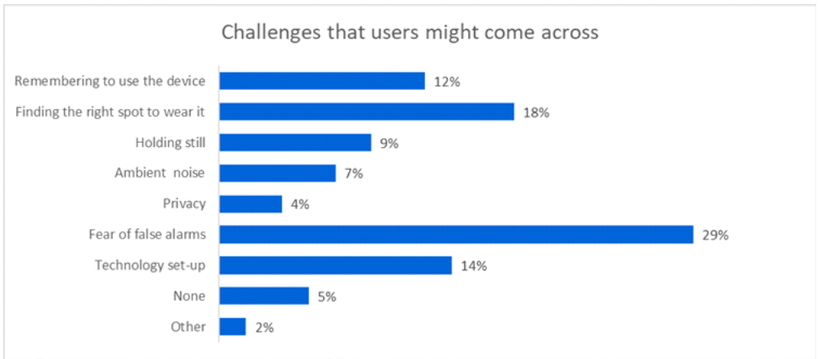


Figure 24. . Quantitative Research (n=105); What challenges users might come across during use.

To understand what participants would expect from the device, they were asked what type of information they would like the accompanying application to display. Responses showed a clear preference for information that helps them make sense of what is happening in their body and that offers reassurance. Many participants expressed a desire for straightforward feedback on whether their heart sounds appear stable compared with previous recordings, as well as a clear indication of when it would be necessary to contact their clinic or hospital. As one respondent summarized, they would like *"something that is clear"*. This highlights the importance of transparency, simplicity, and actionable feedback in the design of both the device and the app interface.

Participants were also invited to reflect on potential challenges they anticipated in using the device. These insights are particularly relevant, since they point directly to design requirements and aspects that could affect acceptance, comfort, and long-term use. The most frequently mentioned concern was the fear of false alarms. Users worried that the device might generate incorrect alerts and it would generate more anxiety. This concern was also strongly emphasized by cardiologists in their interviews, who emphasized that false positive alerts could increase patient stress and lead to unnecessary visits or calls, adding pressure on healthcare services. Addressing the reliability and communication of alerts is therefore central to the design and algorithm development.

The second most common challenge was uncertainty about where to place or wear the device in order to obtain reliable recordings. This raises an important design question about how to support correct placement in a way that is intuitive and does not create additional cognitive effort during use. The third challenge, which aligns with the age profile of the target group, concerned technology set up. The final challenge was remembering to use the device regularly, suggesting that reminder functions and integration into daily routines may be necessary.

Several specific comments also provide useful direction for design. For instance, one participant asked, *"Does it work with hair?"* which points toward concerns about sensor contact and usability in real life conditions. Another mentioned the importance of an *"objective approach to the sounds and changes received",* emphasizing that users want to trust that interpretations are based on consistent and explainable criteria. All of these challenges and expectations are incorporated into the design requirements and will guide the subsequent stages of product and interaction development.

2.5.6 Perceived benefits between visits and reasons for discontinuing use

The final two questions of the questionnaire were open-ended and aimed to deepen the understanding of participants' views. The first asked what would make the device most helpful between appointments. The second asked what would make them stop using it.

Regarding helpfulness, responses converged around a few central themes. Participants emphasized the value of reassurance and peace of mind, and the sense of empowerment that could come from better understanding their condition. Many described how difficult it is to live with a heart condition that they cannot see, and how uncertainty about whether a symptom is benign or an emergency generates significant anxiety. They explained that the device would be especially valuable if it could help them distinguish between normal fluctuations and warning signs that require medical attention, while also offering educational information about what is happening in their body.

"Peace of mind if nothing is wrong, I am constantly worrying that I am missing symptoms."

"Reassurance that things are not serious and if they are when to seek help."

"Having it at home would make me a bit calmer, and I would have something to show my doctor more accurately, so that it anticipates the symptoms I am going to have."

"Would make me feel calmer if this data were stored in an application, so I could not only have the record but also my doctors could see these records."

"The device plus clear instructions would allow me to have only the necessary medical appointments, avoiding the maintenance ones."

"It would give me peace of mind."

"Still more checks in between, a bit more certainty."

These statements show that participants do not only seek more data. They want meaningful interpretation, guidance on when to act, and a way to feel more in control without becoming overly focused on their condition. Several respondents also pointed to the value of having objective records that could be shared with their cardiologist, both to support decision making and to avoid unnecessary appointments.

For the question about what would make them stop using the device, the most frequent themes were unreliability, inaccuracy, lack of usefulness, and a high rate of false alarms. Participants clearly indicated that if the device produced inconsistent or untrustworthy results, if it was perceived as burdensome, or if alerts did not correspond to how they actually felt, they would lose confidence in it and discontinue use. This aligns with concerns raised by clinicians and underscores that reliability, meaningful alerts, and clinical integration are essential design criteria.

"What is a more accurate indicator of heart problems, ECG or hearing something new."

"Untrustworthy results, inconvenient process, excessive cost."

"If results were consistent or ignored by doctors."

"Forgetting, being too busy, decrease in symptoms."

"False reports, malfunction of device itself, uncomfortable to wear."

"It would depend a lot on how the device is placed, whether I would need help or if I could put it on myself, and also whether, once it is on, I can carry out my daily activities as I would with a Holter monitor, or if, on the contrary, I have to remain still or limit my movement."

"That it would not work or maybe tiredness from being attentive all day."

"No correct alerts, so that you worry unnecessarily. I do not want everything to be focused on my heart."

Interestingly, some participants mentioned that they would stop using the device for positive reasons, such as if their cardiologist advised them to discontinue it or if their condition stabilized to the point where ongoing monitoring was no longer required. One respondent wrote, "Provided total good mental and physical condition. After rehabilitation, so when you feel confident again." Another stated, "After years of use without deterioration of the heart, I expect usage to decrease to, for example, weekly." For patients with degenerative heart valve disease, complete resolution is unlikely, although interventions such as TAVR can significantly improve function. However, these answers still highlight an important aspiration. Participants hope that the device will support them through periods of greater uncertainty, and that its use can decrease once they feel stable and confident again.

Overall, these open-ended responses reinforce the central design implications. The device and app must provide clear, trustworthy and clinically relevant feedback, contribute to reassurance rather than anxiety, respect the desire to live beyond the identity of being a patient, and integrate smoothly into both daily life and clinical care.

“Having a heart issue is difficult cause we can not see what is going on inside of us, so I feel like this would be helpful and reassuring. Also when you have a condition like this at least for myself I never know if it is a normal symptom tied to my defect or an actual emergency and that causes me so much anxiety.”

“Recognize the warning symptoms, most of the time we do not know how we feel, whether active or at rest, at least I am always tired.”

“Gaining trust in your own body.”

“I want to live, not be a patient twenty four seven. I do not want to be stressed by every irregular beat of my heart.”

“Feeling of being in control.”

2.5.7 Conclusion Patient Questionnaire

This questionnaire confirms that there is both a clear need and a strong willingness among patients to use a home heart sound monitoring system, provided that it genuinely supports their everyday lives. The device system should therefore be designed to offer reassurance, clear guidance on when to seek care, and meaningful insight into disease progression, rather than simply adding more data.

Several key considerations emerge for the design. First, information presented in the app must be simple, transparent and actionable. Users ask for “something that is clear,” which implies concise messages, intuitive visualizations and straightforward explanations of what measurements mean. Correct placement needs to feel easy and guided, supported through physical affordances and in app feedback, so that users do not feel uncertain about whether they are “doing it right.” Onboarding and technical setup must be smooth, with minimal steps and accessible support for users who may have limited familiarity with digital tools.

Reliability and trust form the core of acceptance. The system has to minimize false alarms and avoid ambiguous or contradictory outputs, since these would increase anxiety, create unnecessary contact with healthcare services, and quickly undermine confidence in the device. Alerts must be clinically meaningful and aligned with cardiology practice, and the data should be useful for doctors in consultations. At the same time, the design needs to respect the wish to “live, not be a patient all day,” by helping users feel more in control without inviting constant self monitoring or worry. In practice, this means creating a device system that is trustworthy, discreet, easy to integrate into daily routines, and clearly connected to professional care, so that it becomes a source of calm and support rather than an additional burden.

2.5.7.1 User Journey Map

Based on the insights gathered from the literature review and the questionnaire, the current user journey map was developed to show how patients experience the pathway of degenerative valvular disease from the first symptoms to recovery. The map brings together actions, touchpoints, gains, pains and emotional shifts across each phase, offering a clear view of what patients go through at every step. It highlights how uncertainty and fear dominate the early stages, how reassurance and clarity appear during diagnosis, and how emotional fatigue and stress increase as the condition progresses. It also shows the momentary relief that comes with surgery and the mixed feelings during rehabilitation. This overview helps identify where support, information and design interventions could improve the overall experience.

Journey phases	Initial Symptoms/ Awareness	First Medical Contact	Initial Assessment + Diagnosis	Treatment & Lifestyle Changes	Monitoring & Progression	Worsening of Vascular Lesion	Decision for Surgery	Operation & Recovery
Actions	• Chest discomfort • Shortness of breath • Fatigue • …	• Books medical appointment with GP	• Auscultation & basic tests • Referred to cardiologist • Cardiologist finds valvular lesion	• Start medication • Diet & exercise adjustments	• Yearly check-ups • Echocardiograms	• Symptoms return but stronger • Urgent hospital visit	• Meets with surgeon • Review risks & benefits • Prepares for surgery	• Undergoes surgery • Hospital recovery • Rehabilitation
Context & Touchpoints	• Self observation • Family observations • Research online	• Calling the GP • Getting an appointment	• Cardiologist consultation • Diagnostic tests	• Pharmacy • Nutritionist • Follow-up visits	• Revision visits • Imaging tests • Lab tests	• Emergency room • Hospitalization • Echocardiogram	• Hospital team • Surgeon • Family	• Surgical team • ICU staff • Rehabilitation programs
Gains	• Patient becomes more attentive to their health	• Reassurance that symptoms are being taken seriously	• Clarity about condition • Access to treatment options • Sense of control through knowledge	• Empowerment from actively managing health • Improved daily wellbeing (if treatment works)	• Reassurance from check-ups • See results from the healthy living habits	• Access to advanced testing and specialist care • Urgency accelerates medical decisions	• Access to potentially life-saving treatment • Hope for long-term recovery	• Relief from surgery • Potential elimination of symptoms • Opportunity for improved quality of life
Pains	• Ignoring symptoms • Anxiety • Fear • Denial	• Waiting times • Difficulty getting appointment	• Overload of medical terminology • Costs • Scheduling delays	• Adherence • Side-effects • Uncertainty	• Emotional fatigue • Financial burden • Time burden • Uncertainty	• Anxiety • Disruption of daily life • Dependence on doctors	• Surgical risks • Recovery time • Possible complications	• Pain • Limited mobility • Dependence • Long rehabilitation

Feelings

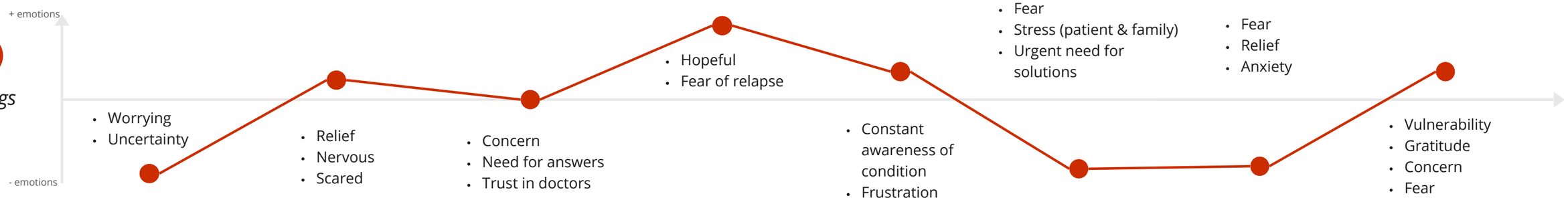
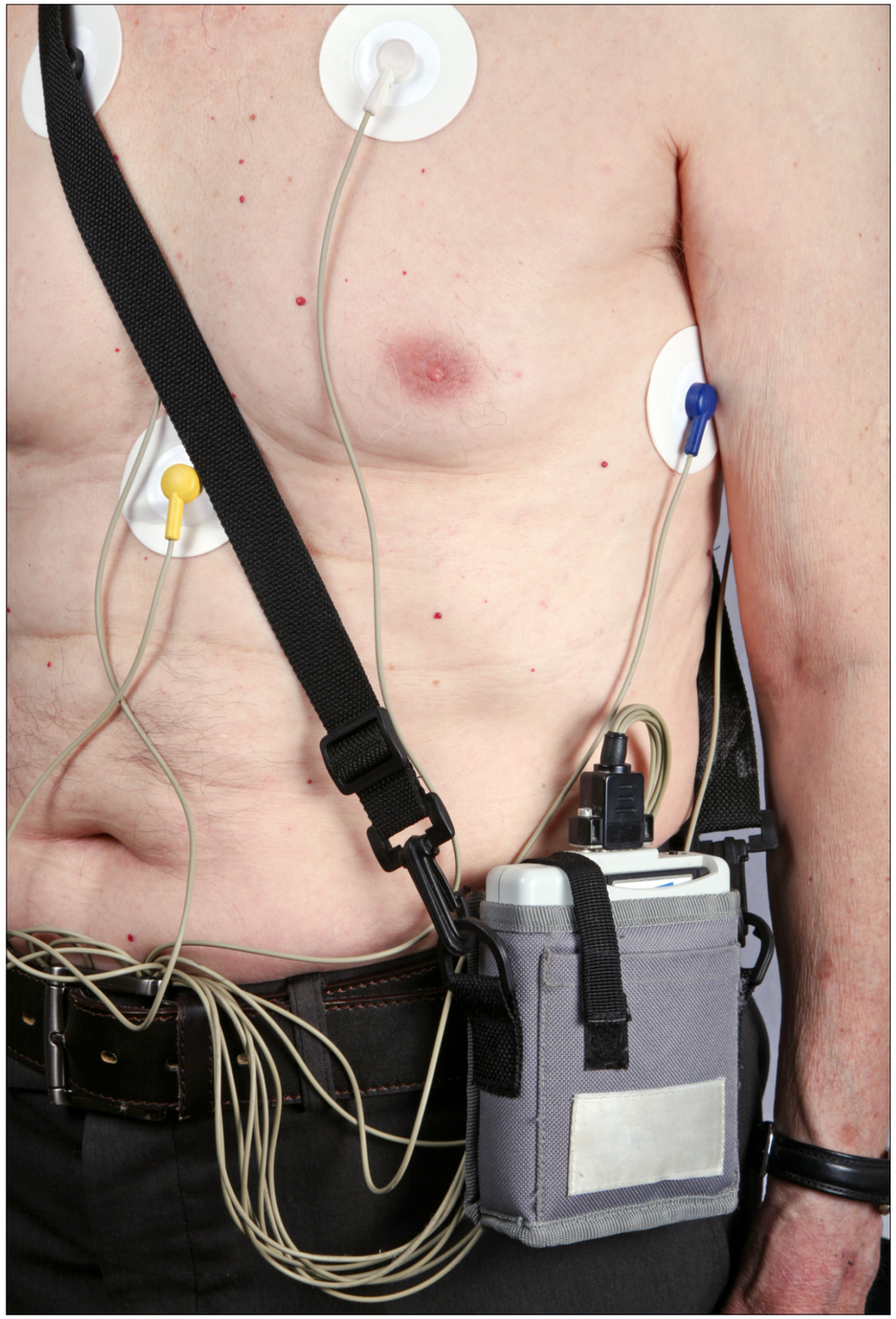


Figure 25. User journey map of the current patient pathway.



2.6 E-Health

2.6.1 Telemonitoring in the Netherlands

Telemonitoring has been increasingly promoted within the Dutch health system as a scalable eHealth solution intended to reduce hospital admissions, improve continuity of care, and alleviate pressure on primary care services (Nurmohamed et al., 2025). In the Dutch context, telemonitoring is generally understood as the remote measurement of vital parameters using digital technologies, often referred to as remote patient monitoring (RPM). Patient experiences in the Netherlands also indicate strong support for telemonitoring. A national survey by the Dutch Patient Federation found that nearly nine in ten patients using home monitoring reported highly positive experiences, describing it as less stressful than in-person check-ups and appreciating the ongoing insight into their health status. Patients valued the sense of safety provided by continuous monitoring, especially the ability to avoid unnecessary visits when values were stable while still receiving timely contact when abnormalities arose (Patientenfederatie Nederland, 2025).

Despite strong policy interest and growing patient demand for home-based monitoring, national uptake has remained limited. Healthcare professionals report that only sixteen percent of patients used telemonitoring in 2022, and insurance claims suggest an uptake of just 5.8 percent among heart failure patients between 2017 and 2019 (Nurmohamed et al., 2025). These figures indicate that, although the Dutch population has high digital literacy and strong readiness for remote healthcare, the routine use of telemonitoring in cardiology is still not fully normalized. To address these challenges, the Dutch Federation of University Hospitals initiated the national citizen eHealth programs, which aimed to scale established telemonitoring services across all university medical centers. By the end of 2021, more than 3100 patients within Dutch university centers were using cardiac telemonitoring, suggesting growing but still uneven adoption (Nurmohamed et al., 2025). Evidence from additional Dutch studies, shows improvements in clinical outcomes and patient satisfaction but also highlights persistent organizational and reimbursement challenges (Van Steenkiste et al., 2024).

Recent regulatory developments have begun to lower these barriers. Since January 2023, a new national reimbursement code (NZa 039133) covers telemonitoring activities such as atrial fibrillation detection and remote rhythm surveillance without requiring separate insurer contracts (Kien et al., 2023). Telemedicine in the Netherlands is also governed by a comprehensive legal framework, including the Medical Device Regulation (EU 2017/745), the WGBO treatment contract law, and oversight by the Health and Youth Care Inspectorate (IGJ) (Kien et al., 2023). Together, these reforms indicate a gradual shift toward structural support for telemonitoring, although large-scale implementation continues to depend on organizational readiness, reimbursement stability, and effective integration into clinical workflows.

A study conducted in the Netherlands in July 2024 (Patiëntenfederatie Nederland, 2024) explored the experiences of 8,926 participants with home monitoring for chronic conditions, with 1,761 participants having direct experience with this practice. The majority of participants were aged 60 or older, and

cardiovascular disease was the leading condition for which home monitoring was implemented. Overall, 68% of those with experience reported a positive outcome with home monitoring, highlighting its benefits in terms of reducing doctor visits, travel time, and providing greater insight into their health. Notably, 46% of participants expressed being "very positive," while 41% were "positive" about the practice, citing the advantages of increased control and mindfulness over their health (Figure 26).

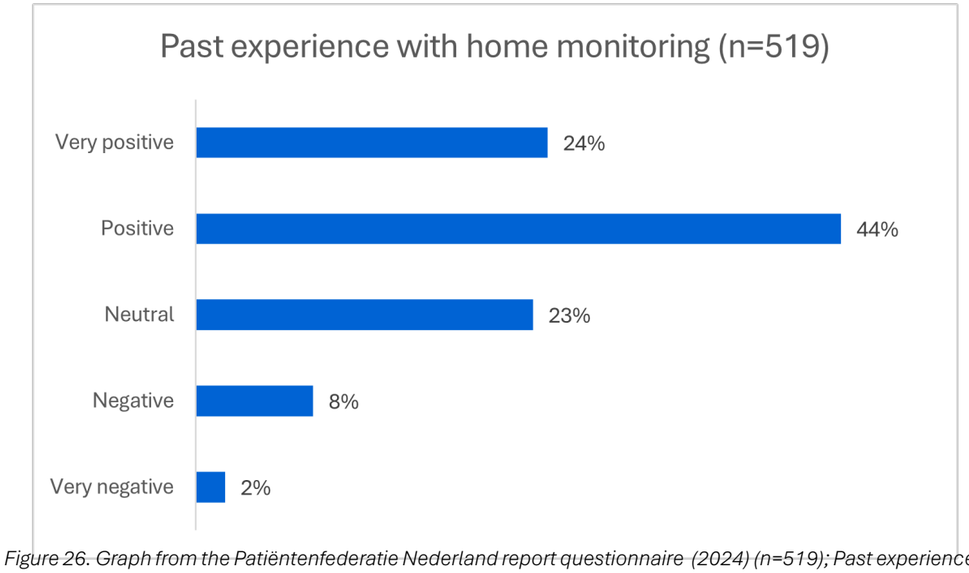


Figure 26. Graph from the Patiëntenfederatie Nederland report questionnaire (2024) (n=519); Past experiences with home monitoring.

At the same time, the report shows that telemonitoring is not yet standard practice for most people and that its success depends strongly on how it is organized. Many participants who stopped monitoring at home did so because the medical team no longer considered it necessary, but a smaller group chose to stop themselves, often because they lacked regular feedback or personal contact. Patients value shared decision making about whether to start telemonitoring, and they experience it as more pleasant when the choice is made together with their clinician or at their own request, rather than when it is imposed without discussion. Clear explanation about how the app or equipment works, what the measurements mean, and what happens with the data is considered important, as is easy access to someone who can answer questions.

As seen in figure 27, in terms of safety, the majority of participants (approximately 80%) agreed with the statements that home monitoring made them feel safe about their health and that sharing their health data online with their healthcare provider was secure. This finding highlights the trust placed in home monitoring systems when they are properly implemented, with effective communication and clear agreements about data usage being central to patient satisfaction. Overall, the results of this study suggest that home monitoring, particularly when used for cardiovascular conditions, can be a valuable tool for improving patient autonomy, convenience, and safety, provided that the technology is reliable and that the process is inclusive and well-explained, with ongoing support from healthcare professionals (Patiëntenfederatie Nederland, 2024).

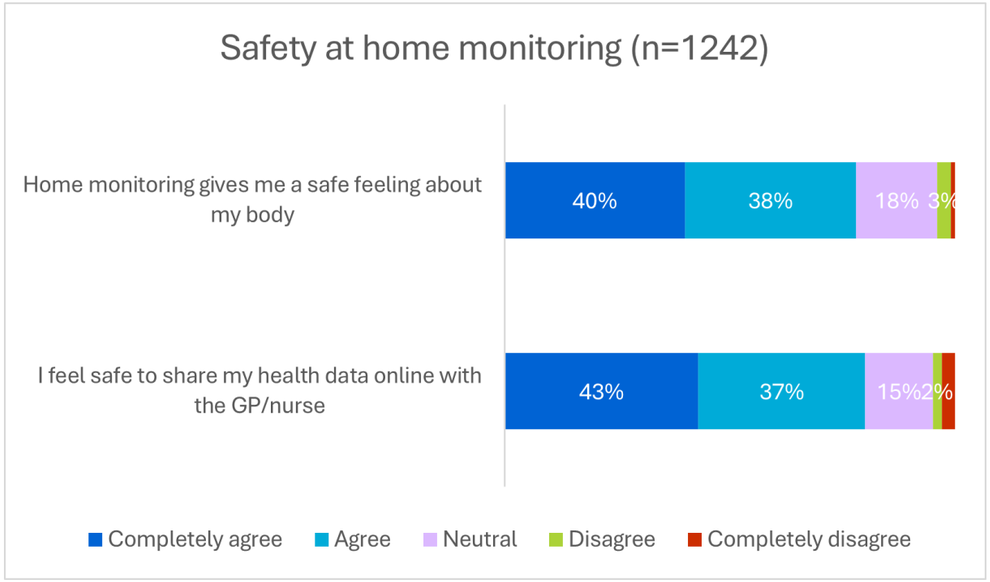


Figure 27. Graph from the Patiëntenfederatie Nederland report questionnaire (2024) (n=519); Feeling of safety for patients that do homemonitoring.

The Dutch perspective on telemonitoring is further illustrated by the IGJ assessment framework, which outlines expectations for safe and well-organized telemonitoring and reflects how professionals experience its use. The framework was informed by interviews with a hospital executive, a strategy project leader, and a nurse, whose comments highlight both enthusiasm for improved patient oversight and concerns about workload, coordination, and information security (Zorg van Nu et al., 2021).

"One step for us is having the confidence that the patient can take control themselves. And this applies to every chronic condition: you have to deal with it, 24 hours a day. You can bury your head in the sand, but that COPD is still there. It's better to manage it as well as possible. Telemonitoring can help with that."

Anja Bijlsma, nurse at Antonius Hospital Sneek

“We see in heart failure that home monitoring leads to significantly fewer hospitalisations. And if people are admitted, the stay is on average 40% shorter.”

"Self-awareness, noticing in time when things are going wrong. That is all very personal and part of daily life at home. That's why we say home monitoring. Telemonitoring sounds too much like it's from a distance; it's about the person living with a condition, not about the healthcare provider."

Marco van Geffen

Project leader strategy and manager of the monitoring center Jeroen Bosch Hospital

“We have proven that patients recover just fine in the home setting. If you consider that we all don't want to spend more money on healthcare, then the movement to keep patients out of the hospital fits perfectly with that.”

Peter van der Meer

Chairman of the Board Albert Schweitzer

Comments translated from IGJ Assessment Framework “telemonitoring of adults at home” (Telemonitoring Van Volwassenen Thuis | Inspectie Gezondheidszorg En Jeugd, 2022)

2.6.2 Telemonitoring for Heart Diseases

Telecardiology has become central in cardiovascular care, supporting both early detection of cardiac problems and long-term management of chronic disease. Remote monitoring programs in countries such as the United States have shown clear improvements for people living with arrhythmias and heart failure, with studies reporting fewer hospital readmissions, lower mortality (figure 28) and reduced healthcare costs through more efficient use of clinical resources (Tolu Akinnawo, Ezekwueme and Awoyemi, 2024). Devices used in these programs range from Holter monitors and blood pressure monitors to implantable cardioverter defibrillators, along with newer wearable sensors that can track heart rhythm, blood pressure and oxygen saturation continuously. These tools allow real-time information to reach clinicians and make it possible to detect abnormalities before they escalate into severe complications.

Continuous data sharing supports health care professionals with clinical decision making and also patients, as it gives them a more active role in their own care. Regular feedback increases awareness of symptoms, encourages adherence to treatment, and helps establish healthier routines. Research shows that virtual follow ups, secure messaging and access to personal health records reduce misunderstandings, strengthen confidence in treatment plans and create a stronger partnership between patients and clinicians (Tolu Akinnawo, Ezekwueme and Awoyemi, 2024). Because emotional and behavioral factors influence cardiac outcomes, this ongoing support has meaningful effects on daily management.

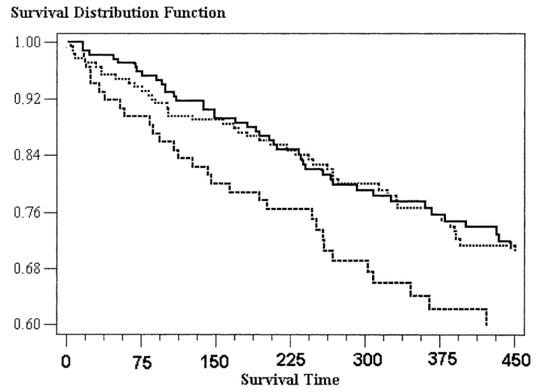


Figure 28. The survival distribution increases with some type of support (like nurse support or telemonitoring). Graph taken from Cleland et al. (2005)

Dashed line = usual care; Dotted line = nurse support; Solid line = telemonitoring.

Evidence from earlier studies reinforces these findings. Cleland and colleagues reported that home based telemonitoring lowered mortality and reduced the need for in-person visits when compared with conventional telephone follow up supported by nursing teams (Cleland et al., 2005). Kulshreshtha and colleagues found fewer readmissions and high satisfaction among participants enrolled in remote monitoring, noting that this approach helped avoid preventable hospital returns (Kulshreshtha et al., 2010). Advances in artificial intelligence and machine learning further extend this potential by improving diagnostic precision and enabling predictive modelling for conditions such as arrhythmias and heart failure (Tolu Akinnawo et al., 2024).

At system level, telemedicine reduces unnecessary travel, shortens clinic waiting times and eases pressure on hospital wards. (Haleem, Javaid, Singh and Suman, 2021). Real-time data exchange is also valuable in urgent cases because it allows quicker clinical decisions and improves the safety of emergency care. Remote monitoring supports secondary prevention programs and has shown encouraging results in cardiac rehabilitation (Tolu Akinnawo, Ezekwueme and Awoyemi, 2024).

Overall, the evidence indicates that telecardiology improves clinical outcomes, increases patient participation and reduces strain on health services. It supports earlier intervention, steadier self-management and continuous follow up. As technology progresses, telemedicine is expected to play an even larger part in cardiovascular prevention and in the long-term care of people with heart disease.

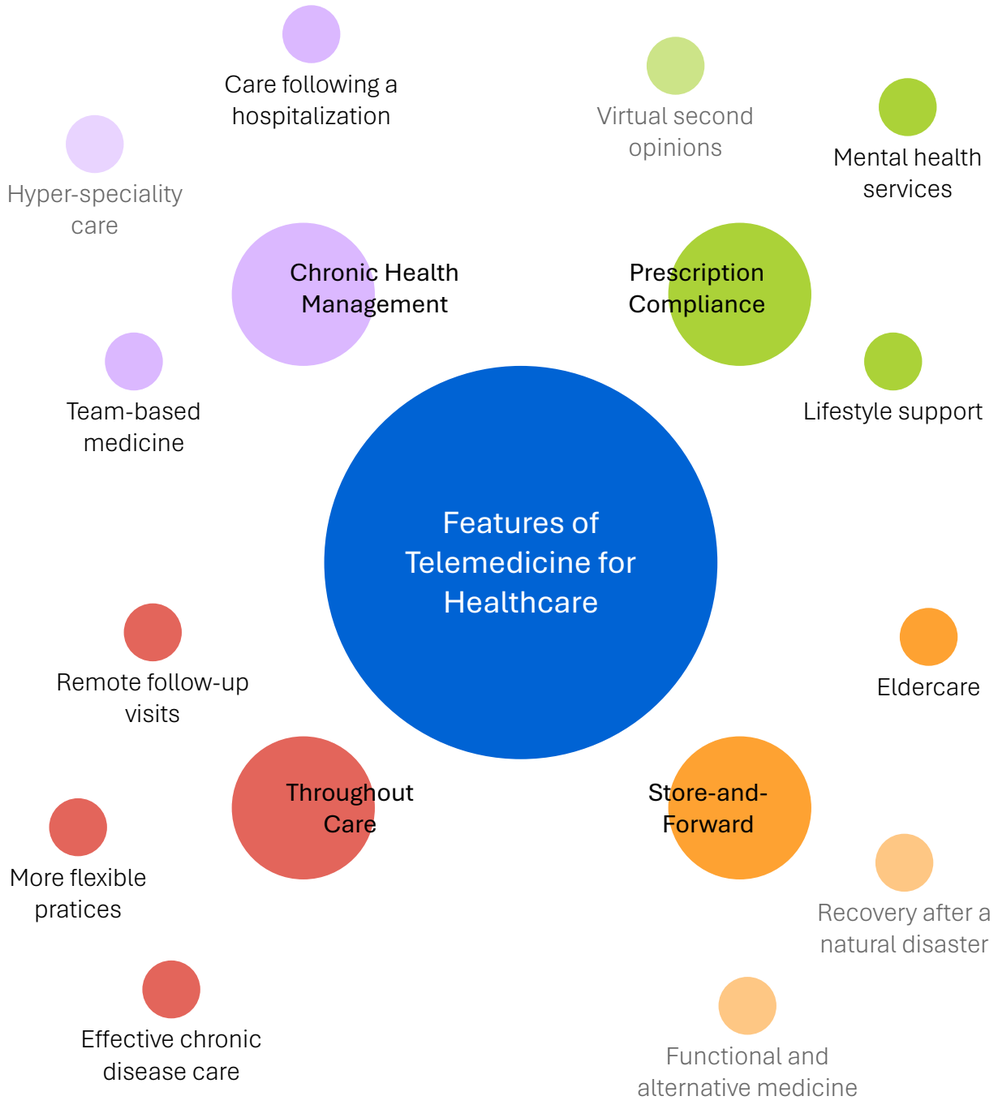


Figure 29. Features of Telemedicine for Healthcare. The features that LYRA system tackles are highlighted. Graph adapted from Haleem et al. (2021)

2.6.2.1 Types of monitoring

2.6.2.1.1 Vital Signs and Symptom Monitoring

Several devices are used to capture routine physiological measurements relevant to cardiovascular health. Home blood pressure monitors remain the most common tool and are recommended for regular self-assessment, particularly when equipped with Bluetooth or cellular transmission capabilities (American Heart Association, 2025). Wearable blood pressure technologies are also emerging, including cuff-less sensors that rely on optical or biomechanical measurements processed through machine-learning algorithms (Min et al., 2025).

Weight scales are routinely used in heart failure to monitor fluid status, as sudden changes may signal worsening congestion (Brust et al., 2022). Additional basic vital-sign tools include pulse oximeters for oxygen saturation and heart rate trackers embedded in wrist-worn devices. These instruments support continuous or intermittent measurement of physiological parameters that are clinically relevant for cardiovascular monitoring.

2.6.2.1.2 Telemonitoring and Integrated Data Platforms

Telemonitoring systems serve as the interface through which patient-generated data are transmitted and organized. These platforms typically aggregate information from home devices and display it for clinician review. They may include dashboards, automatic threshold-based alerts, and structured data logs. Examples include systems tailored for atrial fibrillation monitoring, heart failure surveillance, or general cardiovascular follow-up.

Some platforms are linked to implantable devices, others to wearable sensors, and some function as standalone hubs that integrate measurements from multiple sources. Their primary function is to facilitate the flow of data from home-based monitoring tools into clinical settings, allowing remote review of vital signs, symptoms, or rhythm recordings.

2.6.2.2 Market Research

The wearable health technology sector is experiencing significant innovation these recent years. Numerous companies are actively pursuing the development of small, low-cost, and energy-efficient wearable to be used by individuals at home.

Currently, there is no dominant solution for heart sound monitoring in a home setting. Most existing technologies primarily focus on detection rather than providing continuous monitoring of heart health progression.

Several wearable acoustic devices, have demonstrated the feasibility of using sound-based monitoring techniques. However, these devices predominantly target sleep monitoring or vital sign tracking, rather than being specifically tailored to assess the progression of heart conditions. Furthermore, these devices are not designed with heart sounds as their exclusive focus, thereby limiting their effectiveness in providing a comprehensive understanding of cardiac health.

The majority of available devices aim to monitor multiple health parameters simultaneously, including PPG, EKG, and other sensor-based technologies. These technologies (PPG ad EKG) are more widely used for heart monitoring due to the established baseline for their results, allowing for consistent and standardized comparisons across different individuals. Both provide quantifiable data that can be universally interpreted, making them reliable for tracking heart function. In contrast, phonocardiography (PCG), which captures heart sounds, presents challenges because each individual's heart sounds are unique, making it difficult to establish a universal baseline. Additionally, PPG and EKG sensors are commonly incorporated into consumer-facing wearables, such as fitness trackers and smartwatches, further contributing to their widespread adoption. These sensors offer convenience and accessibility for everyday health monitoring, which has led to their dominance in the wearable technology market.

In contrast, PCG is primarily utilized in clinical settings through devices such as electronic stethoscopes. These stethoscopes rely on PCG sensors to detect heart sounds, demonstrating the technology's effectiveness in clinical diagnostics. However, electronic stethoscopes are specialized instruments used by healthcare professionals in controlled environments, rather than by consumers for personal health monitoring. This limited use in clinical practice highlights that while PCG sensors are capable of capturing heart sounds and are valuable in medical diagnostics, they have not yet been adapted for widespread use in consumer-facing products due to the complexity and specificity of heart sounds, as well as the cost and design challenges involved.

Device/Company	Modality	Wear Style	Focus/Claims
Eko CORE/DUO + AI	PCG + EKG (episodic)	Handheld scope	AI murmur/AFib detection
Sibel ANNE Chest	EKG, RR, temp, activity	Adhesive patch	Continuous vitals; neonatal-safe
M3DICINE Stethee Pro	PCG (episodic)	Handheld scope	Wireless scope + AI software
TytoCare	PCG (guided) + other exams	Handheld kit	Home guided auscultation for tele-visits
Wellysis / LifeSignals	EKG patches	Adhesive patch	Holter/MCT alternatives
Pulsify Medical	Ultrasound	Flexible patch	Continuous cardiac monitoring
BeamO	EKG, microphone, thermometer	Handheld device	Device for personal use & teleconsultation
BioBeat	EKG (session)	Adhesive patch	One time hypertension monitoring

Table 2. Market scan summary of remote monitoring devices, comparing modality, wear style, and primary focus. These devices were chosen as they are the closest competitors to the solution space.

Figure 30. Market matrix mapping remote monitoring products by intended user focus (patient versus clinician), and intended scope (general use versus specific disease).

2.6.3 E-health adaptation

2.6.3.1 Attributes

Clinician requirements for the home monitoring tool focused on generating data that can be trusted over time, and on presenting results in a format that supports efficient clinical decision making. In parallel, user requirements centered on making the measurement process simple and reassuring, while avoiding unnecessary worry caused by false alarms. These priorities indicate that any adaptive behavior in the system should primarily support stable measurement quality, clear interpretation, and conservative alerting.

RQ 4.1 *What are the attributes of monitoring that matter to clinicians? (interviews)*

Clinicians prioritized:

- ***Reliability and repeatability:*** measurements should be consistent across sessions so that trends can be interpreted for physiological change.
- ***Actionable outputs:*** results should be summarized in clinically meaningful indicators and trends.
- ***Low false alarm burden:*** alerts should be specific enough to prevent alert fatigue and to avoid unnecessary follow up and resource use.

RQ 4.2 *What are the attributes of monitoring that matter to patients? (survey)*

Users prioritized:

- ***Ease of use:*** the workflow should be simple, fast, and feasible without supervision, supporting adherence in everyday life.
- ***Confidence and reassurance:*** users want clear confirmation that the recording was performed correctly, and feedback that is understandable and supportive.
- ***Low anxiety experience, including avoidance of false alarms:*** incorrect or ambiguous alerts can increase worry and reduce trust in the tool.

Taken together, these findings suggest that adaptation should emphasize quality checking during capture, personalization to an individual baseline, and alert logic that confirms changes across repeated measurements before escalation.

2.6.3.2 Barriers

In remote cardiac monitoring, Andersen et al. identify frequent feelings of not knowing. Patients felt anxious when symptoms and device detections did not match. Short written feedback reduced worry and supported decisions. The authors propose three design dimensions that are directly relevant to adherence:

1. Connectedness through ongoing contact.
2. Comprehension through simple rules and just in time guidance.
3. Compassion through easy ways to raise concerns and receive personalized reassurance.

These features may help patients persist with medication and behavior change by reducing uncertainty and by linking data to clear next steps (Andersen et al., 2017).

Findings from the interviews and questionnaires also align closely with barriers reported in prior research. As shown in Figure 31, the literature groups barriers into individual level, social and structural level, and technology level factors. Highlighted are the barriers in which this project focuses to tackle.

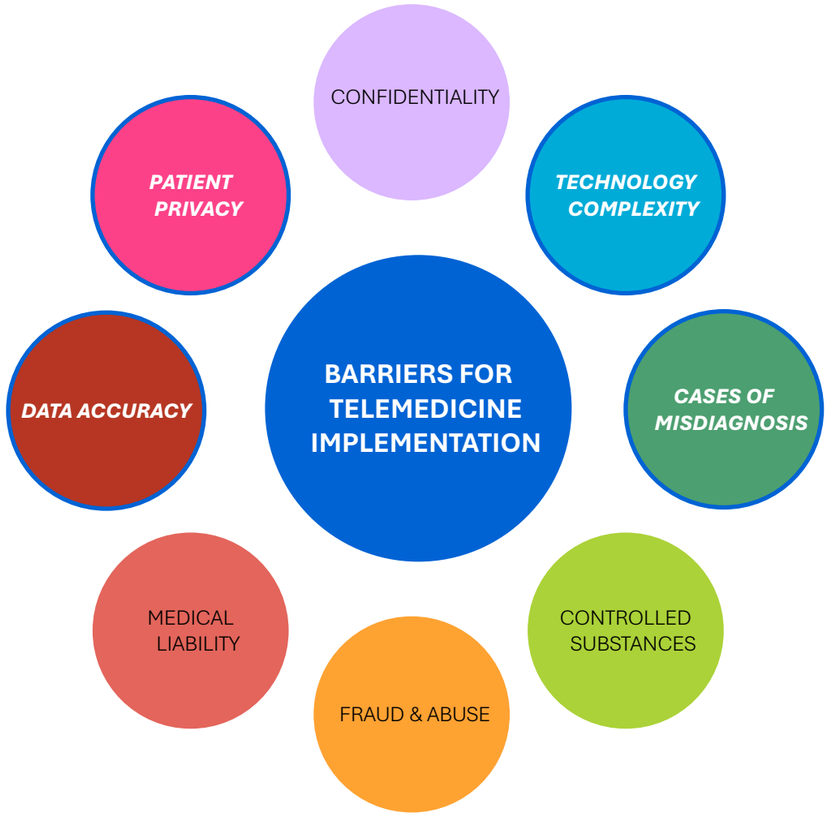


Figure 31. Barriers for telemedicine implementation. Graph adapted from Haleem et al. (2021).

RQ 4.3 *What enablers and barriers would shape adoption in cardiology clinics and at home?*

enablers Adoption will be supported when measurements can be compared against each person's own baseline, and when alerts include clear explanations that match what the patient is feeling.

barriers Uptake and sustained use ***at home*** will also depend on digital skills, trust, previous negative experiences with health technology, access to compatible devices, cost, and local infrastructure. ***In clinics***, telemonitoring is more likely to scale when it fits existing care pathways, and when it can show fewer emergency visits or hospitalizations through earlier detection and better continuity of follow up.

2.6.3.3 Costs

Evidence from chronic disease management research suggests that telemonitoring can generate significant cost benefits by reducing the need for high-intensity healthcare services. A large systematic review reported consistent reductions in hospital admissions, readmissions, emergency department visits, and length of stay across diverse telemonitoring programs for chronic heart failure, stroke, and COPD (Bashshur et al., 2014). In heart failure, mortality reductions of up to 56% have been documented, alongside fewer recurrent admissions and lower overall service utilization (Bashshur et al., 2014). These savings stem from earlier detection of clinical deterioration, closer patient engagement in self-care, and rapid access to specialist support, which collectively reduce avoidable complications and the downstream costs associated with advanced disease management. Similar patterns are observed in telestroke systems, where faster triage and earlier thrombolysis not only improve clinical outcomes but also reduce long term disability costs (Bashshur et al., 2014).

Despite these benefits, the cost profile of telemonitoring is not uniformly positive. A recent scoping review found that although telehealth can reduce travel expenses, prevent costly specialist interventions, and improve system productivity, many programs do not achieve net cost savings for health systems once the expenses of technology, monitoring infrastructure, and workforce requirements are considered (Snoswell et al., 2020). The review also noted that savings often depend on the funding model, with reductions more evident when costs are shared with consumers or when telehealth replaces reimbursed in-person visits (Snoswell et al., 2020).

These indicate that telemonitoring is financially advantageous when it prevents acute events or offsets high-cost care, but it may not lower total system expenditure in settings where implementation costs remain high. Consequently, many authors recommend that health services adopt telemonitoring primarily for its clinical and patient-centered value rather than as a guaranteed cost-reduction strategy.

2.6.4 Conclusion Telemonitoring in Healthcare

Telemonitoring has gained strong institutional support within the Dutch healthcare system and is also viewed positively by many patients. In cardiovascular care, telecardiology is linked with fewer readmissions, improved survival outcomes in some programs, higher satisfaction, and stronger continuity of follow up, particularly for heart failure and rhythm related conditions where earlier detection can enable earlier intervention.

Sustained patient engagement depends on reducing uncertainty during daily use. Adherence is more likely when device feedback aligns with symptom experience and when timely explanations are available, since a lack of feedback can prompt discontinuation even when the technology functions as intended.

Economic evidence indicates that telemonitoring can reduce the use of high intensity services, especially when it prevents acute deterioration and avoids escalation to emergency care or hospitalization. However, cost benefit depends on implementation and service organization.

Current monitoring options range from specialized cardiovascular devices such as Holter monitors to general tools such as blood pressure monitors, oximeters, and smartwatches. Holter monitoring remains relatively bulky and inconvenient, while many consumer devices prioritize usability but do not directly support progression tracking in a clinically meaningful way.

Overall, many available solutions emphasize detection of abnormalities rather than longitudinal monitoring of disease progression. This highlights an opportunity for home monitoring approaches that can support reliable repeatable measurement and interpretable trends, while remaining feasible and acceptable for both patients and clinicians.

2.7 Technology Choices for the Design

2.7.1 Murmur Detection Through Sound

Many clinically relevant changes in valvular disease present as changes in heart sound quality, intensity, and timing. Because of this, acoustic sensing is a direct route to murmur detection that aligns with clinical auscultation while enabling quantitative analysis at home. Traditional auscultation depends on subjective listening and clinician experience, whereas digital acquisition supports more consistent measurement of features such as spectral energy distribution, temporal envelope, and repeatability across recordings.

A key technical challenge is that the frequency content of heart sounds and murmurs is not consistently defined across the literature, and there is overlap with other biological signals (figure 32). Many sources place the fundamental heart sounds, S1 to S4, mainly in the low frequency range of about 10 to 250 Hz as can be seen in figure 28 (Safara and Ramaiah, 2020; Jeong et al., 2021). Murmurs can extend to higher frequencies, for example, murmurs associated with aortic stenosis have been reported roughly between 100 and 450 Hz, and other pathological murmurs may reach around 600 Hz. This creates classification difficulty because respiratory sounds occupy a similar band, commonly reported in the range of about 200 to 700 Hz (Susič, Poglajen, and Gradišek, 2022). Taken together, these ranges indicate that murmur detection cannot rely on a simple frequency cutoff, and instead should combine frequency domain analysis with timing relative to S1 and S2, plus filtering methods that reduce interference from respiration and other artifacts.

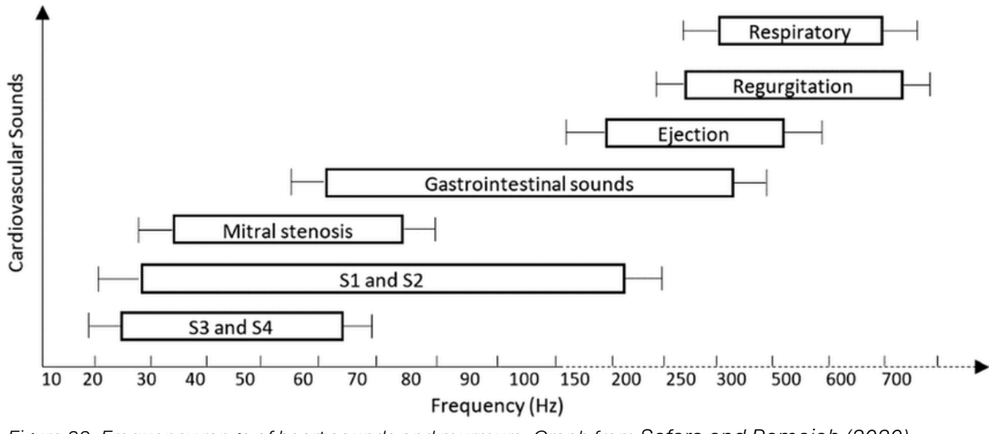


Figure 32. Frequency range of heart sounds and murmurs. Graph from Safara and Ramaiah (2020).

Cardiac Signal			Frequency Range (Hz)
Heart sounds	First heart sound	Normal	100–200
	Second heart sound	Normal	50–250
Heart murmurs	Systolic murmur	Aortic stenosis	100–450
		Pulmonary stenosis	150–400
		Mitral regurgitation	60–400
		Tricuspid regurgitation	90–400
		Atrial septal defect	60–200
		Ventricular septal defect	50–180
	Diastolic murmur	Mitral stenosis	45–90
		Tricuspid stenosis	90–400
		Aortic regurgitation	60–380
		Pulmonary regurgitation	90–150
	Continuous murmur	Patent ductus arteriosus	90–140

Figure 33. Types of heart sounds and corresponding frequency ranges. Graph from Jeong et al. (2021)

These constraints inform both hardware and software decisions. On the hardware side, modified stethoscopes and integrated microphones have been used to capture cardiac sounds for digital processing, showing that microphone based acquisition can support downstream murmur analysis. On the software side, a practical pipeline typically includes preprocessing and noise reduction, segmentation of the cardiac cycle so features are computed in relation to S1 and S2 timing, and murmur characterization using features that capture both how energy is distributed across frequencies and how that energy evolves across systole or diastole.

2.7.2 Specialized Microphones

Commercially available microphones are generally not well suited for capturing heart sounds as the primary signal, because the target band extends into very low frequencies and requires stable response across that range. In this project, heart sound content was treated as spanning roughly 10 Hz to 700 Hz, based on ranges discussed in the murmur section, where fundamental heart sounds cluster at lower frequencies and murmurs can extend upward. For context, the lowest A on a piano is 27.5 Hz, and many low bass notes perceived as “felt” are often discussed in the 30 Hz to 80 Hz region.

Most consumer microphones use MEMS technology (Fueldner, 2020). Their specified frequency response is commonly optimized for voice and general audio, with typical low frequency limits around 80 Hz to 100 Hz and upper limits extending to 10 kHz to 15 kHz, and some designs showing ultrasonic resonances well above the audible band (figure 29) (Trietley, 2022). While some devices can report response down to 20 Hz, published MEMS response measurements often show that the curve becomes meaningfully more stable only after a higher cutoff, around the low hundreds of hertz, depending on the device and measurement setup (D’Emilia et al., 2018; Bojinov et al., 2014). This matters because a “flat” response in the intended band reduces systematic distortion of the recorded signal, which is especially important when comparing recordings over time and extracting features for murmur detection.

For this reason, the microphone requirement

in this project was defined as a relatively flat response from about 10 Hz or 20 Hz up to at least 700 Hz, combined with high sensitivity in that band. This motivated the use of specialized vibration pickup units developed in house at Sonion. These units are closer to vibration sensing than conventional air coupled audio capture, and they were hand manufactured during development. The project work involved close collaboration with the engineer responsible for building these units, with the engineering focus placed on maximizing sensitivity while maintaining a stable response across the target band.

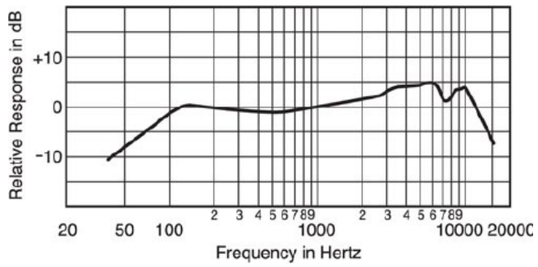


Figure 34. A typical frequency response curve for a microphone. Note that for some frequencies the audio is exaggerated (larger than 0 dB) while for others it is attenuated (smaller than 0 dB). Graph from Bojinov et al. (2014)

2.7.2.1 Sensitivity Testing

Methods

To quantify the relative sensitivity of candidate vibration pickup units across the target band, using controlled mechanical excitation and non-contact vibration measurement, reported as frequency in Hz versus relative response in dB.

Equipment and setup

The sensitivity test setup consisted of a vibration excitation system with an accelerometer based mounting fixture used to securely hold each candidate unit and provide a repeatable mechanical reference. A constant bias supply of 1.3 V was applied to the microphone under test, and its electrical output was recorded using a data acquisition system. Mechanical motion at the top surface of the microphone was measured using a laser Doppler vibrometer, which enabled non contact velocity measurement without adding mass or altering the boundary conditions of the unit. Reflective tape was applied at the laser measurement point to improve optical return and reduce measurement variability due to surface reflectivity. The vibrometer velocity output was configured using a scaling of 100 mm/s/V, ensuring consistent conversion from measured signal to velocity across all trials.

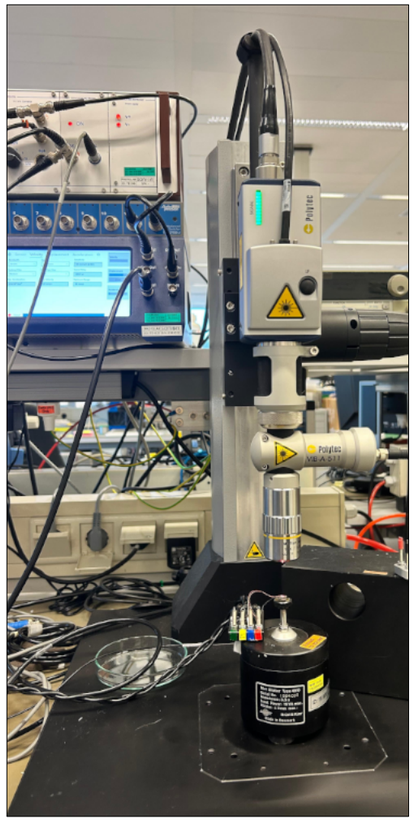
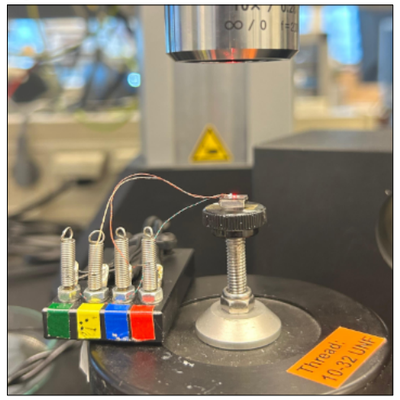


Figure 35. Test set-up

Figure 36. Microphone on the accelerometer



Procedure

1. Mount the microphone in the fixture and verify stable attachment and repeatable alignment.

2. Apply 1.3 V bias and confirm steady supply throughout the measurement.

3. Aim and focus the laser on the reflective tape region at the top surface of the microphone.

4. Configure a frequency sweep from 2 Hz to 2000 kHz with a 5 second duration.

5. Run the sweep while recording, (a) the vibrometer velocity output, and (b) the microphone electrical output, using synchronized acquisition channels.

Data handling and processing

Following acquisition, the raw recordings were exported to spreadsheet format and processed in Microsoft Excel. The vibrometer output was converted to surface velocity using the predefined scaling in mm/s/V, and the corresponding frequency axis in Hz was derived from the sweep configuration. The microphone electrical output was then converted to a relative magnitude in dB using a consistent reference across all samples to support direct comparison between candidate units. Finally, a relative response metric was computed by normalizing the microphone output level by the measured surface velocity at each frequency, yielding a frequency response style representation with frequency in Hz plotted against relative response in dB. This normalization follows common vibroacoustic practice, where vibration sensitivity is expressed relative to a mechanical input to distinguish transducer response from excitation conditions and to account for mechanically induced electrical output that can confound true acoustic pickup.

Selection criteria

Units were accepted for prototyping if they showed consistently high relative response and a comparatively stable response across the project band, without pronounced roll off or narrow resonant peaks within 10 Hz to 700 Hz.

2.7.2.2 Selected Microphones

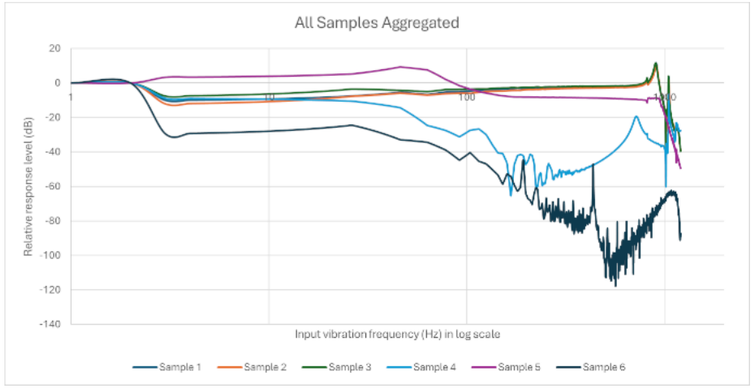


Figure 37. Relative responses plotted for all the samples.

Across the full set of candidate microphones, the aggregated frequency response curves showed clear separation in performance. As can be observed in figure 37, several units exhibited early roll off in the low frequency region, irregular mid band behavior, or instability toward the upper end of the sweep, which would reduce repeatability and complicate subsequent feature extraction for heart sound analysis. In contrast (Figure 38) three microphones demonstrated comparatively consistent response across the band of interest, with limited low frequency attenuation and fewer pronounced deviations within the measured range. On the basis of these sensitivity results, these three microphones were selected for prototyping.

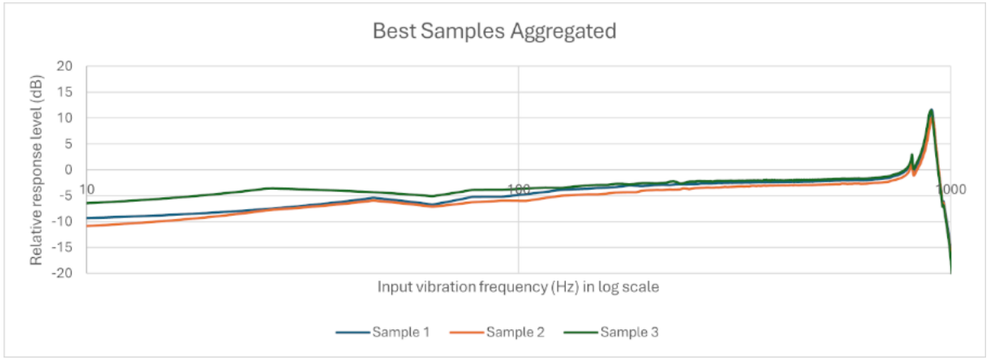


Figure 38. Plotted relative response of the best three samples.

2.7.3 Conclusion E-Health

Sound based murmur detection is well aligned with the clinical logic of auscultation, since it targets the same cardiac signals clinicians listen for, while enabling more consistent and measurable analysis. However, heart sound recordings are affected by overlapping sources such as breathing, motion, and changes in how the sensor contacts the body.

These requirements directly inform the choice of sensing hardware. The relevant cardiac information includes low frequency components that many consumer microphones are not designed to capture accurately, since they are typically optimized for speech and general audio. For this reason, the project pursued a specialized sensor approach that is better suited for detecting heart sounds, with the goal of achieving both high sensitivity and a stable response across the frequencies needed for heart sound monitoring.

Sensitivity testing was used to compare candidate sensors under consistent conditions. The results showed clear differences in performance between units, and three microphones demonstrated the most stable behavior across the tested range. These three were therefore selected for prototyping.

03 DESIGN DEVELOPMENT

3.1 Synthesis of insights

This section synthesizes the main findings from Chapter 2 and shows how they informed the project's design direction. It brings together what was learned about degenerative valvular disease, heart murmurs as early signals of progression, current follow up patterns, and patient experiences of uncertainty. Each point in the summary below shaped design decisions, including what to measure, how to support correct placement and repeatable recordings, and how to present results that patients can understand and clinicians can act on.

2.2. Degenerative Heart Disease

- Degenerative valvular disease is becoming one of the most common cardiovascular conditions. There are no therapies that can reverse this degeneration, just surgery to correct it.
- Elderly patients minimize symptoms which can lead to delays in diagnosis and treatment.
- AS is the most common form of DVD.
- Echocardiography is how patients are monitored currently.
- Surgery is tricky. The decision to operate increasingly involves balancing procedural risk against expected benefit as usually these surgeries are open heart surgeries. The sweet spot is when the risks from the disease progression begins to exceed those of the surgery, like the patient having heart failure or sudden cardiac death.

2.3 Heart Murmurs

- Murmurs are one of the earliest detectable signs of an underlying cardiac pathology, even before symptoms become prominent.
- Murmur changes if the disease progresses as the blood will flow differently through the heart so the murmur could change, pitch, duration, and/or intensity.
- In practice, clinicians see the patient once or twice a year (depending on the severity of the disease), which creates uncertainty for the patient and reduces opportunities to detect deterioration earlier for clinicians.
- Interview insights point to a recurring gap: murmurs likely contain information about progression, but current care cannot capture, store, and compare them over time, leaving changes between imaging visits undocumented.

2.4 Patient Pathways

- It is a very up and down journey for people that suffer from DVD. They have mixed emotions; from reassurance that their disease is being taken care of, to anxiety from having a heart problem, and in a way, waiting until their condition worsens.
- There are many factors that tie patients to their medication adherence and lifestyle adjustment.
- Patients need to be informed of what is going on - this in turn reduces lack of information and the anxiety and unknown that arises from it.
- Cardiac surgery is a big event for these patients; it has both positive and emotions tied to it. Positive as they will start feeling better after the surgery, but negatives as it is a highly invasive open-heart surgery with the risk of death and a hard rehabilitation.

2.5 Perspectives on heart problems and experiences of patients

- Uncertainty between follow up appointments is common, especially soon after diagnosis, and is linked to limited data and information about disease progression.
- Home monitoring is already common, and the procedure of stopping and taking measurements is known. This means a similar routine for heart sound recording would be familiar with users.
- With the device, perceptions improve sharply, with low confidence or high anxiety dropping.
- Main anticipated barriers are fear of false alarms, uncertainty about correct placement, technology setup challenges, and remembering regular use.
- Reported needs translate into project aims: in app explanations, condition information, reassurance through use, and a tool to track symptoms and progress at home.

2.6 E-Health

- Patient reported outcomes show that home monitoring is most effective when it is organized as a shared decision, with clear onboarding, and understandable interpretation of measurements.
- In cardiovascular care, telecardiology is associated with fewer readmissions, improved survival outcomes in some programs, higher satisfaction, and better continuity of follow up.
- Telemonitoring creates value for clinicians when outputs are easy to act on.
- For patients, use depends on reducing uncertainty, matching device feedback with symptom experience, and providing disease explanations.
- Cost evidence indicates that telemonitoring can reduce high intensity service use, especially when it prevents acute deterioration.
- There are many devices in the market, but none offer the possibility of progression in degenerative heart diseases.

2.7 Technology Choices for the Design

- Acoustic sensing is a direct way to detect murmurs at home because clinically relevant changes in valvular disease often appear as changes in heart sound quality, intensity, and timing.
- Fundamental heart sounds S1 to S4 are commonly described in a low frequency band, roughly 10 Hz to 250 Hz. Murmurs go up to 700Hz.

Figure 39. Worry and Stress Vortex. It shows patient uncertainty and the loop they are stuck in with the current care pathway.

3.1.1 Summary of Theoretical and Empirical Findings

The collected research reveals a clear pattern in the daily lives of people who live with cardiac conditions. Their journey is defined by long stretches of uncertainty, limited contact with clinicians, and a strong reliance on subtle bodily cues that are often difficult to interpret. The presence of murmurs in valvular disease serves as an early and important signal, yet these sounds are heard only during clinical visits. Between appointments, patients must rely on guesswork, memory, and fluctuating symptoms. This gap creates a cycle of worry, reduced clarity, and delayed understanding.

The quantitative survey further shows that many patients feel unsure about what their symptoms mean, how their condition evolves, and when to seek help. They often wish for clearer guidance, steadier routines, and a more active role in their care. At the same time clinicians express the need for information that reflects the patient's everyday state, not only the brief moments observed during visits. The absence of such information can complicate decision making and contribute to late recognition of important changes.

Together, these findings suggest that the current system places a heavy burden on patients. Instead of moving through their care with confidence, many navigate a loop (seen in figure 39), in which uncertainty leads to stress, stress reduces adherence, and reduced adherence complicates both recovery and communication with clinicians. This cycle is sustained by the fact that home life remains largely invisible in clinical practice. Without continuous insight into heart sounds or symptom patterns, both patients and clinicians are left without the clarity needed for timely action.

The insights also reveal a strong wish for tools that can support understanding without replacing clinical expertise. Patients do not seek full autonomy in diagnosis. They seek reassurance, comprehension, and a way to arrive at appointments with clearer information and better questions. Clinicians want complementary data that enriches the conversation rather than overwhelming it.

The opportunity lies in creating patient-centered technology that empowers individuals to take control of their own health without placing new burdens on the user. A tool that allows people to observe their condition in a calm and structured way can break the current cycle. It can transform uncertainty into awareness, offer early signals that prompt meaningful action, and open a smoother path for dialogue during consultations. The potential is considerable, but only if the solution respects real routines, reduces cognitive load, and offers value that is immediate and easy to grasp.

Within this framework, the future of home-based cardiac monitoring is not about replacing clinical judgement. It is about building a supportive companion that helps people make sense of their daily health and gives clinicians a clearer foundation for care.

3.1.2 Design Requirements

The research completed so far provides a clear direction for the project. Insights from literature, cardiologist interviews, and early user input support the choice to develop a home-based heart sound recording device that patients can use during the moments between clinical visits. The goal is to create a device that allows people with degenerative valve disease to capture their heart sounds, monitor the progression of it and record symptoms that influence their condition.

The design will rely on the core sensing component produced by Sonion and will focus on creating a product that fits comfortably into daily life. The main elements that require careful development include the body of the device, the placement guide, the recording interface, and the workflow that supports symptom input. Other elements, such as accessories or optional features, will be evaluated but kept secondary to preserve clarity of use.

The new design will have a guided placement procedure and a straightforward recording flow that resembles what happens in a clinical setting but adjusted to a home context. The interface will be shaped to support quick understanding, reduce worry during use, and avoid extra cognitive load.

By developing a device with these characteristics, the project aims to demonstrate how a patient centered recording tool can support continuous understanding of a cardiac condition. This will help confirm the value of a new patient journey in which home recordings complement clinical care and guide people toward steadier routines, clearer conversations with clinicians, and stronger confidence in their long-term disease management.

Functional requirements

- The recorded sounds **must** be suitable for program/clinical interpretation.
- **Must** allow recordings on the classic auscultation points.
- The device **must** maintain steady contact with the skin.
- The device **must** guide the user toward correct placement through simple cues.
- The materials used for the device **must** be biocompatible.
- The device **should** reduce movement-related noise as much as possible during short home recordings.

User requirements

- The device **must** be usable by older adults with reduced strength.
- The device **should** work on users with and without chest hair.
- The device **should** adapt to different chest shapes, including chests with breast tissue.
- The interaction **should** feel simple and calming.

Comfort requirements

- The contact surface **must** feel comfortable on bare skin.

Placement and repeatability requirements

- The device **must** be flat on the chest
- The device **should** include visual or physical placement cues that help the user place it in the correct place.
- The procedure **should** be easy to repeat across sessions in a daily routine.
- The device **should** support a clear and comfortable user posture.

Technical and acoustic requirements

- The device **must** allow integration of a Sonion microphone and electronics.
- The microphone **must** be sensible for 10 Hz to 1kHz sounds.

Practical requirements

- The device **must** be feasible to prototype within my graduation project timeline.
- The device **must** be storable in a typical home drawer or cabinet.
- Cleaning **should** be easy with a simple wipe.
- Charging or battery replacement **should** be simple and clear.

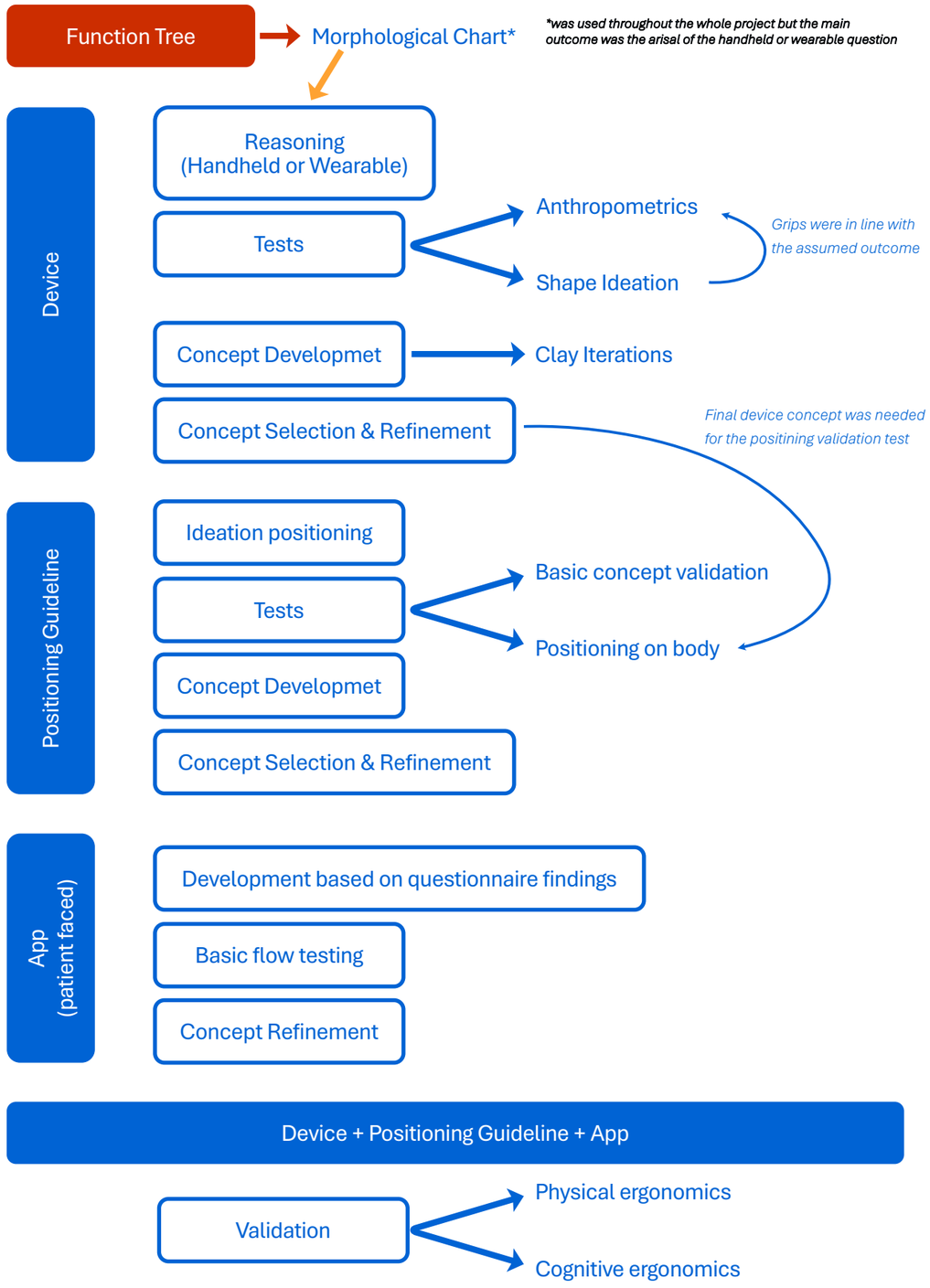


Figure 40. Diagram of chronological decisions taken.

3.2 Ideation and Concept Generation

The ideation phase started by using the requirements as a steady point of reference, then gradually widened to allow open exploration without fixed assumptions. Early thoughts from the research stage naturally evolved into rough sketches, quick notes, and simple models that helped clarify possible directions. With the needs of patients and clinicians in mind, the purpose of this phase was to search broadly, question earlier assumptions, and let new possibilities surface before moving toward more defined concepts.

The ideation process was shaped by the need to support patients through many different situations while keeping the experience calm and easy to follow. A central aim was to create a device that feels familiar from the first use, similar to placing a stethoscope on the chest, yet able to grow into a more supportive companion for daily health routines. This meant the starting point had to be simple enough for anyone to understand, while still allowing a path toward more guidance, more clarity, and more confidence over time.

Another key line of thought was compatibility with the ways patients already manage their condition. The device needed to blend into medication routines, symptom tracking, and everyday behavior without feeling like an added burden. At the same time, it needed to open the door to new abilities, such as recording heart sounds with steadier placement or gathering information that can enrich conversations with clinicians.

This introduced a **core design challenge**. The device had to remain small, comfortable to hold, and easy to position, yet also stable enough to produce recordings that reflect the patient's true condition. This required exploring ways to support the hand, guide placement, and reduce unwanted movement while still keeping the interaction natural.

A final guiding thought was how to create a sense of partnership between the person and the device. Instead of acting as a passive tool, it should help the user feel more in tune with their body, more aware of changes, and more confident when discussing their health. The intention was to shift the experience from simply using a device to working together with it, as if it becomes an extension of the patient's own attention and care.

3.2.1 Ideation and Concept Development

3.2.1.1 Function Tree

To structure the ideation phase, a function tree was developed to translate the project goal into a clear set of required and supporting functions, as seen in figure 41. This created a shared reference for what the system must achieve, independent of any specific concept. By breaking the overall objective into smaller functions, the function tree helped identify key requirements, user interaction needs, and constraints that had to be considered throughout development. It also supported traceability, since later design choices could be linked back to functional intent rather than being driven only by form.

Based on the function tree, a morphological chart was then used to explore multiple solution options for each function, and the full chart is included in appendix E. This exploration led directly to a key question for concept development, should the device be wearable or handheld. The following section addresses this choice, since it strongly influences usability, placement consistency, and repeatability of recordings.

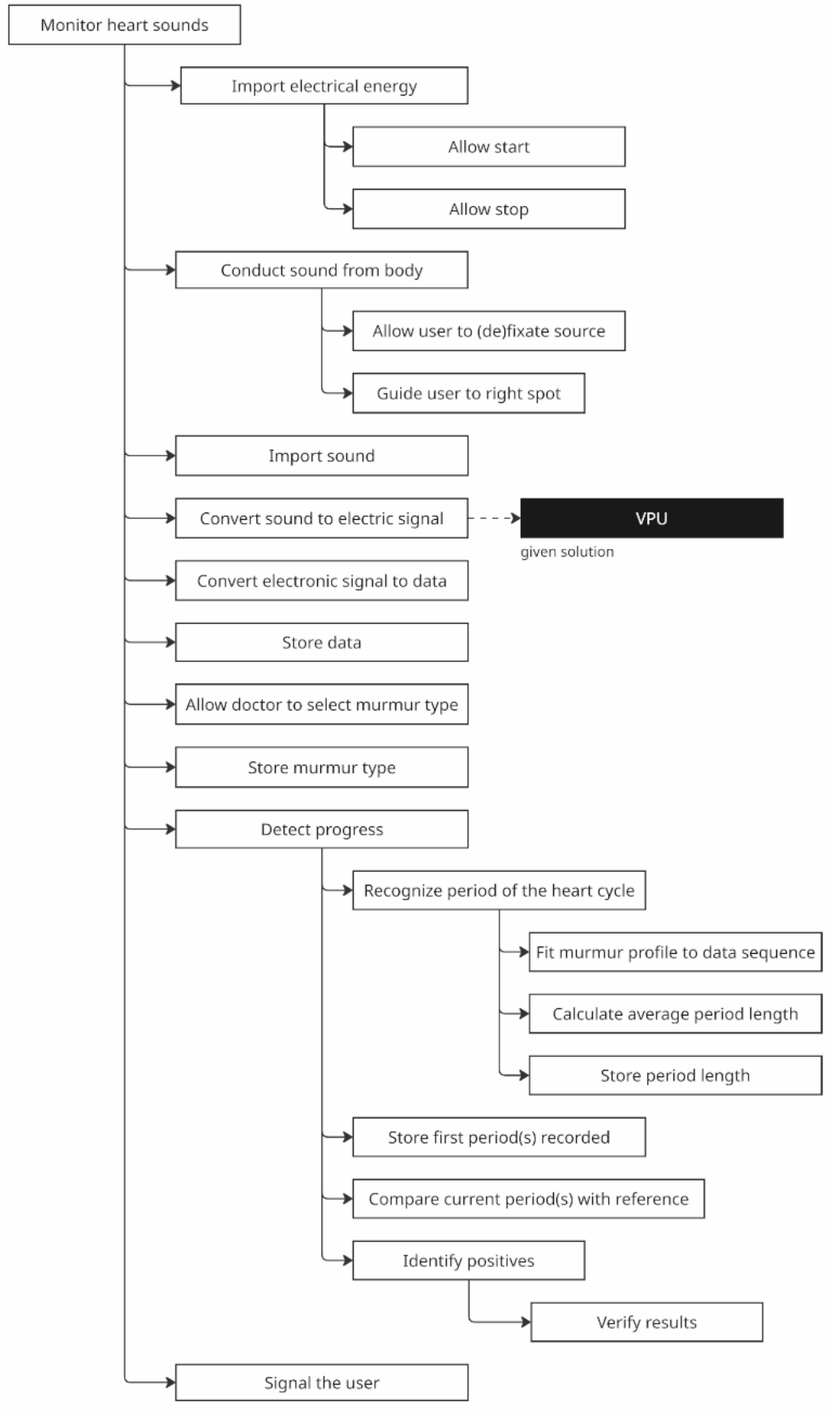


Figure 41. Function Tree of the device.

Figure 42. Start of ideation sketches.

3.2.1.2 Device Reasoning - Handheld or Wearable

The decision between designing the device as a hand-held product or a wearable is a pivotal one, as it significantly influences the direction of the next ideation phase and eliminates a range of design solutions. To make this choice, a method of weighted objectives was employed to assess and compare the potential design concepts based on their overall value across several critical performance criteria. The weighted objectives method allows for a systematic evaluation by assigning a score to each design concept on a scale from 1 (lowest) to 5 (highest) in relation to seven distinct objectives.

Criteria:

1. Measure in all auscultation points, evaluates the device's ability to be used at the key auscultation points on the body, ensuring comprehensive coverage for accurate heart sound monitoring.

2. Placement consistency (same spot) assesses how easily users can position the device at the same location during each use, which is crucial for ensuring consistent measurements.

3. Good repeatability (pressure, angle, etc.) addresses the need for the device to maintain the same pressure, angle, and force during each measurement, which is vital for obtaining reliable, comparable data.

4. The contact with the skin objective focuses on the device's ability to maintain a stable and constant pressure on the user's skin, ensuring a consistent interface for accurate readings.

5. Ease of use evaluates how simple it is for users to operate the device, including placing it on the body and adjusting it for optimal positioning, which is especially important when repeated measurements are required.

6. Effort needed from the user criterion measures how much physical effort the user must apply to set up, place, and remove the device, with a focus on minimizing user burden.

7. Inclusivity (body types, hair, etc.) assesses how well the design accommodates various user body types and factors such as body hair, ensuring that the device is usable by a diverse range of individuals without requiring significant adjustments.

		Importance	*Wearable*	*Handheld*
1	Measure in all auscultation points	5	5	5
2	Placement consistency (same spot)	4	3	3
3	Good repeatability (pressure, angle, etc)	4	4	3
4	Contact with the skin	5	5	5
5	Ease of use	3	3	4
6	(No) Effort needed from user	3	2	3
7	Inclusivity (body types, hair, etc)	4	2	4
	TOTAL		***105***	***119***

Table 3. Weighted objectives for the design decision of whether to use a wearable or a handheld device.

By evaluating the hand-held and wearable design concepts against these objectives, the decision-making process becomes clearer. The weighted objectives method provides a structured approach to identifying which design concept maximizes value across these critical factors, allowing for a decision that balances ease of use, functionality, and inclusivity.

3.2.1.3 Ideation and Tests for the device

3.2.1.3.1 Anthropometrics

To meet the design requirements, particularly the need for steady contact with the skin and a comfortable grip, a comprehensive grip study was conducted. The device needed to support a stable hand position, encouraging the user to rest their hand or wrist on the chest while maintaining a grip that would suit a wide range of hand sizes. The aim was to identify the most effective and comfortable grip that would allow users to apply slight pressure to the device while holding it for extended periods without discomfort.

Grip Research and Selection

The selection of grips for the study was informed by existing literature on pinch strength and common grasp patterns in daily activities. As seen in figure 43, seven grips were included; disk grip, parallel extension, chuck grip, spherical grip, flat hand push, finger scissor, and flat pinch. Previous ergonomics research on these grips usually considers tasks in which an object is grasped and manipulated away from the body, such as lifting an item from a surface or holding a handle in front of the torso. In this project the context is different, since the user holds the object toward the body and presses it against the chest. The focus was on identifying grips that provided stable contact with the skin, supported natural hand movement, and allowed for easy pressure application.

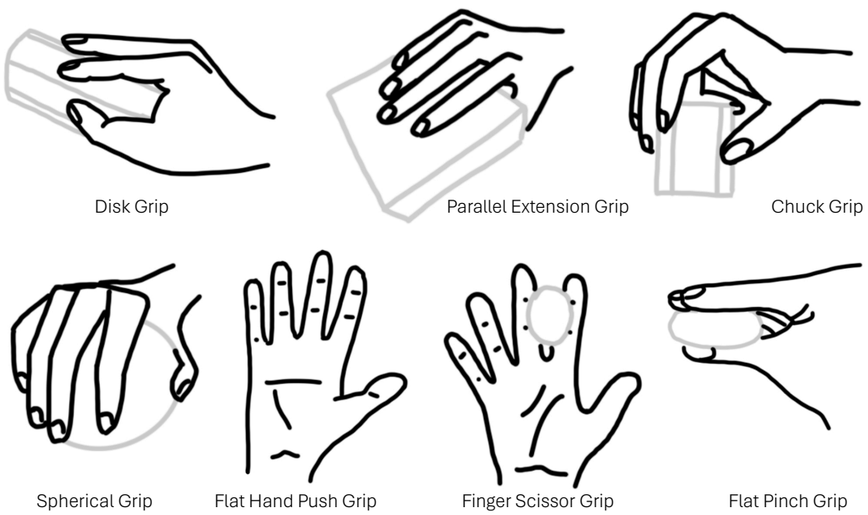


Figure 43. Seven grips selected for the study.

The Prototypes

To explore the potential designs, simple ideation sketches and 3D models of the selected grips were created. The prototypes were constructed with the goal of facilitating a comfortable, steady grip that would allow for consistent and repeatable contact with the chest.

A total of nine prototypes were developed, each representing a different grip configuration with subtle variations in form. Prototypes 2 and 3 differed mainly in width and height, prototypes 5 and 6 incorporated different indent shapes, and prototypes 8 and 9 varied in ring size. The set of prototypes was arranged along a spectrum from more open and loose grips to more precise and controlled grips, so that both relaxed whole hand grasps and more targeted finger based grasps could be evaluated.

These controlled variations were introduced to investigate how small changes in geometry and grip precision influence comfort, ease of use, and user preference. The set as a whole was intended to reveal which forms are more pleasant to hold, easier to understand at first contact, and more suitable for pressing the device against the chest.

Figure 44. Photo of the nine 3D printed prototypes made for the grip study.

Methods

Participants

The study was made up from 5 participants (female and male) aged 45 years and older, selected to evaluate the ergonomics and comfort of different grip designs for a chest-held device.

Procedure

Participants were briefed on the goals of the test, which included identifying the most comfortable, intuitive, and pressure-friendly grip for holding a device to the chest. They were instructed to grab each of the nine prototypes with their right hand and position it against the left side of their chest. The objective was to maintain stable contact with the chest for 10 seconds with each prototype.

Participants were not given specific instructions on how to hold the prototypes. Instead, they were allowed to interact with each grip freely. They were asked to use the "think-out-loud" method, verbalizing their thoughts throughout the process. This included commentary on how easy or difficult it was to hold each object, how comfortable the grip felt, the pressure required to maintain contact with the chest, and any discomfort they experienced as time passed. This technique aimed to gather real-time feedback on both the subjective experience of using each grip and the objective aspects of ergonomics.

To minimize bias during the evaluation, the prototypes were labeled with numbers (1–9) for easy identification. The numbering system was designed to be neutral and prevent any influence on the participant's perceptions of the prototypes. For symmetrical objects, the numbers were placed in the center, while for objects with a specific orientation, numbers were placed on both sides to avoid any assumptions about the proper orientation of the prototype. They were also randomly placed inside a cardboard box and moved around so there was no fixed orientation.

For each object, they were instructed to verbalize their initial impressions on how they believed the object should be held, followed by physically holding it and positioning it against their chest for 10 seconds. During this time, they were encouraged to comment on their experience of grip comfort, ease of use, and the amount of force required to maintain contact with their chest.

Data Collection

After each prototype interaction, participants were asked to rate their experience using a Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree) on several key questions:

1. How easy was it to hold [the object]?
2. How well did it feel and fit in your hand (grip)?
3. Did you feel comfortable grabbing it and positioning it?
4. How much force did you need to apply to maintain chest contact?
5. Did you feel any discomfort after a few seconds?

Following the evaluation of all nine prototypes, the researcher explained the correct grip for any prototypes that the participants may have missed or incorrectly used. The participants were then asked the same questions again to assess whether their feedback had changed after understanding the proper grip.

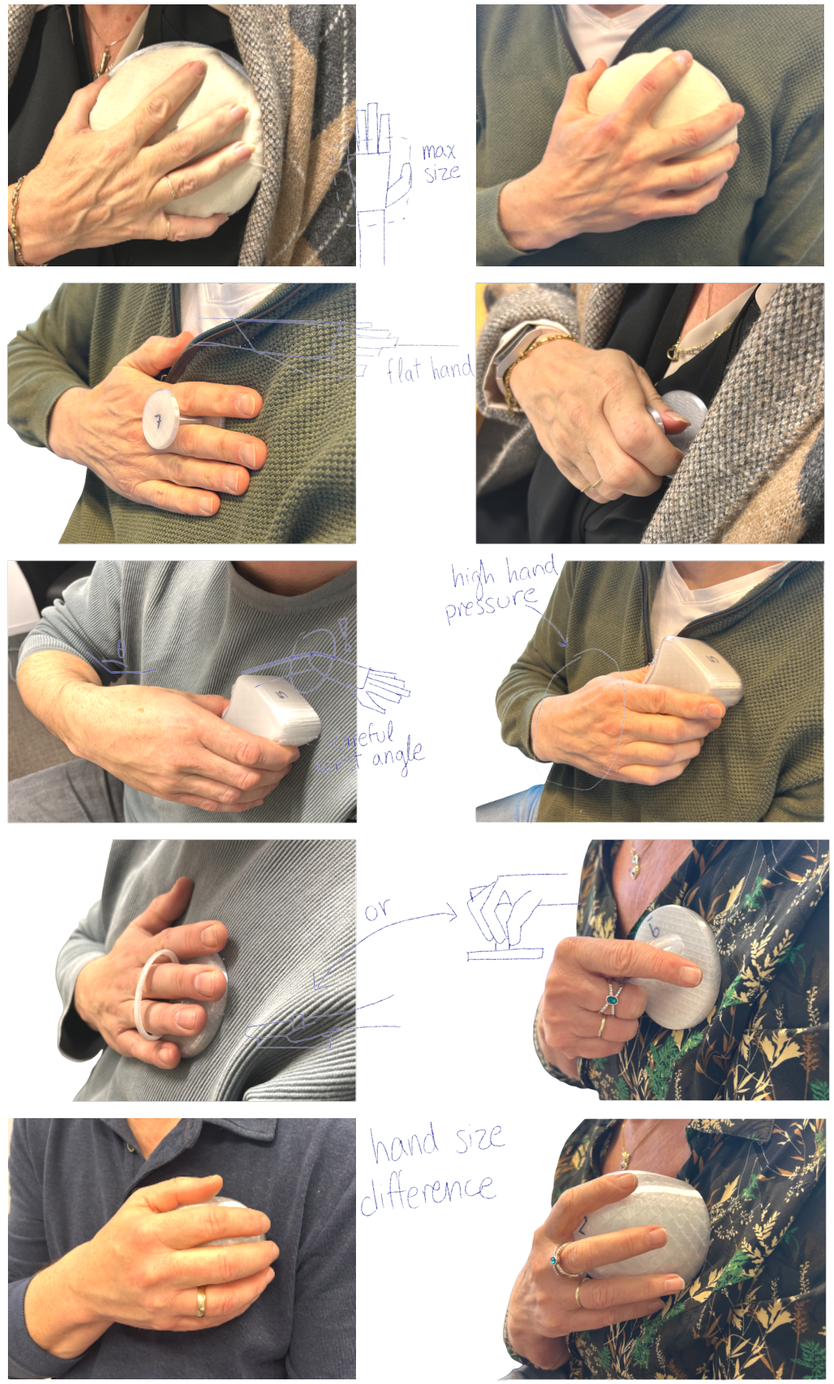


Figure 45. Compilation with annotations of some of the users holding the different grips. All grips and corresponding photos of the participants can be found in appendix E.

Final Ranking and Feedback

To conclude the session, participants were encouraged to provide any additional thoughts or insights regarding their experiences with the grips, which allowed for further qualitative feedback.

Results

User preferences

Across the five participants, clear preferences emerged for some objects and clear rejection for others. Very large or narrow shapes were generally disliked. Object 1 was often described as “too big and hard to hold at the start,” although it became easier once placed on the chest. Women could usually stabilize it using the chest itself, while men often had to support it by placing the pinky and index finger underneath.

Object 2 was perceived as bulky and large, but several participants were surprised that “it fits really well” once in position. It was preferred over object 3 because it felt more stable, even though hand comfort depended on whether the width matched the person’s hand size. Object 3 was considered “too long and narrow,” with comments about “wobbling” and the remark that “wider is better.” Only one participant preferred object 3 over 2.

Objects 4, 5, and 6 were among the least preferred. Object 4 was small and easy to hold, but everyone initially held it incorrectly. After seeing the correct orientation, some participants found it easier, while others felt the wrist was at a “weird angle” and reported that “it is just not completely right.” Object 5 was consistently rejected as “weird in the hand” and “I would not like to hold this,” with people unsure where to place fingers or palm and reporting that they “really have to hold it in place.” Object 6 was also held incorrectly by all participants and described as uncomfortable and confusing, with questions such as “Is it for the left hand” and comments about fingers being at a “really weird angle.”

Object 7 split opinions. Some found it “small, light, and easy to position,” while others felt that the small structure cramped the fingers and said “I do not like this.” When the correct positioning was explained, several participants appreciated it more.

Objects 8 and 9 generated the most interesting preference patterns. Men tended to place a finger through the ring opening, which felt secure and allowed more force on the chest. Women generally avoided putting fingers through, often because they were wearing rings, and instead preferred a pinch style grip. Object 9 was clearly preferred over 8. Participants reported that it offered more space for the fingers and a better stabilizing feeling. Typical comments included “I can really push it down on my chest compared to the others,” “Having multiple fingers helps me stabilize it better,” and “You almost do not feel it, it is so easy to hold to the chest.” Several participants also mentioned that they preferred to hold it outside rather than inside the ring, which shows that having both an open and a closed grip option was appreciated.

Quantitative results and ranking

Alongside the qualitative comments, the Likert scores for the five questions per object were averaged and visualized in a heatmap as seen in table 4. Each object received scores for ease of holding, fit in hand, grip comfort, force used to maintain contact, and discomfort after a few seconds of holding. For the first three questions higher scores indicate better performance, while for force and discomfort lower scores are better.

When combining these five questions into one overall score per object, the resulting ranking from best to worst was: 9, 8, 7, 2, 3, 4, 6, 5, 1

Objects 9 and 8 clearly form the top group. They show high scores on ease of holding, fit in hand, and grip comfort, together with low values for force and discomfort. This matches the verbal feedback that object 9 was “so easy to hold” and allowed users to “really push it down on the chest,” and that both 8 and 9 felt secure once in position.

Object 7 occupies the next place in the ranking. Its scores reflect the mixed opinions in the interviews. Many participants experienced it as “small, light, and easy to position,” while others reported cramped fingers. The mid range scores in the heatmap show that it performs reasonably well on average but is more sensitive to hand size and preferred grip style.

Objects 2 and 3 sit in the middle of the ranking. Both are judged acceptable in terms of stability and comfort, with object 2 performing slightly better overall and being described as “surprisingly” fitting well once on the chest, while object 3 suffers from more wobbling. Objects 4, 5, and 6 fall toward the bottom, in line with the strong verbal rejection of these shapes. Finally, object 1 ranks last, confirming that its large bulk and challenging initial grip outweigh the advantage of better stability once supported by the chest.

The alignment between this quantitative ranking and the qualitative findings strengthens the conclusions on which design directions are most promising, especially the features represented by objects 8 and 9.

Overall, participants favored shapes that felt secure once on the chest, offered enough space for multiple fingers, and did not require them to search for a comfortable position or orientation.

	Ease of holding	Fit in Hand	Grip comfort	Force used to maintain contact	Discomfort after a few seconds of holding	Total
Object 1	2.6	2.4	3	1.8	1.8	3.28
Object 2	4.5	4.6	3.8	1.2	1	4.54
Object 3	4.2	3.8	4.2	1.4	1.4	4.28
Object 4	3.4	3.2	3.6	1.8	2	3.96
Object 5	2.8	2.2	3	1.6	2.2	3.64
Object 6	3	3.2	3.8	1.8	1.8	3.68
Object 7	4.2	3.6	4	1	1.4	4.6
Object 8	4.6	4	4.6	1	1	4.64
Object 9	4.6	4.6	4.6	1	1	4.76

Table 4. Table of the average results for each object. The heatmap visualization was used to easier visualize which objects had better results compared to others.

Ergonomic patterns

The comments reveal consistent ergonomic patterns that go beyond individual preferences.

First, wrist posture was a recurring theme. Participants reacted immediately when the angle between hand and forearm approached or exceeded a right angle. Objects 4 and 6 in particular led to “weird” wrist angles when used as intended, and this strongly influenced comfort scores even when the grip itself was small and easy to hold. Keeping the wrist below roughly ninety degrees emerged as an important condition for comfort.

Second, contact stability and grip style were closely connected. Large, very wide shapes such as object 1 and 2 could be stabilized well on the chest but were awkward in the initial grip and lift. Very narrow or long shapes such as object 3 increased “wobbling” and required more active corrections with the fingers. Participants often tried to compensate for instability by placing extra fingers under the object or closer to the contact surface. The most positively received shapes allowed either an open grip around the body of the object or a more closed configuration where one or more fingers passed through an opening.

Third, size and proportion mattered. From the set of objects, participants gravitated toward shapes with an approximate diameter between 6 and 11 centimeters. Larger shapes felt bulky, distant from the chest, and demanding in terms of hand span. Smaller shapes tended to cramp the fingers, as seen with object 7, or felt insecure unless supplemented by a second hand.

Fourth, orientation cues were crucial. Objects 4 and 6 were held incorrectly by all participants at first. This shows that when the form does not clearly indicate how it should be held, users will create their own grip and may never discover the intended posture in real life use. After explanation, some ratings improved, especially for object 7 and partly for object 4, which suggests that form alone should do more of the guiding work, without relying on instruction.

Fifth, gender related patterns appeared around ring type grips. Men tended to insert fingers through the ring and described this as secure and helpful for applying chest pressure. Women, often wearing rings, avoided this and preferred to hold the object around the ring using a pinch style. Object 9 supported both strategies better than object 8 because it provided more finger space and more perceived control.

Together, these patterns indicate that ergonomics for this device are not only about the contact surface with the chest, but also about wrist alignment, hand span, finger support, and the clarity with which the form invites a grip.

Recommendations for the optimal design

On the basis of these learnings, several design recommendations can be formulated for a future chest held device.

1. Offer both open and closed grip options

   The grip should allow comfortable use in more than one way. An opening that can accommodate one or two fingers can provide a secure closed grip for users who like to insert fingers, while the outer contour should also allow a comfortable open grip or pinch grip. This accommodates differences in preference, hand jewelry, and hand size.

2. Keep the wrist angle below ninety degrees

   The relative position of grip area and chest contact surface should support a wrist posture that remains below a right angle between hand and forearm during use. This reduces strain and helps users maintain stable contact for longer periods. Prototypes that forced the wrist into extreme angles were consistently rejected.

3. Stay within a medium size range

   Results suggest that a diameter or main dimension in the range of about 6 to 11 centimeters is preferable. Larger objects are perceived as bulky and hard to grasp at the start, while smaller objects risk cramping the fingers and feeling insecure. The final design should sit within this medium size range and distribute the contact area in a way that feels stable on the chest.

4. Facilitate stable contact with minimal finger effort

   The contact surface should be shaped to sit securely on the chest, allowing users to rely partly on body support rather than constant finger tension. Mild curvature and sufficient area at the chest side can help reduce wobbling, similar to the effect observed with object 9 where participants felt they could “really push it down” and “almost do not feel it.”

5. Provide clear orientation cues through form

   The shape should make it obvious which side goes to the chest and how the hand should approach. Objects that everyone held incorrectly highlight that subtle geometric differences are not enough. Stronger visual and tactile cues are needed so that users naturally find the correct grip without verbal instruction.

6. Design for diversity in hand size and style of use

   Preferences varied between participants with smaller and larger hands, as well as between men and women in how they interacted with the ring structures. The optimal design should therefore allow slight variations in finger placement and should not depend on a single precise grip configuration to feel comfortable and secure.

These recommendations point toward a device that combines a medium sized, chest conforming contact area with a grip that supports both open and closed use, keeps the wrist in a comfortable angle, and clearly communicates how it should be held, so that users can achieve a stable and comfortable posture with minimal effort.

Conclusions Grip Study

- Object 9 emerged as the most suitable configuration, followed by objects 8 and 7, combining high ratings for ease of holding, grip comfort, and low reported discomfort with strong qualitative endorsement.
- The best shapes allow both an open grip around the body and a more closed grip using an opening, so different users can choose what feels natural.
- Wrist posture is crucial, participants rejected shapes that forced the wrist past roughly a right angle between hand and forearm.
- A medium overall size, with principal dimensions roughly between 6 and 11 centimeters, was preferred. Larger objects were described as bulky and difficult to grasp, whereas smaller objects tended to constrain the fingers and felt less secure.
- Stable contact with the chest matters as much as hand comfort; users value the ability to “push” the device into the chest without extra effort or wobbling.
- Clear form cues are essential, several objects were held incorrectly by everyone at first, which shows that shapes must communicate the intended grip and orientation on their own.
- Participants consistently preferred grips that allowed part of the hand or wrist to rest on the chest. Designs that depended mainly on continuous finger effort were perceived as tiring and less suitable for longer use.
- The close correspondence between quantitative scores and qualitative comments strengthens confidence in the conclusion that an optimal design will be of medium size, clear orientation, and flexible grip options.

Added Design Requirements

With the decision to proceed with the hand-held design solution and the insights from the ergonomic test, new design requirements emerged, especially in terms of ergonomics since the user will be directly handling the device.

Comfort and ergonomics requirements

- The form **must** support a steady grip that encourages resting the hand or wrist on the chest.
- The device **must** be between 6cm and 11cm in size.
- The grip **should** work for a wide range of hand sizes.
- The device **may** include a soft material to improve comfort.

Figure 46. Participants working with clay for the session.

3.2.1.3.2 Shape design and interactions considerations

A brainstorming session was conducted with 10 participants to explore alternative grip shapes and interaction concepts. Participants were first introduced to the project context and intended use scenario, then asked to independently shape what they believed would be comfortable, usable, and intuitive. The group produced 12 distinct grip concepts, enabling immediate externalization of tacit preferences around hand posture, stability, and placement during use.

The fundamental concept of the session was participatory form finding, meaning that potential users were treated as active contributors rather than evaluators of predefined options. By providing only the use context and an open prompt, the session aimed to surface embodied, implicit knowledge about what a comfortable and controllable grip should feel like in the hand. Clay supported fast exploration without technical constraints, allowing participants to translate sensations, habits, and personal heuristics into physical forms. This approach broadened the early design space, revealed shared patterns across independent solutions, and generated tangible artifacts that could be clustered and translated into early design requirements.

One of the key benefits of this design method was that it produced physical artifacts that made ideas easy to compare and critique without relying on participants' ability to describe sensations verbally. Because each concept existed as a shareable object, the discussion and later analysis could reference exact geometries, contact points, and hand positions, which strengthened traceability from qualitative insights to concrete design criteria and prototype decisions.

This method generated ideas across different levels of abstraction, from experiential concepts such as a heart shaped design so it was obvious where it had to be placed, to targeted modifications of familiar devices such as a ring style oximeter that integrates monitoring functionality. During analysis, recurring themes emerged across multiple concepts, particularly open hand configurations and ring-oriented forms, suggesting shared expectations around comfort, perceived control, and ease of positioning.

An interesting concept raised during the session was a lips shaped design. Although the form itself is not ergonomic for the intended hand to chest use, the rationale behind it highlighted interaction qualities that remain relevant. The participant described a multi-layer intention: first, the device could play a brief kiss sound after a successful measurement as a simple cue that the recording is complete. Second, the gesture and sound were framed as a way to address social and emotional context, since many older adults experience loneliness or limited physical contact, a human cue could make the device feel more attentive. Finally, the kiss sound was associated with positive effect, so it could support reassurance by linking the end of a measurement to a comforting emotional signal. These insights suggest that beyond ergonomics, the interaction design should consider feedback that is clear, emotionally supportive, and appropriate for older users as the concept is refined.

Figure 47. Compilation of the way participants envisioned the positioning on the chest.

Figure 48. Final shapes created. They have been grouped in similar shapes and grip. First column: open grip. Second column: closed grip. Third column: open hand/ring.

3.2.1.4 Ideation for positioning on body

During ideation, concepts were developed primarily with aortic placement in mind, while consistently keeping in view that the device must ultimately support placement across all auscultation points. Because the product needs to work in multiple locations, fixed cues on the physical form would only match one orientation and could mislead users in the others. As a result, the positioning guidance was framed as an external layer, separate from the device itself, so it can adapt to the selected listening point while remaining consistent and easy to follow.

Because the ecosystem also includes a patient focused app, positioning ideation followed two parallel directions. The first focused on in app placement guidance, which can adapt instruction based on the selected listening point while maintaining a consistent user flow. The second focused on a physical positioning layer, which supports repeatable device placement on the body without requiring changes to the device form. Keeping both directions external to the device preserves a single hardware geometry while allowing positioning support to adjust across auscultation points.

App Placement Ideation

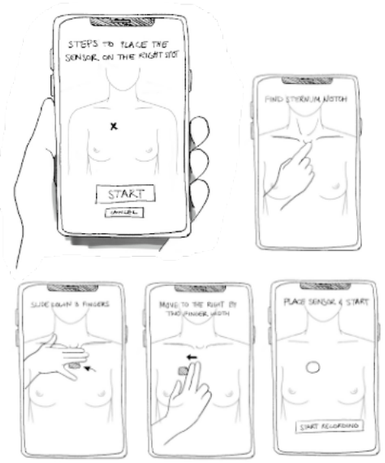


Figure 49. Concept sketch app guideline.

1. App Guideline

This concept uses the app to guide placement through a clear, linear flow that supports consistent use across auscultation points.

It aims to reduce uncertainty by showing users what to do at each stage, helping first time users build confidence and helping returning users repeat the same placement each session.

The main challenges are making the guidance robust across different body types and ensuring it stays short and easy enough that users do not skip steps, since static guidance cannot always catch small placement errors in the moment.

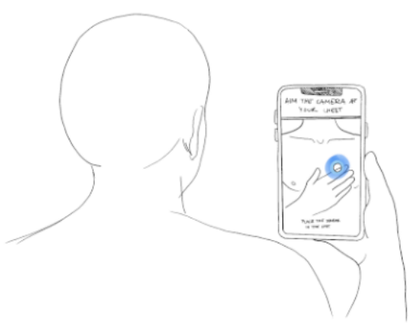


Figure 50. Concept sketch AR overlay.

2. AR Overlay

This concept uses the phone camera to provide on screen positioning guidance mapped onto the user's body view, translating placement instructions into a visual target that can reduce guesswork and speed up alignment.

Measurements are taken with the torso uncovered, which can make some users feel uncomfortable about pointing a camera at their naked torso, even if nothing is recorded.

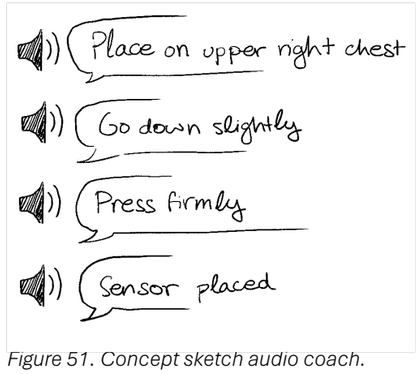


Figure 51. Concept sketch audio coach.

3. Audio Coach

This concept delivers spoken guidance that follows the same logic as the app guideline, so users can focus on positioning while receiving concise prompts without needing to look at the screen. It supports hands free interaction and can lower effort during setup, which can help adherence over time.

The key challenges are keeping the instructions precise without becoming repetitive or annoying, and supporting users who still want a visual confirmation for exact placement.

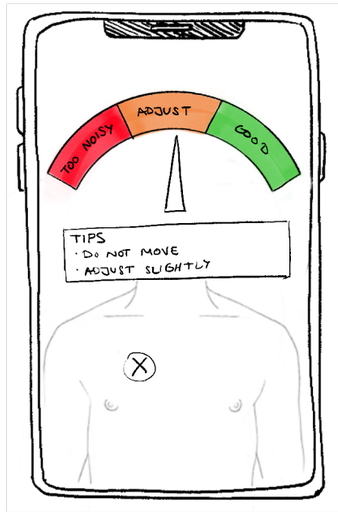


Figure 52. Concept sketch signal meter.

4. Signal Meter

This concept provides a clear indication of recording quality so users can verify that placement is acceptable before committing to a full measurement, supporting more reliable data and fewer failed recordings. It can also help users correct issues early, which reduces frustration and avoids repeating entire sessions.

The main challenges are designing a quality metric that is accurate yet easy to understand, setting thresholds that avoid false reassurance or unnecessary retries, and preventing users from spending too long adjusting to chase a perfect reading, which could increase worry or reduce willingness to measure regularly.

Physical Placement Ideation

1. Wearable template

This concept introduces a dedicated physical layer that the user wears to support repeatable placement across sessions. By constraining where the device can be positioned, it aims to reduce variability caused by user interpretation and make the workflow more confidence inducing at home.

The main challenges are comfort and fit across different bodies, ease of putting it on and taking it off, hygiene, and the risk that a physical constraint may feel inconvenient, which could reduce adherence over time.

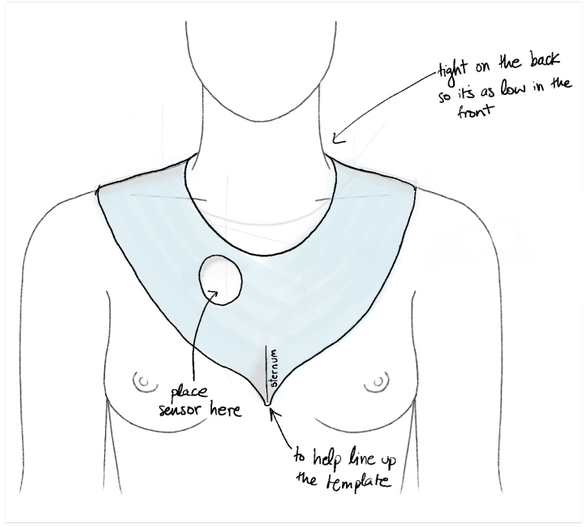
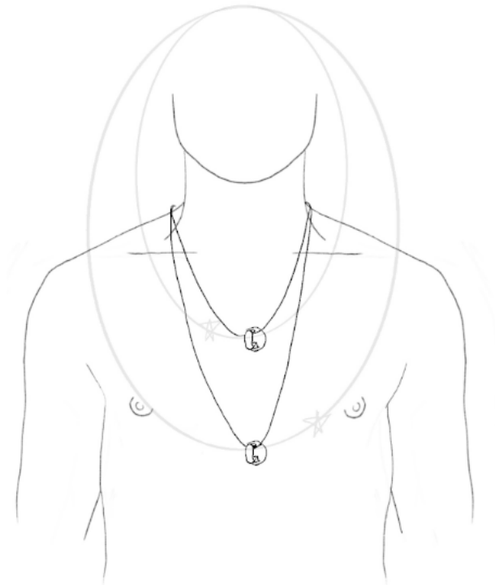


Figure 53. Concept sketch wearable template.



2. Necklace

This concept integrates a wearable carry method with positioning support, so the user can put the system on quickly and then move the device into the correct spot for measurement. It aims to reduce setup steps and make the interaction feel simpler and more routine, while still guiding placement through the wearable's geometry.

The main challenges include achieving sufficient positional accuracy without restricting movement too much, managing different body sizes and auscultation points without creating confusion, and ensuring comfort and stability during positioning.

Figure 54. Concept sketch necklace.

3. Onboarding placement

This concept relies on clinician led setup, where a clear reference point is provided during onboarding to help the user learn where to place the device. It can be effective for early use because it reduces uncertainty and anchors the user's understanding of correct placement.

The main challenges are durability and repeatability, since the reference can fade through normal daily life, and it does not scale well as a long term solution unless it is re-established regularly.

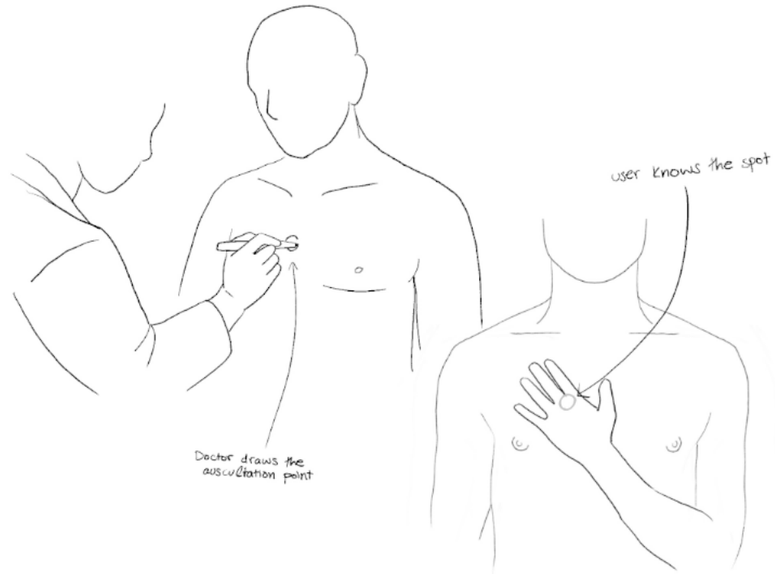


Figure 55. Concept sketch onboarding placement.

3.2.2 Concept Selection

Concept selection was approached by separating the system into three design elements: the device, the positioning guideline, and the app. Each element can be designed independently, since each has its own requirements and performance needs to meet. At the same time, they belong to the same system, so a choice made in one element has consequences for how the other two perform and how the full user journey works.

For the device, the main design dimensions were grounded in physical ergonomics, meaning how the product is held, oriented, stabilized, and operated during a recording. Cognitive ergonomics also played a role, since the device must communicate its correct use through its shape, touch points, and interaction cues, so that first time use is natural and mistakes are less likely.

For the positioning guideline, the design dimensions were primarily cognitive. The goal was to make placement easy to understand and easy to repeat, using instructions that support correct positioning without requiring medical knowledge. The app followed the same cognitive focus, prioritizing an intuitive flow that reduces uncertainty. In addition to guiding the recording steps, it was evaluated on whether it provides the reassurance and clarity users expect, including clear feedback on what happened, what the result means, and what to do next.

The concept selection process followed a simple logic. First, the needs and requirements were defined. Next, the available solution space was explored, and options were assessed against those needs. Based on this assessment, design choices were made for each element. Finally, the selected choices were evaluated together, to check how they function as one integrated system, and to confirm that tradeoffs in one part did not undermine performance or usability in another.

3.2.2.1 Device

To get an initial sense of which concept (figure 56) appeared most promising, the two device concepts were compared on appearance and ergonomics using a brief Harris Profile evaluation, as seen in figure 57. This assessment was intentionally quick and approximate, since both concepts were still in an early conceptual stage.

Five criteria were assessed:

1. Unstable contact → Stable contact
2. Confusing placement → Easy placement (on hand)
3. Tiring grip → Low effort grip
4. Slippery grip → Secure grip
5. Fits few hand sizes → Fits many hands size

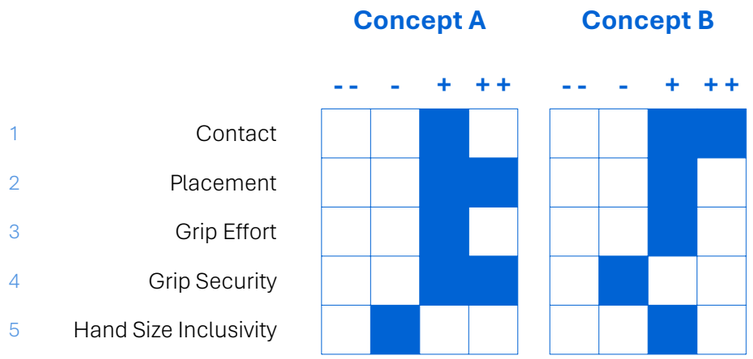


Figure 57. Harris Profile evaluation.

Based on the Harris profile, concept A emerged as the strongest option. Its larger form and multiple grip areas align well with user feedback that emphasized the need for flexibility in how the device is held. The increased size supports steadier placement and makes the device easier to position on the chest, especially during repeated use. These qualities contribute to a stronger sense of control and confidence during recording.

Concept B showed clear strengths in terms of hand inclusivity. Its smaller size and finger based holding approach allow it to accommodate a wider range of hand sizes with less dependence on grip strength. However, this advantage comes at the cost of reduced stability and fewer grip options, which limits its effectiveness compared to concept A. While concept B performs well in specific scenarios, it does not offer the same overall balance of comfort, control, and placement support that defines concept A.

Figure 56 Clay prototypes of concepts A and B.

3.2.2.2 Placement

The generated concepts were compared using the weighted objectives method, using the criteria and weights defined below to score each option in a consistent way. This made trade offs explicit and supported a transparent selection of concepts that best met the key requirements. Based on the total weighted scores, the top three concepts were selected for prototyping and user testing.

Categories used for the Weighted Objectives Method:

1. Cognitive load

   How much the user must remember, interpret, or decide during setup and use. (5 being no cognitive load)

2. Physical effort

   How demanding it is on reach, grip strength, fine motor control, and the need for two hands, including holding the phone or template while placing the sensor. (5 being no physical effort)

3. Repeatability

   How consistently the method helps the user place the sensor in the same correct area over days and weeks.

4. Time it takes

   Time from opening the app to starting a usable recording. (5 being no time)

5. Inclusivity

   Fit across bodies and real world variation, including different chest sizes, and sex differences.

6. User reassurance

   How confident the user feels that they did it right, and whether the system reduces uncertainty and discouragement.

7. Privacy and Dignity

   How comfortable the method feels during use, including camera discomfort, required undressing, perceived exposure, and feelings of embarrassment.

8. Reliability

   How robust it is in real homes, including lighting, noise, shaky hands, and Bluetooth issues.

		Importance	*App Guideline*	*AR Overlay*	*Audio Coach*	*Signal Meter*	*Wearable Template*	*Necklace*	*Onboarding Placement*		
1	Cognitive load	4	5	4	3	4	5	3	5	1	1
2	Physical effort	5	5	3	4	5	3	3	3	5	2
3	Repeatability	5	3	5	3	3	5	3	5	2	3
4	Time it takes	2	3	5	3	4	5	5	5	1	4
5	Inclusivity	3	3	5	5	4	4	5	5	5	5
6	User reassurance	3	3	5	4	5	5	3	5	1	6
7	Privacy and dignity	3	5	1	5	5	5	5	5	5	7
8	Reliability	2	5	2	5	4	5	5	5	5	8
	TOTAL		***109***	***103***	***105***	***114***	***122***	***101***	Total: ***104.5***		
									with dot	no dot	
									125	84	

Top 3

1. Wearable Template
2. Signal Meter
3. App Guideline

Table 5. Weighted objectives for the design decision of placement.

The weighted objectives method identified three leading concepts for further development: the wearable template, the signal meter, and the app guideline. Each scored strongly overall, yet each also showed clear gaps that will need to be addressed through prototyping and user testing.

The wearable template offers strong placement support, but it may demand extra physical effort to don and align, which should be evaluated with older adults. The signal meter prioritizes signal quality and can improve the reliability of collected data, but it increases cognitive load and may reduce repeatability because it does not provide an explicit placement reference. The app guideline is the simplest to implement, but it currently provides limited repeatability and reassurance because it does not verify correct placement.

To reduce these weaknesses across concepts, additional features can be layered in, such as allowing users to hear their heartbeat to confirm adequate contact and signal quality, and integrating a common mistakes and quick fixes screen to prevent predictable placement errors. Beyond usability, manufacturability also influences feasibility, app based solutions are largely software driven, while a wearable template would require either multiple variants or a combined design covering all four points, which could introduce confusion and increase the risk of incorrect placement if users are fatigued or distracted.

3.2.3 Concept Refinement

This section describes how the selected concept was refined into a more coherent system, focusing on the device, the placement approach, and the patient facing app. The refinements presented here are grounded in the report findings, including key takeaways from earlier phases, as well as direct input from users gathered through concept tests and the questionnaire. Together, these insights guided which elements to keep, which to adjust, and which to combine to improve usability, confidence, and consistency of use.

The refinement is structured into three parts. First, the device refinement addresses how users naturally grip and handle the concept, and how the form can better support those behaviors. Second, the placement refinement explains how the selected placement concepts were combined into a flexible approach that supports different user preferences, including an optional physical template and optional in app guidance. Third, the app refinement explains how the app structure and functions were defined based on what participants indicated they need in order to measure confidently and feel supported between consultations.

3.2.3.1 Device Refinement

During user observations with Concept A, participants held the device in multiple ways, but these variations still fell within the three anticipated grip types. Some grips appeared less frequently, which may have been influenced by the device geometry and the absence of clear cues. To address this, the refined design introduces more explicit grip guidance through subtle shape features, such as small indentations and surface cues, helping users settle into stable and repeatable hand positions without needing instruction.

In parallel, the overall device geometry was further refined during detailed CAD development. Once the concept was modeled in SolidWorks, the shape was optimized to improve ergonomics, clarify hand placement, and ensure smoother transitions between surfaces. This digital refinement also supported better control over dimensions and tolerances, creating a more consistent and manufacturable form while preserving the intended user interactions observed during testing.

A second refinement topic concerned the stiffness of the top portion of the handle. Users reported that it felt too rigid to hold comfortably, and it created resistance when users wanted to adjust how many fingers they placed inside the handle. For the final prototype, a flexible material solution was introduced for this area, allowing the grip to adapt to different hand sizes and preferences while reducing perceived effort during handling

3.2.3.2 Placement Refinement

With the three selected placement concepts, the refinement focused on combining their strengths into a single placement approach. To support this decision, a Harris profile (figure 58) was used to compare the concepts across key usability criteria, using a four-point scale for each of the following: consistency of use within the setup routine, speed of learning correct placement, one hand usability, and visibility of placement errors. The wearable template performed strongest on learnability and one hand usability, while the signal meter performed best for making errors visible. The app based options also aligned well with routine fit, since they can be integrated directly into the new recording flow. Although the app guideline scored lowest overall, it was retained because it still adds practical reassurance and reduces uncertainty during placement.

The physical template remains available as a fully usable option on its own, allowing users to position the device without depending on technology during setup. The app is still needed to run the recording flow, but the template reduces the need to rely on digital guidance for every placement action. At the same time, the app can add an extra layer of reassurance for users who want it. The refined flow includes an in app placement guideline and a signal meter during placement. This supports confidence, reduces uncertainty, and can make the overall experience feel calmer and more enjoyable, especially for users who worry about whether they are recording correctly.

For the physical template, multiple prototype iterations were completed to improve alignment and reduce common placement errors.

Neck opening: A large neckline was introduced so users can put the template on by simply sliding it over the head, avoiding closures that can be difficult for elderly users or people with reduced mobility.

Material stiffness: The large neckline created deformation that caused misalignment of the placement holes, which led to the need for stiffer material in the back section of the neckline.

Rigid collarbone reference: A rigid, straight element aligned parallel to the collarbones was added to prevent bending and preserve the intended geometry when the template rests on the body.

Orientation cue: To reduce the risk of users wearing the template backwards, the word “sternum” was added with a perpendicular line relative to the collarbone reference, creating a clear front facing cue that supports correct orientation without requiring conscious effort.

Alignment cues: Two arrows pointing up and down were added so users can align the template with the vertical midline of the body, providing a quick visual reference for centering.

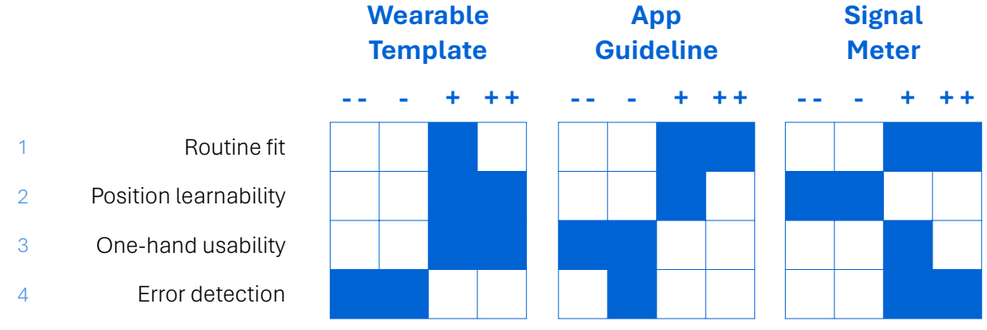


Figure 58. Harris Profile evaluation.

3.2.3.3 App Refinement

The app was developed based on participant needs captured in the questionnaire, with emphasis on clarity, reassurance, and easy access to past information. The refined app is organized into four sections.

Home: The landing page shows a summary of the most recent recording and provides a clear entry point to start a new recording.

New recording: This flow guides the user through connecting the device, placing it correctly, and recording the cardiac rhythm. After the measurement, users can optionally log symptoms they experienced, linking subjective experience to the recorded session.

Past recordings: A history view shows when measurements were taken, what results were recorded, and which symptoms were logged. This supports patient sensemaking and gives reassurance that information is stored and available for later review

Insights: Educational content and resources help users understand their condition, interpret what they might be feeling, and find guidance during moments of uncertainty, reducing reliance on memory or ad hoc searching.

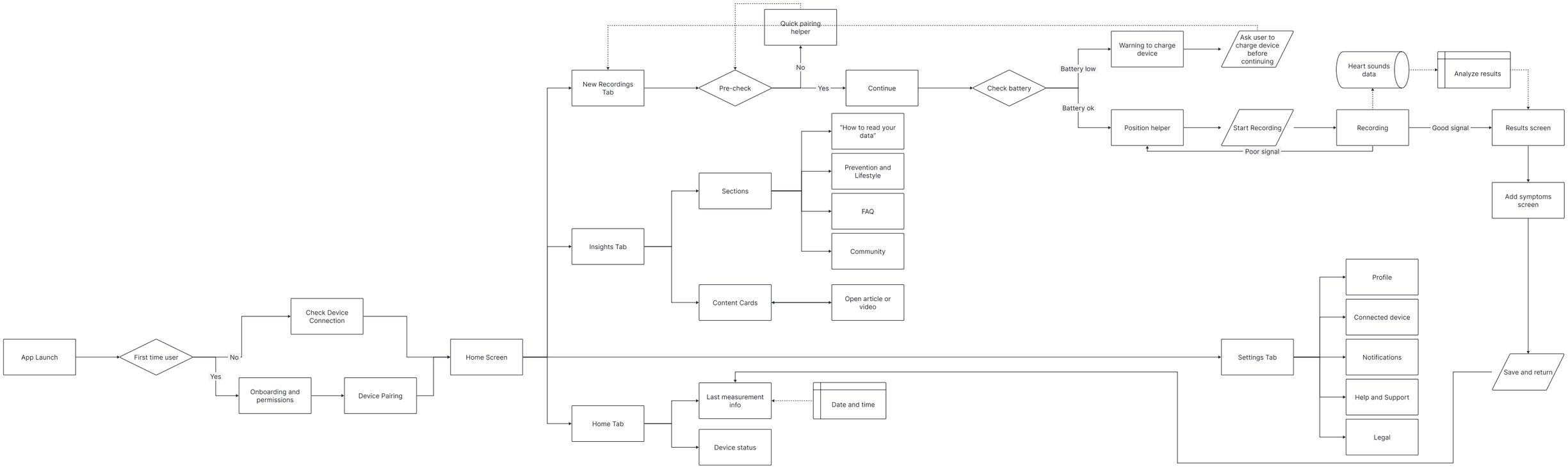


Figure 59. App flow.

3.3 Prototyping and Usability Validation

After further refinements through clay modeling and early stage CAD work, a full scale, 1:1 prototype was produced for user testing.

The full-size prototype was manufactured using 3D printed TPU and included the core physical features needed for realistic handling and placement. It was a looks-like prototype and did not contain any electrical components. While it provided an initial impression of form and size, its main purpose was to evaluate structural stability, comfort, and ergonomics. Most importantly, it enabled realistic user testing in conditions that closely matched intended use.

Two user tests were conducted to evaluate the current prototype in a realistic use scenario. The first focused on whether the physical template supports correct positioning and feels intuitive. The second assessed the ergonomics of the full measurement procedure, including the template, device handling, and app guided flow.

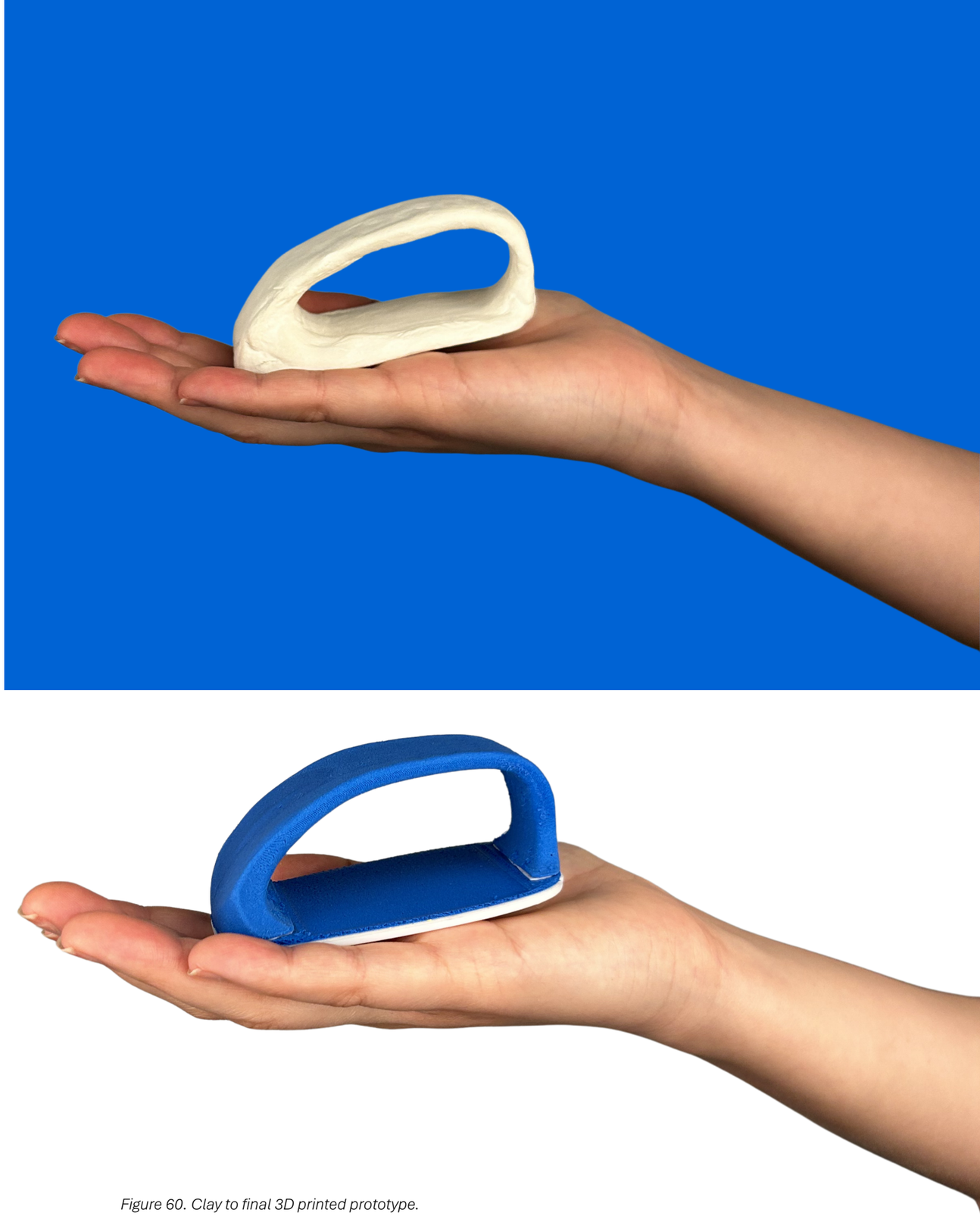


Figure 60. Clay to final 3D printed prototype.

3.3.1 Placement Validation

Aim

To evaluate whether the placement guideline template guides users to appropriate recording locations for the aortic and mitral regions, and whether first time users can achieve these placements without prior instruction.

Methods

Participants

Five participants took part, three women and two men, with ages 24, 56, and 86 for the women, and 22 and 57 for the men. A variety of body types was intentionally included to observe how the template naturally settles across different chests.

Procedure

Participants first put on the template. They then received the device with a blue sticker attached to its bottom surface. Without receiving any instruction, participants placed the device where they believed it should be positioned for the aortic region. They repeated the same process for the mitral region.

The blue sticker transferred to their clothing and marked their chosen placements. After both placements were completed, white reference stickers were placed on the chest to indicate the intended focus points for the aortic and mitral regions. This enabled a comparison between the user selected placement and the intended reference point.

Data collection

Data consisted of the spatial deviation between each user placed blue sticker mark and the corresponding white reference sticker for both anatomical regions. Observational notes were also used to capture general placement behavior during first time use.

Results

Overall, participants placed the device close to the reference points for both the aortic and mitral regions. Some placements overlapped directly with the reference stickers, while the largest observed deviation was 2.1 cm.

As seen in figure 61, aortic placements showed deviations from 0.0 to 1.7 cm, with a mean deviation of 0.46 cm and a median of 0.2 cm. Mitral placements showed deviations from 0.4 to 2.1 cm, with a mean deviation of 1.04 cm and a median of 0.9 cm. All participants placed the device quickly, with each placement taking under 15 seconds.

Participant	Aortic deviation (cm)	Mitral deviation (cm)
P1	0.0	1.3
P2	0.4	0.4
P3	1.7	2.1
P4	0.0	0.5
P5	0.2	0.9

Table 6. Deviation placement results. The number shown is how far the center of the device was placed in relation to the aortic and mitral valve respectively.

Participants consistently understood the mapping between template openings and targets, selecting the top opening for the aortic region and the left opening for the mitral region without instruction.

This level of variation is not necessarily negative, since heart sounds can radiate and users may naturally search for a clearer acoustic window rather than aiming for one exact point. The results support the inclusion of an in-app signal meter to help users fine tune placement to the strongest recording location, and to increase confidence when the first attempt is close but not optimal.

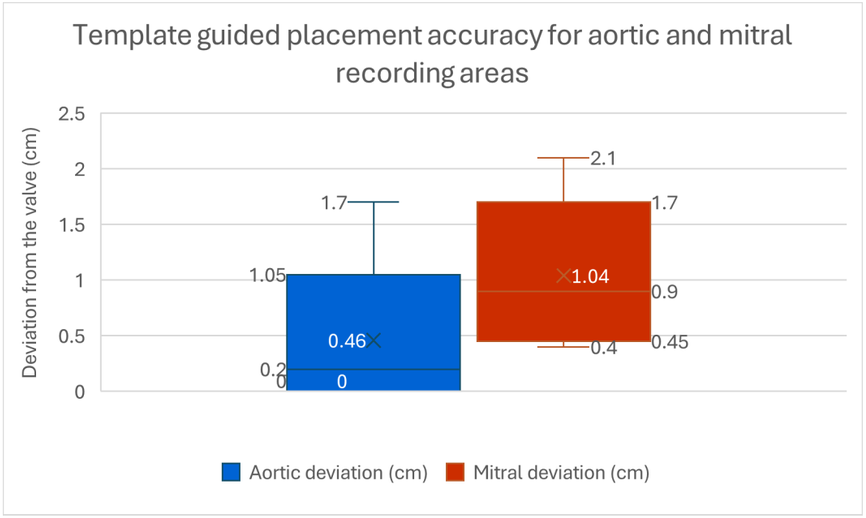


Figure 61. Box plots showing the absolute deviation between participant selected device placement and the reference points for the aortic and mitral recording regions. Boxes indicate the interquartile range, the center line indicates the median, and whiskers indicate the minimum and maximum values. Individual participant values are overlaid, n equals 5. All placements were completed without instruction and in under 15 seconds per region. Deviation is reported in centimeters.

Conclusion

In a first time, no instruction scenario, the placement guideline template enabled users to locate recording positions that were consistently close to the intended aortic and mitral focus points, with deviations ranging from direct overlap to 2 cm. These findings indicate that the template can provide intuitive guidance for initial placement, while also motivating a supportive feedback feature, such as an in-app signal meter, to refine positioning and reinforce user confidence.

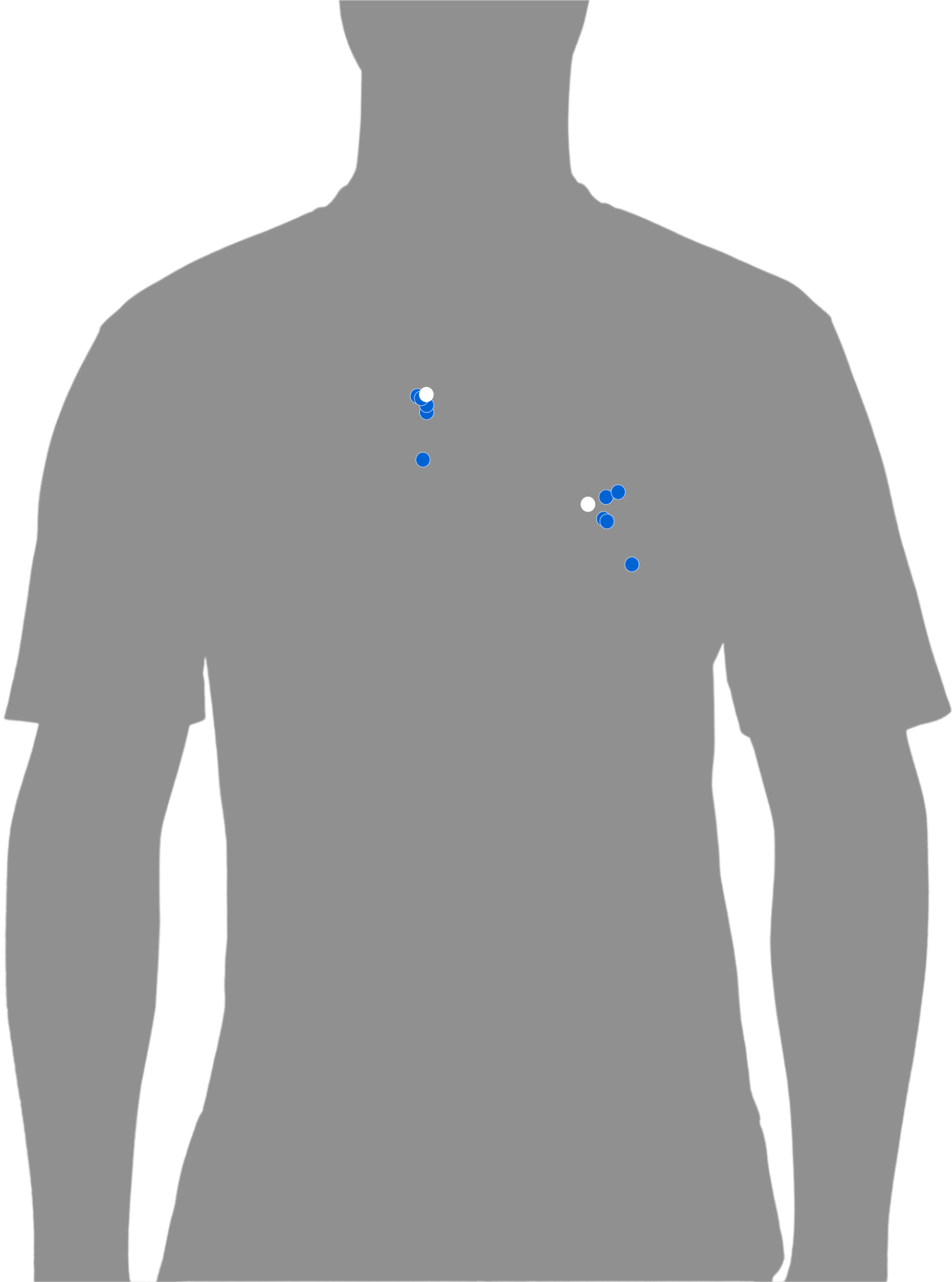


Figure 62. Photos placement validation. Participants with the white placement marks (aortic or mitral valve) and the blue placement (where the device was put).

To the right, the placements from all participants in relation to the respective valve is illustrated.

3.3.2 Ergonomics test for the full procedure

Aim

This formative user test evaluated the ergonomics and usability of the full measurement procedure, including the positioning template, handheld device handling, and the app guided flow. The objective was to identify breakdowns that affect correct placement, stable recording, and user confidence, and to translate these findings into concrete iteration requirements for the device, template, and interface.

Because the measurement procedure combines physical actions on the body with instruction following and interpretation of feedback, results were analyzed through two complementary lenses. Physical ergonomics focused on hand fit, posture, stability, and template fit on the body. Cognitive ergonomics focused on the user's understanding of the procedure, instruction clarity, attention switching, and decision making within the system flow.

Methods

A qualitative, task-based usability study was conducted with direct observation and a think aloud protocol. Participants were instructed to verbalize what they believed the next step was, what they expected the system to do, and what they were uncertain about while performing the procedure. This approach supports early-stage evaluation of learnability, mismatched mental models, and error recovery behavior.

The Wizard of Oz method was used because the app prototype was not functional and the signal quality meter was external. System responses and signal feedback were simulated by the facilitator at predefined moments in the flow, allowing evaluation of the guided experience while keeping the interaction realistic.

Participants

The study was made up from 3 participants (2 male, 1 female) from different age groups (24, 36 and 47). In which they were explained they will have to hold and position the device independently and read and interpret the screen guidance shown on the app.

Procedure

Participants were briefed on the aim of the study. They were then instructed to use the method of think-out loud during the full procedure. Each participant was handed the device, the template, and a phone showing the app screens. No procedural instruction was given beyond, "Please perform a measurement as you believe it should be done." This design choice was made to reveal what is discoverable without training and where the system fails to communicate next actions.

Participants then attempted to complete the full measurement procedure, including template placement, device placement, holding the device during the recording interval, and responding to app prompts. The researcher only intervened when the simulation required a system response or when the participant became blocked, had a question and could not progress.

After task completion, participants completed a short questionnaire and a semi structured interview focusing on comfort, confusion points, perceived effort, and confidence in having performed the measurement correctly.

Data collection

Data was collected through observation, timing, and brief self-report measures.

Data observed by the researcher was:

- Behavioral measures.
- Task completion, partial completion, and points of abandonment.
- Step level errors, including incorrect sequencing, missed actions, and incorrect placement attempts.
- Physical handling observations.
- Grip changes and hand repositioning.
- Template fit issues, including shifting, misalignment, or discomfort.

Data reported by the participants was:

- Self-reported comments.
- Perceived physical effort and fatigue.
- Perceived mental effort and confusion.
- Comfort with holding and placing the device.
- Confidence that the placement and recording were correct.

Results

The collected data was separated into two categories: physical ergonomics and cognitive ergonomics. Within each category, issues were grouped into recurring themes and mapped to the step in the procedure where they occurred. For each theme, the analysis recorded frequency across participants, impact on task completion, and the likely source component, template cues, or app guidance. The output of the analysis was a prioritized list of iteration requirements that can be addressed in subsequent prototypes.

3.3.2.1 Physical ergonomics evaluation

Physical ergonomics assessed the fit between the user's body and the physical artifacts used in the procedure, focusing on the hand, arm, and chest placement interactions. The intent was to determine whether the device and template can be used comfortably and stably, across a realistic range of users, without excessive force, awkward postures, or repeated adjustments.

Across all participants, the template supported placement by acting as a physical anchor and reducing large positioning errors. Clear acceptance feedback increased confidence consistently, and it reduced repeated checking behavior after a successful recording. Device handling was physically feasible for a short recording window, since participants could maintain contact long enough to complete a recording, even though stability was affected by phone interaction.

A primary physical finding was reduced stability during placement and holding when participants interacted with the phone. Even small head and arm movements associated with reading the screen led to contact changes and repositions. A second finding involved the template, where shifting or uncertain alignment increased repositioning. In most cases, the template itself was tolerable, but physical uncertainty about alignment triggered repeated handling and reduced overall smoothness.

3.3.2.2 Cognitive ergonomics evaluation

Cognitive ergonomics assessed how users understand and execute the procedure using the combined cues from the app, the device, and the template. The focus was on clarity of instructions, decision making, interpretation of feedback, and the mental effort required to complete the procedure independently.

A first recurring finding was uncertainty about what to do first and in what order. Participants were not sure whether the procedure should begin in the app, with the template, or with the device, which created early hesitation and increased later rework. A second finding was that poor signal feedback was not sufficiently action guiding. When the simulated system indicated low signal quality, participants understood that change was needed, but they could not reliably decide what to adjust first, such as location, pressure, or angle. A third finding concerned result interpretation, especially an inconclusive outcome, where participants wanted plain meaning plus one clear next action. Finally, attention management was a recurring theme, since frequent checking of the phone increased mental effort and contributed to uncertainty about whether the placement was correct.

Physical finding	Frequency	Severity	Design implication
Stability decreases when checking the phone	3 of 3	High	Minimize phone interaction during holding, support a single stable posture during recording
Template shifting or uncertain alignment increases retries	3 of 3	Medium	Strengthen physical landmark cues, improve template friction or fit, add an alignment check before device placement

Table 7. Summary of physical ergonomics findings and design implications

Cognitive finding	Frequency	Severity	Design implication
First action and order not clear	2 of 3	Medium	Add a single start screen that states the order before any physical action
Inconclusive outcome unclear	2 of 3	Medium	Define meaning in plain language and give one clear next action
High attention switching demand	3 of 3	High	Reduce on screen checking during placement and holding, use a simplified hold screen, consider optional nonvisual cues later
Users seek explicit acceptance confirmation	3 of 3	Medium	Preserve clear acceptance language and make success criteria explicit

Table 8. Summary of cognitive ergonomics findings and design implications

3.3.2.3 Conclusion Physcial & Ergonomics Evaluation

Overall, the results support feasibility of the template guided handheld procedure, since all participants completed the flow and reached an accepted recording under simulation. Elements to preserve include the template as an anchor and explicit acceptance feedback. Key improvements should focus on reducing attention switching during placement and holding, making signal feedback immediately actionable, and clarifying the meaning and next steps for inconclusive results. Future work should validate these changes with a larger sample, include repeat sessions to evaluate learning and consistency, and repeat the study with functional sensing to confirm whether the same breakdowns remain without simulated feedback.

3.3.3 Validation Outcomes

Overall, the tests indicate that the template provides a solid first step for initial placement, while the app should carry the responsibility of guiding the user through a clear sequence and supporting fine tuning. The most direct improvements suggested by these sessions are integrating the signal meter into the app as an actionable placement checkpoint, strengthening the step sequence with explicit confirmations, adding simple posture cues and time expectations at the right moment, and designing a clear completion screen that communicates success and the next action.

Beyond the digital flow, the sessions also highlighted several takeaways for the physical device. Users were generally able to understand how the device should be oriented on the chest, but they benefited from clear physical cues that remove ambiguity, for example a distinct top bottom orientation, and subtle tactile features for finger placement. During placement and recording, participants naturally experimented with grip and hand position, which suggests the housing should actively support stable holding through gentle grip surfaces or finger rests, so users can maintain contact without needing excessive force. It was mention that the device promotes consistent pressure through its form and contact surface, reducing the need for the user to guess how firmly to press. Finally, holding the device against the chest for the duration of a recording was physically easy, as there were no awkward wrist angles and the grip did not feel unstable.

04 FINAL DESIGN

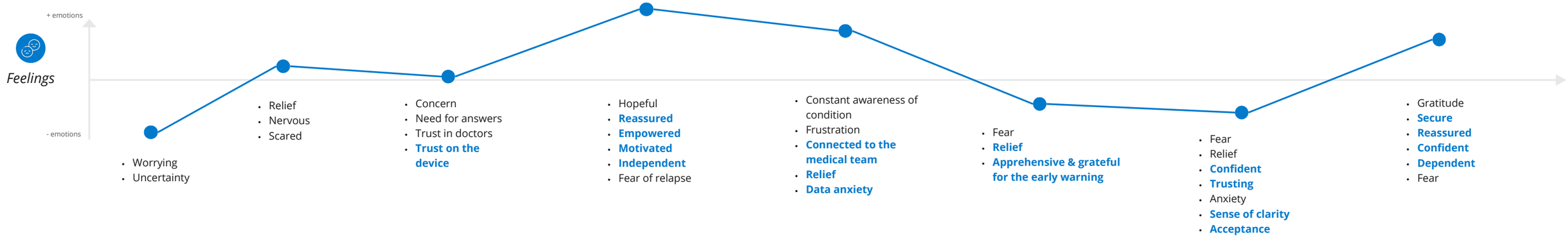
4.1 System Design

The system is designed as a connected home monitoring workflow that links a handheld acoustic device with a patient facing mobile app, within a wider care setting that includes the cardiologist, the clinical team, and the patient. The system is prescribed right after diagnosis for patients with degenerative valve disease in the aortic or mitral area, including aortic stenosis, aortic regurgitation, mitral stenosis, and mitral regurgitation. The goal is to support reassurance between appointments and enable earlier awareness of possible disease progression through repeatable, personalized heart sound measurements.

Users benefits throughout their patient journey with the use of LYRA as seen in the user journey map in the following page.

Journey phases	Initial Symptoms/ Awareness	First Medical Contact	Initial Assessment + Diagnosis	Treatment & Lifestyle Changes	Monitoring & Progression	Worsening of Vascular Lesion	Decision for Surgery	Operation & Recovery
	*LYRA does not replace diagnosis, it enhances monitoring, treatment adherence, and decision-making after diagnosis.							
Actions	• Chest Discomfort • Shortness of breath • Fatigue • ...	• Books medical appointment with GP	• Auscultation & basic tests • Referred to cardiologist • Cardiologist finds valvular lesion	• Start medication • Diet & exercise adjustments • **Use of LYRA to track heart sounds**	• Yearly check-ups • Echocardiograms	• **LYRA alerts of possible worsening of lesion**	• Meets with surgeon • Review risks & benefits • Prepares for surgery	• Undergoes surgery • Hospital recovery • Rehabilitation • **LYRA continues monitoring for complications or recurrence**
Context & Touchpoints	• Self observation • Family observations • Research online	• Calling the GP • Getting an appointment	• Cardiologist consultation • Diagnostic tests • **LYRA**	• Pharmacy • Nutritionist • Follow-up visits • **LYRA**	• Revision visits • Imaging tests • Lab tests • **LYRA**	• Emergency room • Hospitalization • Echocardiogram • **LYRA**	• Hospital team • Surgeon • Family	• Surgical team • ICU staff • Rehabilitation programs • **LYRA**
Gains	• Patient becomes more attentive to their health	• Reassurance that symptoms are being taken seriously	• Clarity about condition • Access to treatment options • Sense of control through knowledge • **Cardiologist prescribes LYRA for at home monitoring.**	• Empowerment from actively managing health • Improved daily wellbeing (if treatment works) • **Real-time feedback on condition** • **Reinforcement of treatment adherence** • **Certainty due to the feedback from LYRA** • **Reduced anxiety thanks to objective data**	• Reassurance from check-ups • See results from the healthy living habits • **Doctor has richer information between visits** • **More precise decisions about adjusting medication** • **No more unnecessary visits**	• **Early detection of deterioration** • **Prevention of sudden crises** • Access to advanced testing and specialist care • **More time to plan treatment options** • **Objective evidence of lesion progression**	• **Greater confidence for both patient and doctor** • **Better planning of surgery (less emergency context, more elective)** • Access to potentially life-saving treatment • Hope for long-term recovery	• Relief from surgery • Potential elimination of symptoms • Opportunity for improved quality of life • **Safer recovery** • **Peace of mind for patient and family**
Pains	• Ignoring symptoms • Anxiety • Fear • Denial	• Waiting times • Difficulty getting appointment	• Overload of medical terminology • Costs • Scheduling delays	• Adherence • Side-effects • **Technical barriers with LYRA**	• Emotional fatigue • Financial burden • Time burden • Uncertainty • **False positives which lead to hospital visits** • **Reliability issues** • **Mistrust in LYRA**	• Anxiety • Disruption of daily life • Dependence on doctors • **Anxious of LYRA signaling worsening before symptoms appear** • **Dependency to device**	• Surgical risks • Recovery time • Possible complications	• Pain • Limited mobility • Dependence • Long rehabilitation • **Fear of LYRA failure** • **Increased dependency**

Feelings



4.1.1 The Device

The LYRA device is a handheld acoustic sensor intended for home use. Its primary function is to capture cardiac sounds at a clinician specified auscultation site, either the aortic area or the mitral area, depending on the patient's diagnosis. For example, a patient with aortic stenosis records at the aortic area only.

The device captures the acoustic signal during a short recording session using its microphone. The signal is conditioned and digitized on the internal electronics, then transmitted to the mobile app via Bluetooth for processing and interpretation. Recordings are stored in the app, creating a consistent history over time. The Bluetooth connection follows a standard pairing flow, and the system is designed so that only the user's phone can access the device's recordings.

The device is powered by an internal rechargeable battery. It is recharged through a cable, similar to a phone, which is a familiar interaction for most users and reduces the learning effort around maintenance. The exterior is designed to tolerate routine wipe down cleaning to support hygienic reuse.

To support consistent recordings, the device is used in direct contact with bare skin, which improves acoustic coupling and reduces variability introduced by clothing. During a session, the patient sits down, relaxes, and records for 15 seconds. Based on the usability validation test, total session duration ranged from about 2 to 7 minutes, mainly driven by how quickly the user understood the procedure. With repeated use, setup time is expected to decrease. The system is designed for repeated recordings over time, with analysis and feedback delivered through the app, which is the primary element for reassurance and uncertainty management.

4.1.2 The App - Patient Focused

The mobile app is the primary interface of the LYRA system that clearly tackles the design vision of “giving people an accessible way to understand their heart sounds and track their condition, to help them feel more confident and informed in their daily lives.” Its main function is to inform the user in a way that reduces uncertainty and anxiety between clinical appointments.

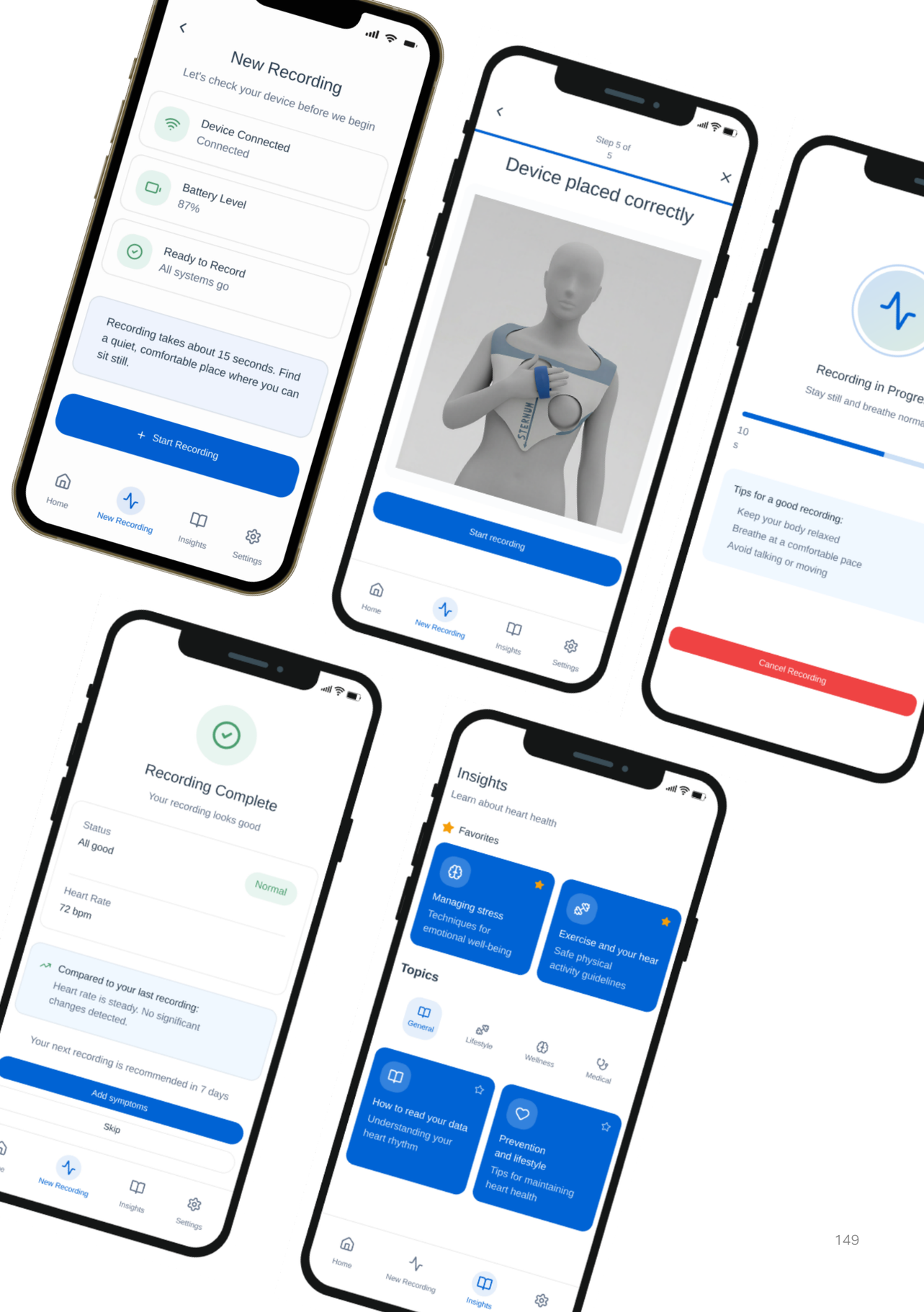
The app coordinates the patient workflow from onboarding to recording, symptom capture, and review of previous sessions. During onboarding, the user enters basic profile information, including age, sex, and diagnosed valve disease type. Sex is used only to present body guidance visuals that match the user, supporting inclusive and clear instruction content.

The recording flow is designed to be short, repeatable, and low effort. The user opens the app, confirms the Bluetooth connection, follows placement guidance, and starts a 15 second recording. During recording, the app shows a timer indicating time remaining. The system provides feedback after data collection and analysis (the exact waiting period should be defined in future work once the algorithm and processing pipeline are implemented). This approach supports a calmer experience and reduces the chance that users heart beat and sounds will fluctuate due to high stress and therefore ceate data that is not clinically meaningful.

After the recording, the app confirms whether measurement quality is sufficient. If quality is sufficient, the user is prompted to log symptoms, if any were experienced. The app also provides a historical view so users can review past recordings and symptom entries over time. An additional information screen explains the diagnosed condition in clear terms, helping users understand what the system is tracking and why.

In the intended future implementation, personalization is enabled through a user baseline built from the first three recordings collected over a period of weeks at home. Once a baseline exists, new recordings are compared against the user’s baseline by assessing S1 and S2 characteristics, timing features, and the presence of additional sounds consistent with murmurs. If a recording differs strongly from baseline, the app requests a repeat recording later the same day or the next day to reduce the influence of temporary factors. If concern persists, the app escalates gradually through confirmation recordings before advising the user to contact the care team, reducing false alarms and unnecessary anxiety.

Outcomes are communicated using a caring, reassuring, and direct tone. The concept includes three results. First, “good result,” meaning no meaningful change relative to baseline. Second, “inconclusive result,” meaning the recording cannot be interpreted and the user is asked to redo it. Third, “please contact a clinician,” reserved for cases where progression is detected and confirmed through repeated recordings. Users can also choose whether they want to listen to their recordings in the app, supporting different preferences for transparency.



4.1.2.1 Code

This codebase was developed as an initial foundation that can be extended in future work. Its primary purpose is to enable reliable signal capture and clear visualization so that cardiac sound recordings can be inspected and validated at an early stage. In particular, the goal was to confirm that the recording setup and sensing approach can capture heart sound information in a measurable way, and to provide a practical workflow for viewing recordings, saving them, and running a basic processing pipeline. As such, the current implementation focuses on accessibility and traceability rather than clinical interpretation, and it is intended to support iterative development toward more advanced analysis and validation.

It can be found in appendix G.

Recording and visualization

The recording script implements a simple desktop interface to capture cardiac sound data through a sound card input. It streams a single channel at a fixed sample rate, stores all incoming samples in an internal buffer, and updates a scrolling plot so the user can monitor the last several seconds in real time. Basic controls allow the user to start and stop the stream, clear the current recording, and save the complete captured signal to disk as a FLAC file for later analysis.

PCG processing

The processing code takes a recorded PCG signal and runs a consistent pipeline to extract features and generate quality checks. The signal can be down sampled to reduce file size and computation, then a raw waveform plot is saved for reference. A saturation check is performed to identify recordings that may be clipped or dominated by large artifacts. The signal is then bandpass filtered, and heart rate is estimated from the filtered data using an FFT based approach. Next, an envelope-based method is used to detect and suppress outliers, so brief disturbances have less impact on later steps, and simple signal level metrics are estimated from envelope extrema.

To identify cardiac events, the code detects S1 and S2 peaks using separate frequency bands and a threshold based peak detector. Using the detected peak indices, it calculates timing intervals between S1 and S2 and between S2 and the next S1 and summarizes these intervals using mean and median values. Finally, it builds an S1 aligned ensemble to support visual comparison across beats, and exports both diagnostic plots and a CSV file with the computed figures of merit.

Future works on the code can be found in chapter 6.2.

4.1.2.2 Clinician Interface

A dedicated clinician interface was not designed in this project, because the focus and scope were centered on the patient experience at home, especially reducing uncertainty between appointments through clear guidance, consistent recordings, and understandable feedback in the app. Clinician needs were still captured through interviews and background research, and they inform a set of requirements for future work.

Future work for a clinician interface should prioritize the following:

1. Patient overview and triage
   A dashboard that shows a clinician's patient list with clear status indicators, recent recording dates, adherence patterns, and any cases flagged for review.

2. Longitudinal review
   Access to a time ordered history of recordings and symptom logs, with trend views and the ability to compare new measurements to the user baseline.

3. Data transparency and interpretability
   Summarized report from the recordings to lower clinician work load.

4. Alerts and escalation logic
   Configurable thresholds and alert routing so that notifications fit existing workflows, minimizing alert fatigue while still catching meaningful changes.

5. Integration and interoperability
   A pathway for secure export and integration with hospital systems, ideally using established interoperability approaches, so LYRA supports clinical documentation rather than creating parallel work.

4.1.3 Positioning Guideline

Consistent placement is supported through two complementary guidance modes, a physical positioning template and an app guided placement flow. Users can rely on either method on its own, or combine both, depending on preference and confidence.

Physical Template

The physical positioning template is a lightweight silicone guide that is worn by slipping it over the head, so it rests on the upper chest. It aligns to the body through simple visual cues, including straight alignment lines that help the user center the template on the sternum. Small integrated weights help it hang in a stable position, reducing shifting during setup. The template includes two cutouts, one aligned to the aortic area, and one aligned to the mitral area. The user places the handheld device into the cutout associated with the clinician prescribed recording site, which supports repeatability across sessions and reduces placement related measurement variability.

Digital Positioning Guides

The app-based placement guide provides sequential instructions that mirror the logic of the physical template and helps users understand where and how to place the device, even when the template is not used. The app also addresses factors that influence repeatability beyond location, including posture and breathing. Before the recording starts, users are guided to sit comfortably, relax, and follow brief breathing instructions to reduce motion and sound artifacts, supporting more consistent measurements.

As an additional reassurance feature, the concept includes a pre recording signal meter that guides the user toward the strongest signal region before starting the 15 second measurement. This element is currently theoretical and would require future work to verify technical feasibility and to define how reliably the algorithm can compute and present a stable signal quality indicator in real time.

4.2 Producibility Evaluation

This section evaluates producibility by assessing whether the proposed design can be manufactured, assembled, cleaned, and scaled with consistent quality and reasonable effort. For this device, producibility is mainly shaped by four factors: material behavior at the patient contact and grip interfaces, process capability to achieve repeatable geometry and tolerances that support reliable sensing, cleanability and durability under repeated disinfection cycles, and a manufacturing and assembly strategy that can transition from rapid iteration in early batches to later on high-volume production. The evaluation therefore focuses on material selection, manufacturing strategy and scalability, cost drivers, and practical assembly and service access, since these aspects most directly influence feasibility, safety, and long-term adoption.

4.2.1 Material

Device body and handle, TPU

The device housing is produced in thermoplastic polyurethane, selected for its durability, comfort in hand, and suitability for rapid prototyping. A temperature sensitive TPU grade was used so different tactile zones can be achieved within the same part. In material extrusion printing, process temperature influences how well adjacent roads and layers fuse, which affects the final mechanical behavior of the printed part. This makes it possible to produce a softer, higher grip handle area, while keeping the region that supports the chest interface stiffer and more stable.

Chemical resistance guidance for TPU indicates that ethyl alcohol at 50 to 98 percent is rated excellent at 21°C and good at 66°C (Buitink Technology, 2016), which supports ethanol based wipe disinfection for routine cleaning of the printed parts. This rating is provided as a general selection guide, so the final design should still be validated through repeated cleaning cycles. In practice, how many disinfection cycles the TPU can tolerate with acceptable changes in surface feel, hardness, discoloration, tackiness, or mechanical performance, while also confirming that cleaning remains effective over time (Luchini et al., 2021).

Chest contact plate, stainless steel

The surface that contacts the chest is a stainless-steel plate. Stainless steel is widely used in medical applications because it combines corrosion resistance with established biocompatibility for many device contexts, and it tolerates repeated cleaning and disinfection cycles without rapid degradation (Barmouz et al., 2025).

This choice also separates the patient contact surface from the printed polymer body, which supports consistent cleaning behavior over time and simplifies inspection of wear at the main hygiene critical interface.

Placement template, silicone with rigid reinforcement

The placement template is primarily silicone. Silicone was selected because it can flex for easy donning and conform to different bodies, while still retaining enough shape to preserve the reference geometry needed for repeatable placement. It also aligns with the tactile expectation of many clinical accessories and supports routine wipe cleaning. Chemical resistance charts for silicone show strong compatibility with isopropyl alcohol and generally good compatibility with aqueous sodium hypochlorite solutions, which supports common disinfection routines (ASTM International, n.d.).

Some regions of the template require added stiffness to prevent deformation and to maintain alignment. In the prototype, metal elements were used to provide this rigidity. In a later design, this reinforcement can be implemented as an embedded insert, using a material that meets stiffness requirements while remaining compatible with the same cleaning approach used for the silicone body.

4.2.2 Manufacturing Strategy and Scalability plan

For early production batches below 1000 units, TPU 3D printing is the most suitable approach. At this stage, volumes are low and the priority is learning from real use rather than minimizing unit cost. Printing removes the need for upfront tooling, supports fast iteration, and enables limited personalization because each unit is produced individually. This makes it practical to offer a small set of size or fit variants and to adjust ergonomics, housing geometry, or interface details in response to clinician and patient feedback without restarting a tooling process.

Once demand grows and the design stabilizes, injection molding becomes the preferred route. Tooling is justified by higher repeatability, faster throughput, and a much lower cost per unit at scale, alongside better control over tolerances, surface finish, and mechanical performance. This is especially important for a device where the rigid base must deliver consistent pressure against the body and where electronics must be protected inside a stable enclosure. A scalable architecture is a molded rigid structural base that defines the sensing interface and protects the electronics, combined with a soft overmolded grip region for comfort in hand. This translates the two-hardness requirement into material defined production, reduces assembly steps, and improves durability and cleanability compared with small batch methods.

4.2.3 Cost Analysis

Cost estimates (table 9) were built from a component level breakdown that separates purchased parts from custom manufactured parts. Purchased parts, mainly the electronics, were estimated using market research and typical low volume supplier pricing. Custom parts were estimated from the manufacturing approach and the CAD and slicer outputs, so the calculations remain traceable and easy to update as the design and suppliers evolve.

For the first batch, the housing is treated as a custom manufactured part produced through 3D printing in TPU. The TPU material usage per unit was taken directly from the slicer output in grams, then converted into euros using the known spool price and spool mass to derive a cost per gram. The stainless steel plate is treated as a separate purchased insert and added as its own line item.

Labor is estimated from measured process time per unit, including post processing, meaning support removal, cleaning, sanding, and assembly time for installing electronics and soldering. This time is multiplied by an assumed Netherlands hourly rate and added to the piece cost total. Testing and calibration are not included at this stage, but should be added later as the device moves toward more controlled use.

For larger batches, the cost methodology shifts to injection molding. Tooling is treated as a fixed upfront investment that is amortized across the production volume to derive a per unit tooling cost. Variable cost is then estimated from molded material consumption and machine time based on cycle time. Electronics and the stainless steel plate remain line items added to the molded housing cost. This scale up model reflects why injection molding becomes economically favorable at higher volumes, since the per unit cost decreases as the tooling investment is spread across more units and the process becomes more repeatable than additive manufacturing.

In Chapter 5.3.1, it will be shown how these costs can be earned back, and how the benefits received through insurance can more than fully cover the first batch build expenses.

Part	***Value***	***Notes***
Device, 3D printed unit		
TPU per unit	42.48 g	From slicer output
TPU spool	700 g for 45 €	Material price basis
TPU cost per unit	2.73 €	42.48 × (45 ÷ 700)
Electronics per unit	37.00 €	All electronic components (prices are assumed)
Stainless steel plate per unit	0.50 €	13 mm diameter, 0.08 mm thick (price is assumed)
Device piece cost per unit	40.23 €	TPU plus electronics plus plate
Including labor:		
Device labor time per unit	4.0 h	1.0 h post processing, 3.0 h assembly with soldering
Device labor cost per unit	80.00 €	4.0 × 20
Device total per unit, with labor	120.23 €	40.23 + 80.00
Placement guideline template, silicone cast		
Silicone per template	10 g to 15 g	Assumed range
Silicone price	40 € per kg	Material price basis (price is assumed)
Silicone cost per template	0.60 €	Based on 10 g to 15 g (price is assumed)
Rigid insert per template	1.00 €	Estimate for laser cut polycarbonate insert
Casting consumables per template	0.20 €	Gloves, cups, release, trimming supplies, placeholder
Template piece cost per unit	1.80 €	Silicone plus insert plus consumables
Including labor:		
Template labor time per unit	1.5 h	Cleanup and trimming estimate
Template labor cost per unit	30.00 €	1.5 × 20
Template total per unit, with labor	31.80 €	Piece cost plus labor
Full kit total, device plus template		
Kit piece cost per unit, no labor	42.03 €	Device plus template
Kit total per unit, with labor	**152.03 €**	Device plus template
Kit piece cost total, 100 units, no labor	4,203.09 €	Range × 100
Kit total, 100 units, with labor	15,203.09 €	Range × 100

Table 9. Etimated unit cost for a small batch (100 devices) produced using additive manufacturing (3D printing). Manufacturing and assembly are assumed to take place in the Netherlands, and the estimate includes both direct component costs and, where stated, associated labor for post processing and assembly.

4.2.4 Assembly

In the small batch phase, electronics integration is best handled through a defined internal cavity and a dedicated access strategy, so components can be installed after printing and serviced during development. This keeps assembly practical while the electronics package, internal layout, and sealing approach are still evolving, and it avoids the added risk and inflexibility of encapsulating electronics inside a print, which limits repair and makes changes more costly.

Two physical prototypes were developed with distinct validation goals. The works-like prototype was used as the functional platform for early electronics integration and assembly exploration. The looks-like prototype was intentionally non-functional and contains no electronics, because its role was to validate external form, ergonomics, and interaction qualities without being constrained by a finalized electronics stack.

Even though the looks-like device was not populated, its handle was explicitly designed to house the needed electronics. Three dedicated volumes were incorporated to match the expected system layout. A cavity behind the chest interface was reserved for the acoustic pickup chain, accommodating the microphone and its analog front end amplifier close to the sensing surface to minimize signal path length and reduce routing complexity. In addition, the two cavities formed at the start of the handle on each side were designed as electronics bays for the main PCB assembly, including the microcontroller and Bluetooth connectivity, plus the rechargeable battery. A defined charging route was also incorporated so the battery can be charged via a cabled connection, and a power button location was planned to reflect the intended user interaction and to ensure the external form supports that control without compromising grip comfort.

To support fit confidence at the design stage, they were dimensioned in CAD using product dimensions for the expected board, battery, and interconnects.

05 EVALUATION

5.1 Desirability

5.1.1 Patient Desirability

Patients described a clear unmet need, the difficulty of living with a condition that cannot be directly observed:

“Having a heart issue is difficult cause we can not see what is going on inside of us, so I feel like this would be helpful and reassuring.”

In the same direction, participants emphasized uncertainty when interpreting symptoms, for example, “I never know if it is a normal symptom tied to my defect or an actual emergency, and that causes me so much anxiety.” These experiences align closely with the intended experience of LYRA, which is framed around reducing uncertainty and offering reassurance between clinical visits.

The desirability of the final product is also supported by the way patients described the benefit in simple, outcome based terms. Several quotes point to reassurance and reduced rumination, including, “Peace of mind if nothing is wrong, I am constantly worrying that I am missing symptoms.” and “Still more checks in between, a bit more certainty.” Importantly, desirability was not expressed as constant measurement, but as the ability to respond when doubt appears, as reflected in, “If you feel a bit off, that you can check this.” The product concept supports this situational use, by enabling quick recordings at home while preserving a structured flow that helps the user feel confident that the measurement was completed correctly.

In addition, questionnaire findings strengthen the plausibility of sustained use. Many respondents already use monitoring tools such as smartwatches and blood pressure monitors. This pattern suggests that the target group has a preexisting willingness to track health metrics and integrate device use into routines, which increases the likelihood of adherence for a system positioned as reassurance-oriented progression monitoring.

Finally, patient desirability depends on whether the system increases confidence rather than anxiety. The final product messaging and interaction goals are aligned with this requirement. In practice, this direction is reinforced by the design choice to combine a physical placement aid with app guidance, so the user can move from uncertainty to a clear completion state, rather than repeating recordings due to doubt.

5.1.2 Clinician Desirability

Clinician desirability is driven by whether home recordings can be trusted and whether the resulting information supports clinical decisions without increasing workload. The final product directly addresses these requirements through standardization of placement and a guided recording sequence that promotes repeatability across sessions. This aligns with the refinement learning that the template supports initial placement while the app should guide the sequence and fine tuning, supporting consistent use and reducing measurement variability.

Clinicians also benefit from role clarity and controlled responsibility. The system concept has been framed with clinician led protocols, which supports acceptability and reduces medico legal ambiguity, as expressed previously: “the demand will be said by the cardiologist, its up to the user to use it as it is explained or more if they need extra reassurance.” This structure makes the system desirable for clinicians because it keeps decision making and escalation thresholds within established care pathways, while still giving patients a tool for reassurance.

From a workflow perspective, desirability increases when the system reduces unnecessary contact and supports earlier recognition of change. The final product intent emphasizes tracking progression over time and enabling earlier detection of deterioration, which fits common follow up needs in valvular disease management. When recordings are comparable over time and the experience is simple enough to sustain, the output becomes more likely to support triage and follow up planning, rather than producing isolated, hard to interpret snapshots.

5.1.3 Conclusion

Taken together, the evidence indicates that the final product is desirable to patients because it addresses uncertainty, anxiety, and the need for reassurance in moments of doubt, while remaining feasible for repeated use. It is desirable to clinicians because it aims for repeatable measurements, embeds clinician led protocols, and supports longitudinal assessment without shifting clinical responsibility to the patient. This overlap is important, because adoption depends on a shared belief that the system is both meaningful for the patient and credible for the clinician.

5.2 Feasibility

As stated earlier in Chapter 1.4 (Scope), it was not feasible within this project to collect longitudinal patient data to test feasibility over time. Repeated recordings per patient in realistic home conditions, linked to clinical reference outcomes, would require a clinical study and a longer timeframe than available.

Within that scope, the technological feasibility targeted in this project was to demonstrate that the proposed system can acquire cardiac sounds using the intended sensing approach and form factor, and that the resulting recordings can be captured, stored, and inspected through a functional software flow. This was demonstrated in the “works like” prototype. The system can capture cardiac sounds through the device, transfer recordings into the app, and complete the recording flow end to end. This confirms that the sensing approach, the hardware architecture, and the basic software pipeline are viable. It also indicates that the solution does not depend on speculative or immature technology to deliver its main function, namely, enabling at home cardiac sound recordings as an input for longitudinal monitoring.

The project demonstrated that the system can operate as an integrated solution. The device and app support a complete recording flow, from user action to a saved recording that can be reviewed, which reduces implementation risk and confirms that the concept can be realized as a usable system rather than a standalone sensor demonstration.

Furthermore, the project implemented a baseline processing and visualization pipeline to inspect recordings and evaluate whether the captured signals contain usable heart sound structure. This code was developed as a foundation for later work, and its purpose in this project was feasibility focused, namely to visualize signals, apply initial processing steps, and support early checks of recording quality and interpretability.

The remaining feasibility steps required for future development are addressed later in the report in Chapter 6.2.

5.2.1 Error Consequences for Patients and Clinicians

For LYRA, the preferred error mode is to minimize false positives, even if that increases the risk of false negatives. The main reason is that LYRA is designed as an addition to routine cardiology follow ups, rather than a replacement for clinical evaluation. Patients remain on a scheduled check up pathway, so the system’s role is to support monitoring between appointments, not to serve as the sole gatekeeper for detection.

Patient

From the patient perspective, false positives carry a high emotional and behavioral cost. A flagged result can trigger panic, repeated measurements, and unnecessary care seeking, even when the underlying condition is stable. If this happens more than once, users may lose confidence in the system and disengage, which reduces adherence and weakens the long term value of home monitoring. By contrast, a false negative may delay an earlier prompt to seek care, but it does not typically create the same immediate anxiety response, and it preserves trust in day to day use when most measurements are expected to be stable.

Care Team

From the clinician perspective, false positives translate directly into increased workload. Each alert can generate extra phone calls, triage effort, and confirmatory testing, much of which may be low yield. In interviews, cardiologists indicated that, if forced to choose, they would rather deal with false negatives than a system that produces frequent false alarms, because alarm burden can make remote monitoring impractical at scale. This reinforces a design stance that prioritizes specificity and actionability, so that alerts are rare enough to be taken seriously and managed within existing clinical capacity.

This choice does not mean false negatives are harmless. The risk is that a patient with subtle progression receives a stable result and postpones contact. The justification for accepting this risk rests on the care pathway context, since patients are still seen during planned check ups where progression can be detected with standard diagnostics. In addition, the system should be framed and implemented in a way that reduces the harm of missed detections. LYRA should avoid absolute reassurance language, it should emphasize symptom based escalation, and it should use decision gates that prevent low quality recordings from being interpreted as stable. In this way, the system can reduce unnecessary anxiety and clinician burden, while still supporting timely escalation when users report symptoms or when recordings meet quality criteria and show consistent change.

5.3 Viability

5.3.1 Business Model

The proposed solution addresses an unmet need in long term cardiac monitoring by enabling repeated, at home data collection that can be interpreted by clinicians and used longitudinally in routine follow-up. Within the European healthcare context, direct competition for this specific combination of home measurement, structured review, and clinical decision support remains relatively limited. However, adoption of new medical technologies is typically constrained by regulatory requirements, procurement cycles, and the practical realities of integrating new tools into established clinical workflows. These factors can slow diffusion even when technical feasibility is demonstrated.

To support implementation under these constraints, the business model is designed as a prescription led service rather than a consumer purchase. A cardiologist prescribes the system to eligible patients, the patient uses the device and app at home, and the care team reviews the stored recordings to inform follow up consultations and subsequent clinical decisions. This structure aligns with the Dutch telemonitoring framework, which defines telemonitoring as digital collection of patient data via a mobile device or care application combined with professional interpretation under clinical responsibility. It also positions the product as part of an ongoing care pathway, rather than a standalone device transaction, which improves affordability by removing the requirement for patients to buy the device (Regeling Medisch-specialistische Zorg 2026 - Nederlandse Zorgautoriteit, Article 26.5, n.d.).

The cost analysis in Chapter 4.2.3, provides an estimate of what it takes to produce and provide the system as part of care delivery. In the Dutch context, these costs can be positioned to be covered through insurer funded specialist care by registering telemonitoring as an add on activity (039133), which is declared within the medical specialist pathway. The regulation specifies that the ad one can be declared at most once per 120 days while the patient uses telemonitoring, provided its use is traceable in the medical record. The NZa states that telemonitoring has no contract requirement and lists a 2026 maximum tariff of 194.92 euros, which supports a recurring service model that can fund delivery activities rather than relying on a patient purchase (Hoe Registreren En Declareren We De Inzet Van Een Tool Die Zorg Op Afstand Monitort? | Nederlandse Zorgautoriteit, 2024).

This reimbursement led structure is expected to support uptake among both patients and cardiologists. For patients, it removes an upfront financial barrier and frames the system as part of standard care. For cardiologists, it lowers friction in recommending the solution because enrollment and follow up can be embedded in routine care and justified within an established reimbursement mechanism. At the same time, this model concentrates the adoption barrier at the payer level, since implementation at scale requires insurers to be convinced of clinical utility, operational reliability, and cost effectiveness. Building that confidence requires partnerships with clinicians and hospitals, clear documentation practices, and evidence that the service improves decision making while contributing to efficient use of care resources within the pathway.

The cost rationale is that the reimbursed telemonitoring service can fund the operational bundle behind the program, including provisioning, onboarding, software and data handling, and clinician review time, while aiming to reduce expensive acute utilization. Evidence from remote patient management in heart failure shows fewer days lost to unplanned cardiovascular hospital admissions and all cause death in a telemonitoring supported care pathway, which supports the general mechanism that structured monitoring plus clinician review can reduce unplanned care use (Koehler et al. (2018) & Scholte et al. (2023)).

Viability therefore depends on creating confidence across multiple stakeholders. Clinical uptake requires trust in data quality, interpretability, and workflow fit, while payer support requires evidence that the service can be delivered reliably and that it contributes to better resource use in care delivery. Building partnerships with healthcare professionals is central to this process, since clinical endorsement reduces implementation friction and strengthens the case for reimbursement. In parallel, framing the system as a sustainable service, including operationally realistic reuse and reprocessing strategies and a credible pathway to scale, can further support trust from insurers, hospitals, and potential funding partners.

5.3.2 Sustainability

Sustainability is framed as a reusable ecosystem, where circular design principles guide material selection, surface geometry, and assembly choices so the system can remain in use for longer, with fewer discarded components. This is increasingly relevant because health care waste has become a major concern, both for environmental impact and for safe handling and disposal, as highlighted by the World Health Organization (World Health Organization: WHO, 2024). European policy work on health care waste management similarly emphasizes moving toward lower waste generation and circular solutions, which reinforces the relevance of designing for reuse from the start (Sustainable Healthcare Waste Management in the EU Circular Economy Model | Circular Cities and Regions Initiative, n.d.).

At the product level, the device is intended to contact intact skin, which aligns with the noncritical equipment category in infection prevention guidance, where cleaning and low-level disinfection is generally appropriate rather than sterilization. The intended service model therefore depends on designing for reliable disinfection and providing validated reprocessing instructions for reuse, consistent with international expectations for manufacturer supplied processing information for noncritical devices (ISO 17664-2:2021, n.d.).. This supports a practical circular flow, where devices can be retrieved, disinfected, checked, and reassigned when appropriate.

Whether cross patient reuse is appropriate in practice should be treated as a defined follow up study for the final prototype. This should include validation of the cleaning and disinfection workflow, assessment of material degradation under repeated disinfection cycles, and alignment with hospital infection prevention protocols, since these factors determine whether retrieval and reassignment is feasible at scale (Recommendations for Disinfection and Sterilization in Healthcare Facilities, 2023).

Beyond materials and reprocessing, sustainability is also defined by system level effects on care delivery. By enabling structured monitoring and clinician review outside the hospital, the system has the potential to reduce avoidable workload tied to unplanned escalations and reactive follow up, while improving the efficiency of longitudinal decision making. If monitoring supports earlier recognition of deterioration and reduces unplanned admissions, patients are more likely to maintain daily functioning and participation, which has economic relevance beyond the hospital budget (Scholte et al., 2023).

Finally, the sustainability case extends to societal impact. Cardiovascular disease carries a large economic burden in the European Union, including productivity losses, and OECD reporting estimates total costs above EUR 282 billion (Oecd, 2025). In this context, keeping patients healthier for longer can support continued participation in daily life and work, which strengthens the value proposition for insurers and health systems, particularly when the solution is positioned as a scalable, reusable service integrated into routine specialist care.

06 DISCUSSION

6.1 Conclusion

This thesis developed LYRA, an at home cardiac sound monitoring system that integrates a handheld recording device, a physical placement template, and a companion app to support patients living with progressive cardiac conditions and the clinicians who monitor them. Although the initial goal focused on demonstrating that a personalized microphone could capture cardiac sounds and on designing a handheld device that enables users to perform recordings correctly, the target group was not fully defined at the outset. As the research progressed and the clinical and user context became clearer, it became evident that patients living with degenerative valvular heart disease could benefit substantially from repeated at home recordings, since longitudinal data can support the creation of an individual baseline and enable monitoring for meaningful change over time. This insight produced a clear shift in focus, moving the work from the development of a recording device in isolation toward the design of an integrated system that supports this population through guidance, interpretation, and escalation pathways that are safe, understandable, and feasible in everyday life and in clinical follow up.

The work also highlights that home monitoring must be positioned at the right point in the broader care pathway to produce meaningful benefit. Patients with progressive cardiac conditions often experience periods of ambiguity, in which symptoms can be difficult to interpret and reassurance is limited by time gaps between checkups. In parallel, clinicians face constraints in capacity and must balance workload with timely decision making. LYRA is positioned to address this gap by enabling repeatable recordings and structured context in the home environment, which can support more informed conversations and earlier review when change is suspected.

Finally, the project demonstrates that progress toward a credible monitoring system requires sustained collaboration with end users and stakeholders. The design direction and the usability findings were only achievable by prioritizing patient and clinician perspectives, translating them into concrete interaction requirements, and iterating through prototyping and testing. At the same time, the thesis reinforces that a device and an app alone cannot resolve all challenges in chronic care. Real impact requires an evidence driven approach that aligns technology, behavior, workflow, and governance. In this sense, LYRA represents a first step toward a reusable and scalable monitoring ecosystem that can be expanded through clinical validation, integration work, and a clear regulatory and data stewardship pathway.

6.2 Limitations & Future works

Limitations

This project was executed within a six-month graduation timeline, which shaped the level of evidence that could be generated and the maturity that could be reached (scope of the project mentioned in chapter 1.4). The work therefore focused on design feasibility and system integration, meaning the handheld device, the positioning guidance, and the app were developed as connected elements with consistent interaction logic and shared requirements. Within this boundary, the project could credibly translate user needs and clinical expectations into requirements, iterate form and interface choices through prototyping, and demonstrate that the proposed sensing setup can capture cardiac sound recordings in a controlled prototype context. The resulting outcome is a validated direction for an at home monitoring system concept.

The main limitation was the absence of longitudinal patient data. Degenerative valvular conditions progress over extended periods, and repeated measurements across months are needed to establish each user's baseline variability and to distinguish meaningful change from noise. Collecting such data was outside the project scope and infeasible within six months, particularly because it would require formal clinical study execution. As a result, the project could not validate long term monitoring performance, progression detection accuracy, or alert reliability. The work can demonstrate a plausible pathway toward those goals, but it cannot substantiate clinical claims about detecting deterioration over time.

A second limitation was the gap between controlled testing and real-world home use. At home recordings are affected by placement variation, contact pressure, posture, ambient noise, clothing, user anxiety, and differences in adherence over time. Even when the design reduces error through ergonomics and guidance, the system must be resilient to inevitable variability. Within the project, this variability could be anticipated and designed for, but it could not be quantified across diverse households and repeated sessions. This constrains the ability to specify definitive performance thresholds for signal quality, re-recording prompts, or escalation rules.

The last limitation relates to algorithmic maturity. The project could implement and demonstrate signal visualization and early processing to confirm that recordings contain cardiac sound content, and it could outline the logic required to compare new recordings to a baseline. However, a reliable change detection program requires extensive datasets spanning different anatomies, disease severities, sensor placement differences, and recording environments. Without longitudinal data and clinical labels, algorithm development remains at the stage of feasibility demonstration and architecture definition, rather than validated classification or decision support.

Future works

The recommendations that follow from these limitations center on how the project outcomes should be interpreted. The work supports claims about design feasibility, system coherence, and the plausibility of capturing cardiac sound recordings with the proposed device and guidance approach. It does not support claims about diagnostic accuracy, disease progression prediction, or safety critical decision making. The most defensible contribution is that the project reduces uncertainty in the design space, identifies critical requirements for correct placement and user reassurance, and establishes a prototype direction that can be carried forward into engineering development and clinical research.

Future work should proceed in coordinated technical, clinical, and implementation tracks. On the technical track, the priority is repeatability: defining a recording protocol, quantifying within user variability across sessions, and implementing objective signal quality metrics that determine whether a recording is usable before analysis. In parallel, user studies of the app intreface need to be developed. This would give clearer insights on the structure of the app and what it offers.

On the clinical track, an initial supervised pilot should compare recordings to a clinical reference, followed by a longitudinal study that is designed around the intended use, endpoints, and target population. This progression enables the system to move from feasibility toward evidence supported clinical utility.

Future work on the signal processing code should enable personalized longitudinal monitoring. The code should first build a curated baseline for each user by collecting multiple recordings and selecting only those that meet signal quality criteria. Each accepted recording should be processed to detect S1 and S2 reliably, then the acoustic content between S1 and S2 should be segmented and analyzed, since this interval is likely to contain murmur related information. Features from this segment should be stored per session, together with quality metadata. For new recordings, the same pipeline should run and compare the extracted S1 to S2 features against the user's baseline and prior sessions. If the between peak signature deviates beyond the user's normal range, and the change is consistent across repeat high-quality recordings, the code can flag a meaningful difference that may reflect progression.

6.3 Reflection

This project was exactly how I wanted to close the chapter of my MSc in Industrial Design Engineering. Getting the chance to design a medical device felt like the right moment to bring my ambitions into real practice. I started this thesis with a clear direction in mind: I wanted to work on a medical grade instrument that could genuinely support people living with heart conditions, while also challenging me to grow as an engineer and designer.

Methodologically, this project became a summary of what I have learned during my years in Delft. I used many design and engineering tools, but for me, the most important one is context mapping. Personally, it remains one of the strongest ways to understand what people live through, what they worry about, and what they actually need from a product. It forces you to step outside assumptions and listen with more care. It also keeps the project honest. If the goal is to create a solution that matters, then the work must start with real experiences, real pain points, and real routines.

That mindset carried into other methods I used, especially when translating insights into decisions. I worked with user journey thinking to make sure the device and app were not treated as isolated objects, but as part of a routine that has to make sense from start to finish. I also leaned on iterative prototyping as a decision tool. Building and testing early versions helped me uncover practical issues that no sketch or rendering can fully reveal.

One of the most meaningful parts of the process was learning how to handle tradeoffs without losing direction. I tend to want to include everything I know, every method, every idea, every improvement. In a long project, that instinct can become a burden. I learned that there is a point where more inputs do not automatically lead to a better outcome, they can overload decision making and slow momentum. A crucial lesson for me was learning when to step back, recognize what was already working, and commit to a path forward. That shift, from adding more to choosing better, is something I expect to carry into every future project.

Another skill I am proud of is consistency. Planning is easy to talk about, but following through day after day is the real challenge. I set a clear goal for myself to work in a steady, healthy rhythm. I wanted to avoid last minute panic, avoid exhausting late nights, and keep the project moving through regular progress rather than bursts of effort. Staying consistent made the work more sustainable, and it also made it more enjoyable. I had space to reflect, to iterate, and to improve with intention. I believe that rhythm improved the quality of my decisions and helped me stay connected to why I was building this in the first place.

At the start of the project I set goals that were both technical and personal. I wanted to grow in engineering ability, deepen my understanding of manufacturing and how products are made, and develop strong CAD work that communicates form and function clearly. I also wanted to validate a user-friendly concept through real input. I am proud to say I achieved these goals.

To close, this thesis has confirmed the kind of designer I want to become. I want to keep working in healthcare, keep designing for patients, and keep building systems that respect both human experience and clinical reality. I am proud of the outcome, but even more proud of the growth behind it. I feel ready to take what I learned here and apply it in my career, with the same focus on real needs, careful methods, and steady progress.

6.4 Acknowledgements

I would like to express my sincere gratitude to everyone who supported me throughout this thesis and helped bring this project to life.

I want to thank my supervisors at TU Delft, Wilfred van der Vegte and Richard Goossens, for their guidance and support. Wilfred, thank you for the time you invested throughout the process, and for the many conversations that helped me make sense of complex decisions. I am especially grateful for your support in developing the function tree, which shaped the decision making that followed. Richard, thank you for your input and direction, and for consistently bringing the discussion back to what matters in healthcare, the patient, early detection, and meaningful impact. You gave me room to explore, while also stepping in with clear feedback when it mattered most.

To Sonion for making this project happen, but specially to Ashesh Shah. My supervisor and colleague at Sonion, thank you for your guidance, support, and the many conversations that kept the project moving. I appreciated the quick check-ins, the small moments of eye contact between screens when I needed your point of view, and your calm way of helping me see the next step. I also want to thank Raymond, Joost, Camiel, and Mark for your technical expertise and for the time you dedicated to helping me solve problems and move forward. Thank you to Vijay for your patience and persistence through the many prototype iterations and 3D printing attempts.

I would also like to thank everyone who contributed directly to the research, including all participants who filled out the questionnaire and took part in the user tests. Thank you to the doctors and cardiologists who shared their time and insights, your perspectives were essential in grounding the work in real clinical needs.

Finally, I want to thank the people who supported me personally throughout this thesis. To my parents, my brother, and my whole family, thank you for your constant support and for helping with user testing when I needed it. And to Emiel, thank you for being there through every step, for your patience, and for supporting me all throughout this wonderful journey.

Bibliography

Aluru, J. S., Barsouk, A., Saginala, K., Rawla, P., & Barsouk, A. (2022). Valvular heart disease epidemiology. *Medical Sciences, 10*(2), 32. https://doi.org/10.3390/medsci10020032

American Heart Association. (2025, August 14). Monitoring your blood pressure at home. www.heart.org. https://www.heart.org/en/health-topics/high-blood-pressure/understanding-blood-pressure-readings/monitoring-your-blood-pressure-at-home

Andersen, T. O., Andersen, P. R. D., Kornum, A. C., & Larsen, T. M. (2017). Understanding patient experience. In Proceedings of the 11th EAI International Conference on Pervasive Computing Technologies for Healthcare (PervasiveHealth '17) (pp. 221–230*). Association for Computing Machinery*. https://doi.org/10.1145/3154862.3154868

Armstrong, G. P. (2025, June 16). *Aortic stenosis*. MSD Manual Professional Edition. https://www.msdmanuals.com/professional/cardiovascular-disorders/valvular-disorders/aortic-stenosis

ASTM International. (n.d.). *Silicone rubber Chemical Resistance Chart*. https://lk-flow.de/wp-content/uploads/Chemical-Resistance-Chart-Silicon.pdf

Bashshur, R. L., Shannon, G. W., Smith, B. R., Alverson, D. C., Antoniotti, N., Barsan, W. G., Bashshur, N., Brown, E. M., Coye, M. J., Doarn, C. R., Ferguson, S., Grigsby, J., Krupinski, E. A., Kvedar, J. C., Linkous, J., Merrell, R. C., Nesbitt, T., Poropatich, R., Rheuban, K. S., . . . Yellowlees, P. (2014). The Empirical Foundations of Telemedicine Interventions for Chronic Disease Management. *Telemedicine Journal and e-Health, 20*(9), 769–800. https://doi.org/10.1089/tmj.2014.9981

Barmouz, M., Steinhäuser, F., Azarhoushang, B., Bucher, V., & Sauer, D. (2025). Surface Finish-Dependent Stability of Stainless Steel under Long-Term Cleaning, Disinfection, and Sterilization Process: AISI 420 in Medical Applications. *Journal of Hospital Infection*. https://doi.org/10.1016/j.jhin.2025.11.046

Beerman, L. B. (2023, April 18). *Ventricular septal Defect (VSD)*. MSD Manual Professional Edition. https://www.msdmanuals.com/professional/pediatrics/congenital-cardiovascular-anomalies/ventricular-septal-defect-vsd

Bojinov, H., Michalevsky, Y., Nakibly, G., & Boneh, D. (2014). Mobile device identification via sensor fingerprinting. ResearchGate. https://www.researchgate.net/publication/264558809_Mobile_Device_Identification_via_Sensor_Fingerprinting

Brown, D. W., Giles, W. H., & Croft, J. B. (2009). Association of cardiac ausculatory findings with coronary heart disease mortality. *North American Journal of Medical Sciences, 1*(7), 332–337. https://doi.org/10.4297/najms.2009.7327

Brust, M., Gebhardt, W. A., Van Der Voorde, N. A., Numans, M. E., & Jong, J. C. K. (2022). The development and validation of scales to measure the presence of a teachable moment following a cardiovascular disease event. Preventive Medicine Reports, 28, 101876. https://doi.org/10.1016/j.pmedr.2022.101876

Buitink Technology. (2016). *TPU Chemical Resistance Manual*. https://www.buitink-technology.com/pdf/tpu-chemical-resistance.pdf

Causes of death. (2024, may). Our World in Data. https://ourworldindata.org/grapher/annual-number-of-deaths-by-cause

Chatterjee, D. (n.d.). *Mitral valve disease: clinical features focusing on auscultatory findings including auscultation of mitral valve prolapse*. https://www.escardio.org/Journals/E-Journal-of-Cardiology-Practice/Volume-16/Mitral-valve-disease-clinical-features-focusing-on-auscultatory-findings-including-auscultation-of-mitral-valve-prolapse

Chong, B., Jayabaskaran, J., Jauhari, S. M., Chan, S. P., Goh, R., Kueh, M. T. W., Li, H., Chin, Y. H., Kong, G., Anand, V. V., Wang, J., Muthiah, M., Jain, V., Mehta, A., Lim, S. L., Foo, R., Figtree, G. A., Nicholls, S. J., Mamas, M. A., Januzzi, J. L., Chew, N. W. S., Richards, A. M., & Chan, M. Y. (2024). Global burden of cardiovascular diseases: projections from 2025 to 2050. *European Journal Of Preventive Cardiology*. https://doi.org/10.1093/eurjpc/zwae281

Cleland, J. G., Louis, A. A., Rigby, A. S., Janssens, U., and Balk, A. H. (2005). Noninvasive Home Telemonitoring for Patients With Heart Failure at High Risk of Recurrent Admission and Death. *Journal of the American College of Cardiology, 45*(10), 1654 to 1664. https://doi.org/10.1016/j.jacc.2005.01.050

CoD viz. (z.d.). Institute For Health Metrics And Evaluation. https://vizhub.healthdata.org/cod/iung

Davidsen, A. H., Andersen, S., Halvorsen, P. A., Solis, J. C. A., Schirmer, H., & Melbye, H. (2025). Heart murmurs in the general population: Diagnostic value and prevalence from the Tromsø Study. *Heart*. https://doi.org/10.1136/heartjnl-2024-325499

Davies, S. W., Gershlick, A. H., & Balcon, R. (1991). Progression of valvar aortic stenosis: A long-term retrospective study. *European Heart Journal*, *12*(1), 10–14. https://doi.org/10.1093/oxfordjournals.eurheartj.a059815

Digitale zorg | RIVM. (n.d.). https://www.rivm.nl/digitalezorg

Delgado-Trejos, E., Quiceno-Manrique, A., Godino-Llorente, J., Blanco-Velasco, M., & Castellanos-Dominguez, G. (2008). Digital auscultation analysis for heart murmur detection. *Annals of Biomedical Engineering, 37*(2), 337–353. https://doi.org/10.1007/s10439-008-9611-z

D'Emilia, G., Gaspari, A., Natale, E., & Schiavi, A. (2018). Validated data mining technique: a case study on pressure-field digital MEMS microphone calibration. ResearchGate. https://www.researchgate.net/publication/327558602_Validated_data_mining_technique_a_case_study_on_pressure-field_digital_MEMS_microphone_calibration

DesJardin, J. T., Chikwe, J., Hahn, R. T., Hung, J. W., & Delling, F. N. (2022). Sex differences and similarities in valvular heart disease. *Circulation Research, 130*(4), 455–473. https://doi.org/10.1161/circresaha.121.319914

DEXON Systems Ltd. (2025, May 6). What is frequency response? why does it matter? | DEXON Systems. DEXON Systems- Visual Quality Innovation. https://dexonsystems.com/blog/frequency-response

Dr Raghu. (2023, October 6). Aortic valve stenosis symptoms and treatment in Hyderabad. *DrCRaghu*. https://drraghu.com/services/conditions/aortic-stenosis/

Edder, A., Ben-Bouazza, F.-E., Manchadi, O., Bigane, Y. A., Sangare, D., & Jioudi, B. (2025). A Deep Learning Framework for Early Detection of Potential Cardiac Anomalies via Murmur Pattern Analysis in Phonocardiograms. Engineering Proceedings, 112(1), 63. https://doi.org/10.3390/engproc2025112063

Eveborn, G. W., Schirmer, H., Heggelund, G., Lunde, P., & Rasmussen, K. (2012). The evolving epidemiology of valvular aortic stenosis: The Tromsø Study. *Heart, 99*(6), 396–400. https://doi.org/10.1136/heartjnl-2012-302265

Everett, R. J., Clavel, M., Pibarot, P., & Dweck, M. R. (2018). Timing of intervention in aortic stenosis: A review of current and future strategies. Heart, 104(24), 2067–2076. https://doi.org/10.1136/heartjnl-2017-312304

Faggiano, P., Ghizzoni, G., Sorgato, A., Sabatini, T., Simoncelli, U., Gardini, A., & Rusconi, C. (1992). Rate of progression of valvular aortic stenosis in adults. The American Journal of Cardiology, 70(2), 229–233. https://doi.org/10.1016/0002-9149(92)91280-h

Fueldner, M. (2020). Microphones. In Elsevier eBooks (pp. 937–948). https://doi.org/10.1016/b978-0-12-817786-0.00048-7

Ganguly, A., & Sharma, M. (2017). Detection of pathological heart murmurs by feature extraction of phonocardiogram signals. *Journal of Applied and Advanced Research*, 200–205. https://doi.org/10.21839/jaar.2017.v2i4.94

Goldbarg, S. H., Elmariah, S., Miller, M. A., & Fuster, V. (2007). Insights into degenerative aortic valve disease. Journal of the American College of Cardiology, 50(13), 1205–1213. https://doi.org/10.1016/j.jacc.2007.06.024

Haleem, A., Javaid, M., Singh, R. P., and Suman, R. (2021). Telemedicine for healthcare: Capabilities, features, barriers, and applications. *Sensors International, 2,* 100117. https://doi.org/10.1016/j.sintl.2021.100117

Hawkey, M., Lauck, S., & Straiton, N. (2021). Valvular heart disease. *In Processes of Care and Evaluation Pathway for Patients with Valvular Heart Disease.* https://doi.org/10.1007/978-3-030-86233-6

Henkel, J. (2023, March 23). Mental health after a cardiac event or procedure. Loma Linda University Health News. https://news.llu.edu/health-wellness/mental-health-after-cardiac-event-or-procedure

Henriksen, E., & Rosenqvist, U. (2003). Understanding cardiac follow-up services—A qualitative study of patients, healthcare professionals, and managers. European Journal of Cardiovascular Nursing, 2(2), 95–104. https://doi.org/10.1016/s1474-5151(03)00003-3

Higgins, R. O., Murphy, B. M., Nicholas, A., Worcester, M. U., & Lindner, H. (2007). Emotional and adjustment issues faced by cardiac patients seen in clinical practice. Journal of Cardiopulmonary Rehabilitation and Prevention, 27(5), 291–297. https://doi.org/10.1097/01.hcr.0000291296.62894.e5

Hirata, K., Arakaki, T., Tamashiro, M., & Kakazu, M. (2022). Absent pansystolic murmur in Eisenmenger ventricular septal defect. *European Heart Journal - Case Reports, 7*(1), ytad031. https://doi.org/10.1093/ehjcr/ytad031

Hoe registreren en declareren we de inzet van een tool die zorg op afstand monitort? | Nederlandse Zorgautoriteit. (2024, November 11). https://www.nza.nl/vraag-en-antwoord/medisch-specialistische-zorg/msrz-hoe-registreren-en-declareren-we-de-inzet-van-een-tool-die-zorg-op-afstand-monitort

Iung, B., & Vahanian, A. (2011). Epidemiology of valvular heart disease in the adult. Nature Reviews Cardiology, 8(3), 162–172. https://doi.org/10.1038/nrcardio.2010.202

Iung, B., & Vahanian, A. (2014). Epidemiology of acquired valvular heart disease. Canadian Journal of Cardiology, 30(9), 962–970. https://doi.org/10.1016/j.cjca.2014.03.022

ISO 17664-2:2021. (n.d.). ISO. https://www.iso.org/standard/74152.html

Ivarsson, B., Larsson, S., & Sjöberg, T. (2004). Patients' experiences of support while waiting for cardiac surgery: A critical incident technique analysis. European Journal of Cardiovascular Nursing, 3(2), 183–191. https://doi.org/10.1016/j.ejcnurse.2004.03.001

Jeong, Y., Kim, J., Kim, D., Kim, J., & Lee, K. (2021). Methods for improving deep learning-based cardiac auscultation accuracy: Data augmentation and data generalization. *Applied Sciences, 11*(10), 4544. https://doi.org/10.3390/app11104544

Kemp, M., Rising, K. L., Laynor, G., Miao, J., Worster, B., Chang, A. M., Monick, A. J., Guth, A., Camacho, T. E., McIntosh, K., Amadio, G., Shughart, L., Hsiao, T., & Leader, A. E. (2025). Barriers to telehealth uptake and use: a scoping review. *JAMIA Open, 8*(2), ooaf019. https://doi.org/10.1093/jamiaopen/ooaf019

Kien, U. N., De Geus, C., & LS&H Lawyers & Mediators. (2023). Telemedicine: A Global approach to Trends and Practices. *BA Healthcare and Life Sciences Law Committee Telemedicine Survey*. https://www.ibanet.org/document?id=Healthcare-Telemedicine-Survey-The-Netherlands

Kodali, S. K., Velagapudi, P., Hahn, R. T., Abbott, D., & Leon, M. B. (2018). Valvular heart disease in patients ≥80 years of age. Journal of the American College of Cardiology, 71(18), 2058–2072. https://doi.org/10.1016/j.jacc.2018.03.459

Koehler, F., Koehler, K., Deckwart, O., Prescher, S., Wegscheider, K., Kirwan, B., Winkler, S., Vettorazzi, E., Bruch, L., Oeff, M., Zugck, C., Doerr, G., Naegele, H., Störk, S., Butter, C., Sechtem, U., Angermann, C., Gola, G., Prondzinsky, R., . . . Stangl, K. (2018). Efficacy of telemedical interventional management in patients with heart failure (TIM-HF2): a randomised, controlled, parallel-group, unmasked trial. *The Lancet, 392*(10152), 1047–1057. https://doi.org/10.1016/s0140-6736(18)31880-4

Kulshreshtha, A., Kvedar, J. C., Goyal, A., Halpern, E. F., and Watson, A. J. (2010). Use of Remote Monitoring to Improve Outcomes in Patients with Heart Failure: A Pilot Trial. *International Journal of Telemedicine and Applications,* 2010, 1 to 7. https://doi.org/10.1155/2010/870959

Leening, M. J. G., Siregar, S., Vaartjes, I., Bots, M. L., Versteegh, M. I. M., Van Geuns, R. M., Koolen, J. J., & Deckers, J. W. (2013). Heart disease in the Netherlands: A quantitative update. *Netherlands Heart Journal, 22*(1), 3–10. https://doi.org/10.1007/s12471-013-0504-x

Luchini, K., Sloan, S. N. B., Mauro, R., Sargsyan, A., Newman, A., Persaud, P., Hawkins, D., Wolff, D., Staudinger, J., & Creamer, B. A. (2021). Sterilization and sanitizing of 3D-printed personal protective equipment using polypropylene and a Single Wall design. *3D Printing in Medicine, 7*(1), 16. https://doi.org/10.1186/s41205-021-00106-8

Maganti, K., Rigolin, V. H., Sarano, M. E., & Bonow, R. O. (2010). *Valvular heart disease: diagnosis and management. Mayo Clinic Proceedings, 85*(5), 483–500. https://doi.org/10.4065/mcp.2009.0706

Matthias, M. S., Salyers, M. P., & Frankel, R. M. (2013). Re-thinking shared decision-making: Context matters. *Patient Education and Counseling, 91*(2), 176–179. https://doi.org/10.1016/j.pec.2013.01.006

McGee, S. (2010). Etiology and diagnosis of systolic murmurs in adults. *The American Journal of Medicine, 123*(10), 913–921.e1. https://doi.org/10.1016/j.amjmed.2010.04.027

Mead, H., Andres, E., Ramos, C., Siegel, B., & Regenstein, M. (2009). Barriers to effective self-management in cardiac patients: The patient's experience. Patient Education and Counseling, 79(1), 69–76. https://doi.org/10.1016/j.pec.2009.08.003

Min, S., An, J., Lee, J. H., Kim, J. H., Joe, D. J., Eom, S. H., Yoo, C. D., Ahn, H., Hwang, J., Xu, S., Rogers, J. A., & Lee, K. J. (2025). Wearable blood pressure sensors for cardiovascular monitoring and machine learning algorithms for blood pressure estimation. Nature Reviews Cardiology, 22(9), 629–648. https://doi.org/10.1038/s41569-025-01127-0

Monitor digitale zorg. (n.d.). RIVM. https://www.rivm.nl/digitalezorg/monitor#:~:text=De%20Monitor%20Digitale%20Zorg%20volgt%20de%20ontwikkeling%20van,het%20gebruik%20en%20ervaringen%20van%20zorggebruikers%20en%20zorgverleners.

Mrsic, Z., Hopkins, S. P., Antevil, J. L., & Mullenix, P. S. (2018). Valvular heart disease. Primary Care: Clinics in Office Practice, 45(1), 81–94. https://doi.org/10.1016/j.pop.2017.10.002

Nivel. (2024). *Monitor Digitale Zorg 2024-2027 | Nivel*. https://www.nivel.nl/nl/project/monitor-digitale-zorg-2024-2027

Nivel. (2025). *Tien jaar monitoring van de digitale zorgtransitie: beschikbaarheid en gebruik van digitale zorg, 2024-2025 | Nivel*. https://www.nivel.nl/nl/project/tien-jaar-monitoring-van-de-digitale-zorgtransitie-beschikbaarheid-en-gebruik-van-digitale

Nurmohamed, S. A., Buskens, E., Van Eldik, N., Janssen, M., Kasteleyn, M., Kool, R., Lahr, M., & Snoeren, M. (2025). Four years upscaling telemonitoring to future-proof health care delivery in Dutch university hospitals: Before and after - where do we stand and what are the results? *Health Policy and Technology, 15*(1), 101132. https://doi.org/10.1016/j.hlpt.2025.101132

Oecd. (2025). The state of cardiovascular health in the European Union. In *OECD Publishing eBooks*. *https://doi.org/10.1787/ea7a15f4-en*

Onderzoek naar ervaringen met thuismonitoring. (2025, May 8). Patiëntenfederatie Nederland. https://www.patientenfederatie.nl/over-ons/onderzoeken/onderzoek-naar-ervaringen-met-thuismonitoring

Physiology, G. A. H. T. O. M. (2024, 17 mei). Heart Valves and Heart Sounds; Valvular and Congenital Heart Defects. *Clinical Tree.* https://clinicalpub.com/heart-valves-and-heart-sounds-valvular-and-congenital-heart-defects/

Recommendations for disinfection and sterilization in healthcare facilities. (2023, December 7). Infection Control. https://www.cdc.gov/infection-control/hcp/disinfection-sterilization/summary-recommendations.html

Regeling medisch-specialistische zorg 2026 - Nederlandse Zorgautoriteit. Article 26.5. (n.d.). https://puc.overheid.nl/nza/doc/PUC_806723_22/2/

Rostagno, C. (2019). Heart valve disease in elderly. World Journal of Cardiology, 11(2), 71–83. https://doi.org/10.4330/wjc.v11.i2.71

Roy, J. K., Roy, T. S., & Mukhopadhyay, S. C. (2018). Heart sound: Detection and analytical approach towards diseases. In *Smart sensors, measurement and instrumentation* (pp. 103–145). Springer. https://doi.org/10.1007/978-3-319-99540-3_7

Saeed, S., Ali, A. M., Wasim, D., Risnes, I., & Urheim, S. (2022). Correlation between Murmurs and Echocardiographic Findings; From an Imaging Cardiologist Point of View. *Current Problems in Cardiology, 48*(2), 101479. https://doi.org/10.1016/j.cpcardiol.2022.101479

Safara, F., & Ramaiah, A. R. A. (2020). RenyiBS: Renyi entropy basis selection from wavelet packet decomposition tree for phonocardiogram classification. *The Journal of Supercomputing, 77*(4), 3710–3726. https://doi.org/10.1007/s11227-020-03413-9

Scalia, I. G., Farina, J. M., Padang, R., Jokerst, C. E., Pereyra, M., Mahmoud, A. K., Naqvi, T. Z., Chao, C., Oh, J. K., Arsanjani, R., & Ayoub, C. (2023). Aortic valve calcium Score by Computed tomography as an adjunct to Echocardiographic Assessment—A review of clinical utility and applications. *Journal of Imaging*, *9*(11), 250. https://doi.org/10.3390/jimaging9110250

Scholte, N. T. B., Gürgöze, M. T., Aydin, D., Theuns, D. a. M. J., Manintveld, O. C., Ronner, E., Boersma, E., De Boer, R. A., Van Der Boon, R. M. A., & Brugts, J. J. (2023). Telemonitoring for heart failure: a meta-analysis. *European Heart Journal, 44*(31), 2911–2926. https://doi.org/10.1093/eurheartj/ehad280

Sengupta, P. P., Kluin, J., Lee, S., Oh, J. K., & Smits, A. I. P. M. (2024). The future of valvular heart disease assessment and therapy. *The Lancet*, *403*(10436), 1590–1602. https://doi.org/10.1016/s0140-6736(23)02754-x

Snoswell, C. L., Taylor, M. L., Comans, T. A., Smith, A. C., Gray, L. C., & Caffery, L. J. (2020). Determining if telehealth can reduce health system costs: Scoping review. *Journal of Medical Internet Research, 22*(10), e17298. https://doi.org/10.2196/17298

Susič, D., Poglajen, G., & Gradišek, A. (2022). Machine learning models for detection of decompensation in chronic heart failure using heart sounds. In *Ambient intelligence and smart environments*. IOS Press. https://doi.org/10.3233/aise220063

Sustainable healthcare waste management in the EU Circular Economy Model | Circular Cities and Regions Initiative. (n.d.). https://circular-cities-and-regions.ec.europa.eu/support-materials/papers-and-reports/sustainable-healthcare-waste-management-eu-circular-economy

Tavel, M. E. (1996). Cardiac auscultation. *Circulation, 93*(6), 1250–1253. https://doi.org/10.1161/01.cir.93.6.1250

Telemonitoring van volwassenen thuis | Inspectie Gezondheidszorg en Jeugd. (2022, March 10). Inspectie Gezondheidszorg En Jeugd. https://www.igj.nl/documenten/2022/03/10/telemonitoring-van-volwassenen-thuis

Themes, U. (2016, July 1). *Aortic stenosis.* Thoracic Key. https://thoracickey.com/aortic-stenosis-7/

Themes, U. (2016, November 3). Valvular heart disease. *Basicmedical Key*. https://basicmedicalkey.com/valvular-heart-disease-2/

Thomas, S. L., Heaton, J., & Makaryus, A. N. (2023, July 17). *Physiology, cardiovascular murmurs.* PubMed. https://pubmed.ncbi.nlm.nih.gov/30247833/

Thompson, W., Hayek, C., Tuchinda, C., Telford, J., & Lombardo, J. (2001). Automated cardiac auscultation for detection of pathologic heart murmurs. *Pediatric Cardiology, 22*(5), 373–379. https://doi.org/10.1007/s002460010253

Tokmaji, G., J, B., R, D., & De, B. A. (2013). Bicuspid aortic valve. In *InTech eBooks*. https://doi.org/10.5772/55325

Tolu-Akinnawo, O., Ezekwueme, F., & Awoyemi, T. (2024). Telemedicine in cardiology: Enhancing access to care and improving patient outcomes. *Cureus, 16*(6), e62852. https://doi.org/10.7759/cureus.62852

Trietley, H. (2022, December 2). Introduction to MEMS Microphone Technology—Analog vs Digital Microphones. *Technical Articles*. https://www.allaboutcircuits.com/technical-articles/introduction-to-microelectromechanical-systems-microphone-technology/

Vahanian, A., Alfieri, O., Andreotti, F., Antunes, M. J., Barón-Esquivias, G., Baumgartner, H., Borger, M. A., Carrel, T. P., De Bonis, M., Evangelista, A., Falk, V., Iung, B., Lancellotti, P., Pierard, L., Price, S., Schäfers, H., Schuler, G., Stepinska, J., Swedberg, K., . . . Walther, T. (2012). Guidelines on the management of valvular heart disease (version 2012). *European Heart Journal, 33*(19), 2451–2496. https://doi.org/10.1093/eurheartj/ehs109

Van Steenkiste, J., Verberk, I., Versmissen, J., Dohmen, D., & Jainandunsing, S. (2024). Home blood pressure telemonitoring in the Netherlands: a pilot study in GP practices. *BMC Digital Health, 2*(1). https://doi.org/10.1186/s44247-024-00072-1

Wingham, J., Dalal, H. M., Sweeney, K. G., & Evans, P. H. (2006). Listening to patients: Choice in cardiac rehabilitation. European Journal of Cardiovascular Nursing, 5(4), 289–294. https://doi.org/10.1016/j.ejcnurse.2006.02.002

World Health Organization: WHO. (2025, July 31). *Cardiovascular diseases (CVDs)*. https://www.who.int/news-room/fact-sheets/detail/cardiovascular-diseases-(cvds)

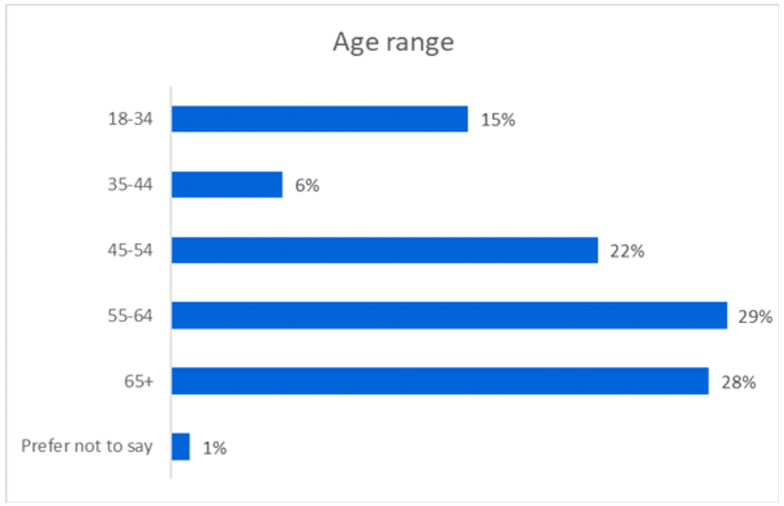
World Health Organization: WHO. (2024, October 24). *Health-care waste*. https://www.who.int/news-room/fact-sheets/detail/health-care-waste

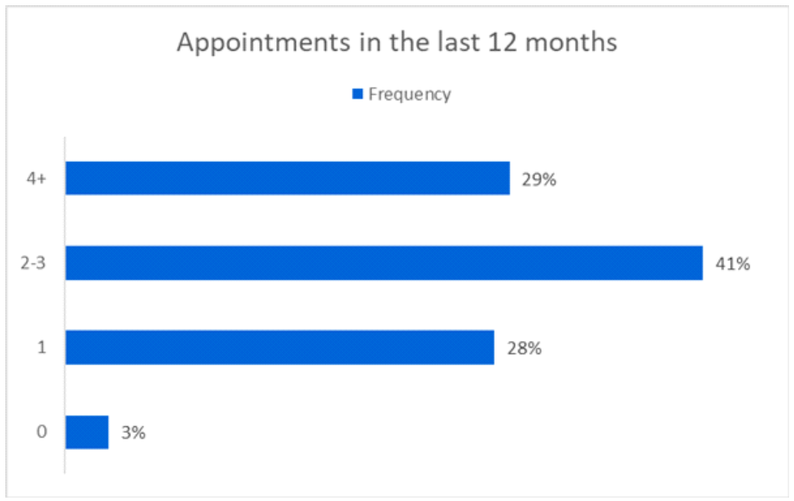
Zorg van Nu, Patientenfederatie, & Veldman, D. (2021). Toetsingskader IGJ Telemonitoring van volwassenen thuis. *In Toetsingskader IGJ*. https://www.igj.nl/binaries/igj/documenten/publicaties/2022/03/10/telemonitoring-van-volwassenen-thuis/Boekje+bij+Toetsingskader+IGJ+Telemonitoring.pdf

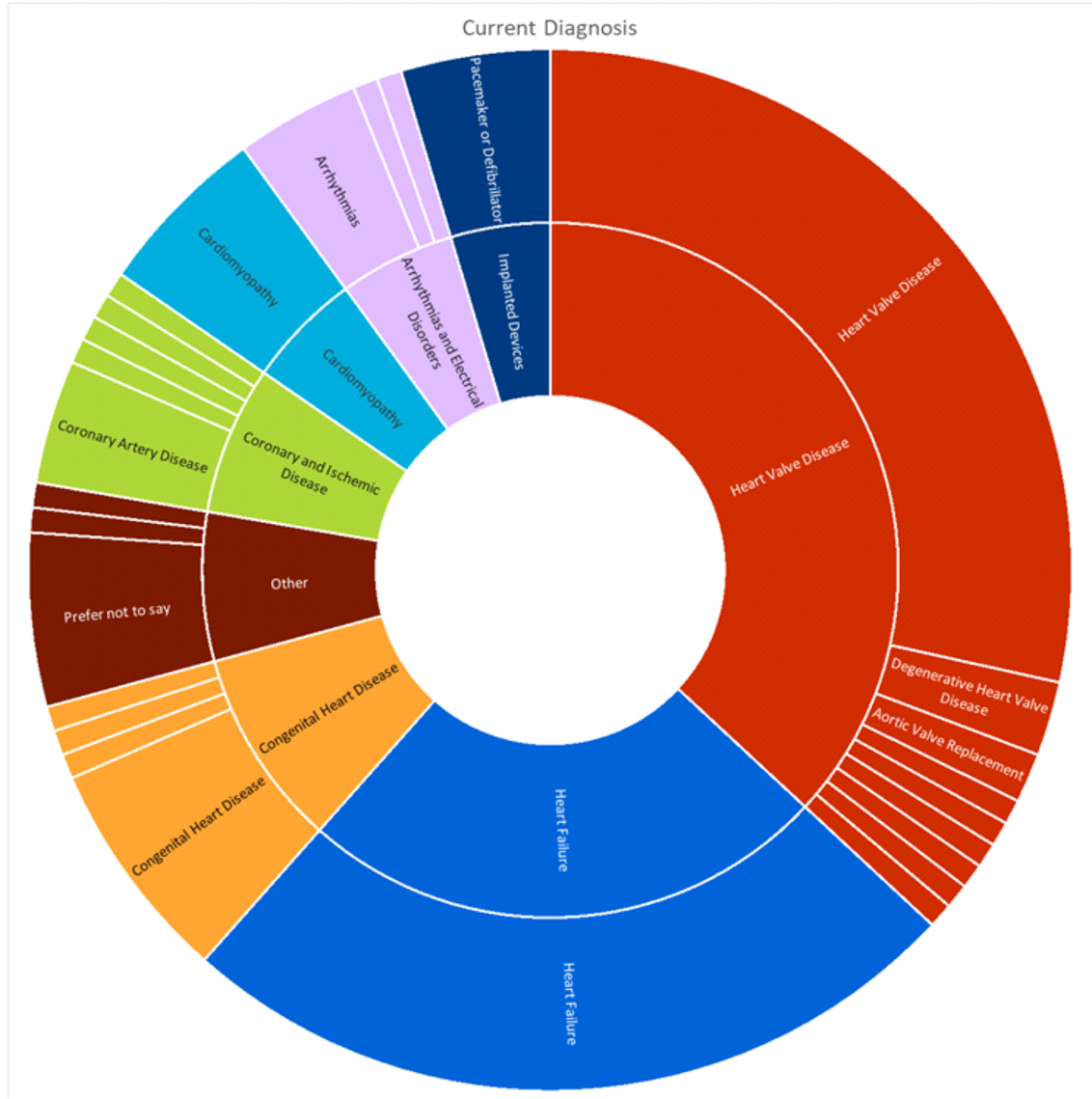
APPENDICES

Appendix A – Questionnaire Questions and Answers

Below are the questions that were not shown in the previous chapter of the questionnaire. It is demographic data.







Appendix B – Profile of Doctors Interviewed

Dutch Doctors:

Prof.dr. Douwe E. Atsma

Interventional Cardiologist at Leids Universitair Medisch Centrum (LUMC)

Dr. J. Atsma is a Professor of Cardiology at Leiden University Medical Center (LUMC) and Professor of eHealth at TU Delft. He serves as Chief Medical Information Officer for Digital Care Applications and eHealth at LUMC and sits on the boards of the National eHealth Living Lab and the Association of Arts and Lifestyle. His academic and clinical work bridges interventional cardiology, regenerative medicine, and digital innovation in cardiovascular care. After obtaining his PhD in 1996 on the biochemical mechanisms of heart cell death during ischemia, he specialized as a cardiologist and has since led pioneering research and clinical programs. At LUMC, he established the world's largest single-center cardiac cell therapy program for chronic heart disease, the Cardiogenetics outpatient clinic, and the Lifestyle Clinic. His current focus combines regenerative therapies with digital health solutions like The Box, integrating remote monitoring, artificial intelligence, and patient-centered eHealth systems to enhance cardiovascular treatment and quality of life.

Dr. Alexander. J. Wardeh

Cardiologist at Haaglanden Medical Center (H+MC)

Dr. Wardeh earned his PhD at Erasmus Medical Center/Thorax Center Rotterdam under the supervision of Professor P. W. Serruys, completed his cardiology residency at Radboud University Nijmegen Medical Centre, and carried out a fellowship in interventional cardiology at Leiden University Medical Center. He currently leads the Cardiology Research Department and focuses his clinical and academic efforts on acute coronary syndrome, heart attack care, hypertension, and renal artery denervation. His extensive publication record spans interventional cardiology, coronary disease, and the translation of research findings into clinical practice, reframing how patients with high-risk cardiovascular conditions are treated and monitored.

Spanish Doctors:

Dr. Paula Awamleh García

Cardiologist at Hospital Universitario de Getafe

Dr. Paula Awamleh García is a cardiologist at Hospital Universitario de Getafe and an expert in acute cardiac care. Throughout her career, she has authored multiple scientific papers published in peer-reviewed medical journals and has received numerous awards from leading professional societies for her research. She is co-author of the landmark population study "Prevalence of Electrocardiographic Patterns Associated with Sudden Death in the Spanish Population Aged 40 Years or Older," published in the Revista Española de Cardiología, the highest-impact Spanish-language journal in cardiovascular science. This was the first large-scale national study in Spain to analyze the prevalence and clinical factors linked to electrocardiographic patterns associated with sudden cardiac death, including Brugada syndrome and long- and short-QT syndromes. The work earned four major recognitions from the Spanish Society of Cardiology, highlighting Dr. Awamleh's role in advancing the understanding of cardiac arrhythmias and risk prediction in clinical cardiology.

Anonymous Doctor

Rural General Practitioner in Spain

The contribution of this participant was valuable due to his long-standing experience as a general practitioner in rural regions of Spain. In such settings, primary care physicians must possess broad and adaptable clinical expertise, as they often manage a wide range of conditions with limited resources and delayed access to specialist care. Rural Spain is characterized by an aging population with a high prevalence of chronic and degenerative diseases, including cardiovascular conditions. Over the course of his career, this physician encountered numerous patients presenting with symptoms related to heart disease and developed extensive practical knowledge in early detection, symptom management, and emergency response prior to hospital referral. His insights provided a grounded perspective on how telemonitoring solutions could support earlier intervention, improve continuity of care, and empower both patients and practitioners in resource-limited environments.

One doctor is not shown as she asked for full anonymity.

Appendix C – Table of types of degenerative valve diseases

Type	Frequency	Etiology	Symptoms		Severity	Prognosis	Other
Aortic stenosis (AS)	Most common degenerative valve disease in Europe	Progressive calcific thickening of valve leaflets, restricting left ventricular outflow	Exertional dyspnea, fatigue, angina, syncope (usually ages 50–70 with bicuspid valves, later with age-related calcification)		Murmur timing correlates better with severity than intensity	Once symptomatic, rapid deterioration; prompt intervention essential	TAVR preferred in elderly or high-risk patients, reduces perioperative mortality and improves recovery
Aortic regurgitation (AR)	1–5% of adults over 65, varies by region and method	Diastolic backflow into the left ventricle, causing progressive dilation and failure	Dyspnea, reduced exercise tolerance (often asymptomatic until late)		Murmur duration correlates better with severity than loudness	Poor if untreated; requires surgery before irreversible ventricular dysfunction	Follow-up every 6–12 months once severe; murmur is high-frequency, early diastolic, decrescendo, best heard leaning forward in end-expiration
Mitral regurgitation (MR)	Affects ~24 million people worldwide; MVP in 2–3% of population	Myxomatous degeneration and mitral valve prolapse	High-pitched holosystolic murmur radiating to axilla; midsystolic click in MVP		Severity varies; linked to degree of leaflet prolapse and regurgitant volume	Untreated symptomatic severe MR: ~30% 5-year survival; early repair improves outcomes	Early surgical or transcatheter repair recommended for best prognosis
Mitral Stenosis (MS)	Developed countries have an estimated incidence of 1 in 100,000. The prevalence is higher in developing nations. In Africa, for example, the prevalence is 35 cases per 100,000	Caused by the narrowing of the mitral valve orifice	shortness of breath, fatigue, swollen ankles/feet, heart palpitations, dizziness, and coughing, sometimes with blood		Loss of the loud S1 and diminishing murmur intensity may indicate disease progression with extensive valve calcification	Once symptoms become apparent, the progression of the disease generally accelerates, particularly when it is secondary to rheumatic fever. Approximately 80% of patients will not survive ten years from symptomatic onset	Once the diagnosis of mitral stenosis is made, the patient should be educated about the need for surgery. Those who remain asymptomatic will need annual exams, including echocardiograms. Patients with palpitations may require a Holter monitor to confirm the presence of atrial arrhythmias.
Tricuspid regurgitation (TR)	Moderate to severe in 1–3% of older adults	Often secondary to left-sided disease or pulmonary hypertension	Signs of right-sided heart failure		Mortality up to 40% at three years in some studies	Worsens if left untreated; management evolving with new interventions	Expected to increase with population ageing and more cardiac device implantation; preventive and transcatheter strategies under study

Appendix D – Table for Auscultatory characteristics of cardiac murmurs

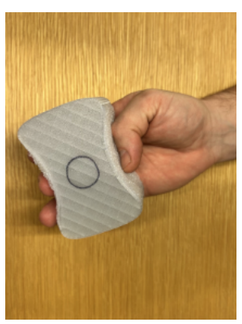
Condition	Mild	Moderate	Severe
Aortic Stenosis	Quiet, short “whooshing” sound during the heartbeat, often heard high on the chest.	Clearer and longer “whooshing” sound during the heartbeat, often heard into the neck.	Often long and late peaking during the heartbeat, but in very advanced cases with weak pumping it can actually get softer and shorter.
Aortic Regurgitation	Soft, brief “blowing” sound right after the heartbeat.	Same “blowing” sound after the heartbeat, usually easier to hear and lasts longer.	Often longer after the heartbeat, sometimes an extra low “rumble” can appear, and in acute severe cases it may be surprisingly soft or hard to hear.
Mitral Regurgitation	May be a faint “blowing” sound during the heartbeat, sometimes only at the end of the heartbeat.	Classic “blowing” sound through most or all of the heartbeat, usually best heard at the apex area.	Often very obvious, sometimes heard more widely, and an extra heart sound can appear, but loudness still does not consistently track severity across patients.
Mitral Stenosis	A “click” after the heartbeat, then a soft, low “rumble” after the heartbeat.	The “click” happens sooner after the heartbeat, and the low rumble tends to last longer.	The “click” can become softer or disappear if the valve is stiff from calcium, and the rumble may be long, but it can also become softer when less blood is flowing across the valve.

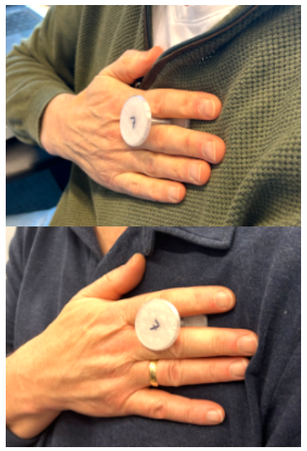
Appendix E – Morphological Chart

The function tree served as a foundational tool for developing the morphological chart, a crucial step in the design process. By systematically breaking down the primary functions and their associated sub-functions, the function tree provided a clear framework for identifying and exploring all possible solutions. These functional elements were then translated into a morphological chart, where each function was represented by various design alternatives. This method allowed for the visualization of the full spectrum of potential solutions for each aspect of the project, facilitating a more thorough exploration of design possibilities. Through the morphological chart, a key question emerged: whether the device would be best designed as a hand-held product or as a wearable, such as a sticky patch. By evaluating and comparing different combinations of solutions, it became possible to explore the advantages and challenges of both options, ensuring that no viable alternatives were overlooked. This structured approach ultimately enabled the selection of the most promising configurations, balancing innovation with feasibility in the development of the final design.

Morphological chart based on the function tree. Shown is different ideation sketches for all the functions and sub-functions previously defined.

Appendix F – Grip Test - Photos and grips from the participants





Appendix H - Current Code

This is for the Recording UI code:

```
# title: RecordingUI
# description: This python scripts creates a UI to record, plot and save data from a sound card.
#       Some parts of the script are taken from sounddevice documentation: https://python-sounddevice.readthedocs.io/en/0.4.4/examples.html#plot-microphone-signal-s-in-real-time
# date: 2025-11-30


import queue
import sounddevice as sd
import numpy as np
import soundfile as sf
import pyqtgraph as pg
from PySide6.QtCore import QTimer, QObject, Signal, Slot
from PySide6.QtWidgets import QWidget, QHBoxLayout, QPushButton, QLabel, QGridLayout, QFileDialog, QMessageBox, \
    QApplication

from pathlib import Path
from time import time
from src.SignalProcessor.DigitalFilters import ButterworthBandpass

MIN_WIDTH = 1200
MIN_HEIGHT = 800

class UpdatePlotCommunicator(QObject):
    """
    management.
    """
    update_plot = Signal(int, name="update_plot")


class SingleChannelAudioRecorder(QWidget):
    """
    This class represents a QWidget for recording audio from a sound card
    """
    def __init__(self, sample_rate: int, acquisition_duration_seconds: int=0):
        """

        Parameters
        ----------
        sample_rate: Integer number representing the sample rate for data acquisition
        acquisition_duration_seconds: Integer number of seconds of audio signal to be acquired. Default=0 means continuous recording.
        """
        super().__init__()
        # window decorations
        self.setWindowTitle("RITMO/LYRA/VPU Recording")
        self.setMinimumSize(MIN_WIDTH, MIN_HEIGHT)

        # sound management
        self._list_sound_devices = sd.query_devices()
        self._block_size = 9600
        self._sample_rate = sample_rate
        self._recording_stream = sd.InputStream(samplerate=self._sample_rate, dtype='int16', blocksize=self._block_size, channels=1,
                                                callback=self.audio_recording_callback)

        # time management
        self._start_time = 0
        self._acquisition_duration_seconds = acquisition_duration_seconds
        recording_timer_init_value = "0"
        self.timer = QTimer()
        if self._acquisition_duration_seconds > 0:
            recording_timer_init_value = str(self._acquisition_duration_seconds)
            self.timer.timeout.connect(self.count_down_timer)
        else:
            self.timer.timeout.connect(self.count_up_timer)

        # plot management
        self._number_of_seconds_to_plot = 10
        self._number_xaxis_points = self._sample_rate * self._number_of_seconds_to_plot
        self._xaxis_values = np.linspace(0, self._number_of_seconds_to_plot, self._number_xaxis_points)
        self._yaxis_values = np.zeros(self._number_xaxis_points, dtype=np.int16)
        self.update_graph_communicator = UpdatePlotCommunicator()

self.update_graph_communicator.update_plot.connect(self.update_plot)
        self._pcg_signal_filter = ButterworthBandpass(cutoff=(1, 150), order=1)

# data managment:
self._audio_queue = queue.Queue()
self._audio_data = np.zeros((0 , 1), dtype=np.int16)

#window layout
self._button_layout = QHBoxLayout()

self.start_button = QPushButton("Start")
self.start_button.setObjectName("__start__")
self.start_button.setDefault(True)
self.start_button.clicked.connect(self.start_measurement)
self.stop_button = QPushButton("Stop")
self.stop_button.setObjectName("__stop__")
self.stop_button.setDisabled(True)
self.stop_button.clicked.connect(self.stop_measurement)
self.clear_data_button = QPushButton("Clear Data")
self.clear_data_button.setDisabled(True)
self.clear_data_button.clicked.connect(self.clear_data)
self.save_button = QPushButton("Save")
self.save_button.setObjectName("__save__")
self.save_button.setDisabled(True)
self.save_button.clicked.connect(self.save_data)
exit_button = QPushButton("Exit")
exit_button.setObjectName("__exit__")
time_label = QLabel("Recording Time (s):    ")
self.time_text = QLabel(recording_timer_init_value)
self.time_text.setObjectName("__timer__")
time_label.setBuddy(self.time_text)
top_layout = QHBoxLayout()
top_layout.addWidget(self.start_button)
top_layout.addWidget(self.stop_button)
top_layout.addWidget(self.save_button)
top_layout.addStretch(1)
top_layout.addWidget(time_label)
top_layout.addWidget(self.time_text)
top_layout.addStretch(2)
top_layout.addWidget(self.clear_data_button)

self.plot_widget = pg.plot(title="RITMO/LYRA/VPU Recorder")
# plot_item = self.plot_widget.getPlotItem()
# plot_item.setTitle(self._channel_to_record.name + ":" + self._channel_to_record.type)
self.plot_widget.setBackground("w")
self.plot_widget.showGrid(x=True, y=True, alpha=0.25)
plot_pen = pg.mkPen(color=(200, 50, 50))
self._plot_data = self.plot_widget.plot(pen=plot_pen, name="VPU Data")

main_layout = QGridLayout(self)
main_layout.addLayout(top_layout, 0, 0, 1, 5)
main_layout.addWidget(self.plot_widget, 1, 0)


def count_up_timer(self):
    current_time = time() - self._start_time
    self.time_text.setText(current_time.__format__("2.1f"))
    self.update_graph_communicator.update_plot.emit(0)

def count_down_timer(self):
    current_time = time() - self._start_time
    time_remaining = self._acquisition_duration_seconds - current_time
    self.time_text.setText(time_remaining.__format__("2.1f"))
    self.update_graph_communicator.update_plot.emit(0)

@Slot()
def start_measurement(self):
    self._start_time = time()
    self.timer.start(100)
    self._recording_stream.start()
    self.stop_button.setDisabled(False)
    self.start_button.setDisabled(True)
    self.clear_data_button.setDisabled(True)

def audio_recording_callback(self, indata, frames, time, status):
    """This is called (from a separate thread) for each audio block."""
    if len(indata) != self._block_size :
        return
    if status:
        print(status)
    self._audio_data = np.append(self._audio_data, indata, axis=0)
    self._audio_queue.put(indata)

@Slot()
def stop_measurement(self):
    self._recording_stream.stop()
    self.timer.stop()
    self.start_button.setDisabled(False)
    self.stop_button.setDisabled(True)
    self.save_button.setDisabled(False)
    self.clear_data_button.setDisabled(False)

@Slot()
def clear_data(self):
    self._audio_data = np.zeros((0 , 1), dtype=np.int16)
    self._yaxis_values = np.zeros(self._number_xaxis_points, dtype=np.int16)
    self._plot_data.setData()
    self.clear_data_button.setDisabled(True)

@Slot()
def save_data(self):
    data_file = QFileDialog.getSaveFileName(self,
                                            caption="Save File",
                                            dir=str(Path.cwd()),
                                            filter="FLAC (*.flac)")
    if len(data_file[0]) > 0:
        sf.write(data_file[0], self._audio_data, self._sample_rate)
        if Path(data_file[0]).exists():
            saved_dialog = QMessageBox(self, text="File Saved!")
            saved_dialog.setWindowTitle("Saved!")
            saved_dialog.exec()
            self.clear_data()

@Slot()
def update_plot(self, frames):
    """
    Typically, audio callbacks happen more frequently than plot updates,
    therefore the queue tends to contain multiple blocks of audio data.
    """
    try:
        new_data = self._audio_queue.get_nowait()
    except queue.Empty:
        return
    len_new_data = len(new_data)
    self._yaxis_values = np.roll(self._yaxis_values, -len_new_data, axis=0)
    self._yaxis_values[-len_new_data:] = new_data[:,0]
    # self._yaxis_values = self._pcg_signal_filter.filter_data(self._yaxis_values, self._sample_rate)
    self._plot_data.setData(self._xaxis_values, self._yaxis_values)


if __name__ == "__main__":
    app = QApplication()
    audio_recorder = SingleChannelAudioRecorder(sample_rate=96000, acquisition_duration_seconds=0)
    audio_recorder.show()
    exit(app.exec())
```

IDE Master Graduation Project

Project team, procedural checks and Personal Project Brief

In this document the agreements made between student and supervisory team about the student's IDE Master Graduation Project are set out. This document may also include involvement of an external client, however does not cover any legal matters student and client (might) agree upon. Next to that, this document facilitates the required procedural checks:

- Student defines the team, what the student is going to do/deliver and how that will come about
- Chair of the supervisory team signs, to formally approve the project's setup / Project brief
- SSC E&SA (Shared Service Centre, Education & Student Affairs) report on the student's registration and study progress
- IDE's Board of Examiners confirms the proposed supervisory team on their eligibility, and whether the student is allowed to start the Graduation Project

STUDENT DATA & MASTER PROGRAMME

Complete all fields and indicate which master(s) you are in

Family name	
Initials	
Given name	
Student number	

IDE master(s) IPD DfI SPD

2nd non-IDE master	
Individual programme *(date of approval)*	
Medisign	
HPM	

SUPERVISORY TEAM

Fill in he required information of supervisory team members. If applicable, company mentor is added as 2nd mentor

Chair		dept./section	
mentor		dept./section	
2nd mentor			
client:			
city:		country:	
optional comments			

! Ensure a heterogeneous team. In case you wish to include team members from the same section, explain why.

! Chair should request the IDE Board of Examiners for approval when a non-IDE mentor is proposed. Include CV and motivation letter.

! 2nd mentor only applies when a client is involved.

APPROVAL OF CHAIR on PROJECT PROPOSAL / PROJECT BRIEF -> to be filled in **by the Chair** of the supervisory team

Sign for approval (Chair)

[redacted]

Appendix H - Project Brief

CHECK ON STUDY PROGRESS

To be filled in **by SSC E&SA** (Shared Service Centre, Education & Student Affairs), after approval of the project brief by the chair. The study progress will be checked for a 2nd time just before the green light meeting.

Master electives no. of EC accumulated in total _____ EC

Of which, taking conditional requirements into account, can be part of the exam programme _____ EC

	YES	all 1st year master courses passed
	NO	missing 1st year courses

Comments:

Sign for approval (SSC E&SA)

[redacted]

APPROVAL OF BOARD OF EXAMINERS IDE on SUPERVISORY TEAM -> to be checked and filled in by IDE's Board of Examiners

Does the composition of the Supervisory Team comply with regulations?

YES		Supervisory Team approved
NO		Supervisory Team not approved

Comments:

Based on study progress, students is …

	ALLOWED to start the graduation project
	NOT allowed to start the graduation project

Comments:

Sign for approval (BoEx)

[redacted]

Personal Project Brief – IDE Master Graduation Project

Name student _____ **Student number** _____

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT

Complete all fields, keep information clear, specific and concise

Project title _____

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

➔ *space available for images / figures on next page*

introduction (continued): space for images

image / figure 1

image / figure 2

Personal Project Brief – IDE Master Graduation Project

Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.
(max 200 words)

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence) As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

Project planning and key moments

*To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a **kick-off meeting**, **mid-term evaluation meeting**, **green light meeting** and **graduation ceremony**. Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).*

Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting _____

Mid-term evaluation _____

Green light meeting _____

Graduation ceremony _____

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	
For how many project weeks	
Number of project days per week	

Comments:

Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five.
(200 words max)

Conflict of Interest

The author declares no conflict of interest. This thesis was conducted with support of a company. The company did not influence the results or conclusions presented in this work. All presented views reflect those of

the author and involved individuals. The thesis does not claim to reflect the views of the company.

Use of AI

This thesis made use of AI tools, such as ChatGPT, Vizcom and Figma AI, to help improve language, carry out quick initial research, organize ideas, and generate images and videos. All content and conclusions remain the author's own, and critical analysis was conducted independently.

Nidia Bejar Kurtin

Student Number: 5006767

Delft University of Technology

Faculty of Industrial Design Engineering

Feb 2026