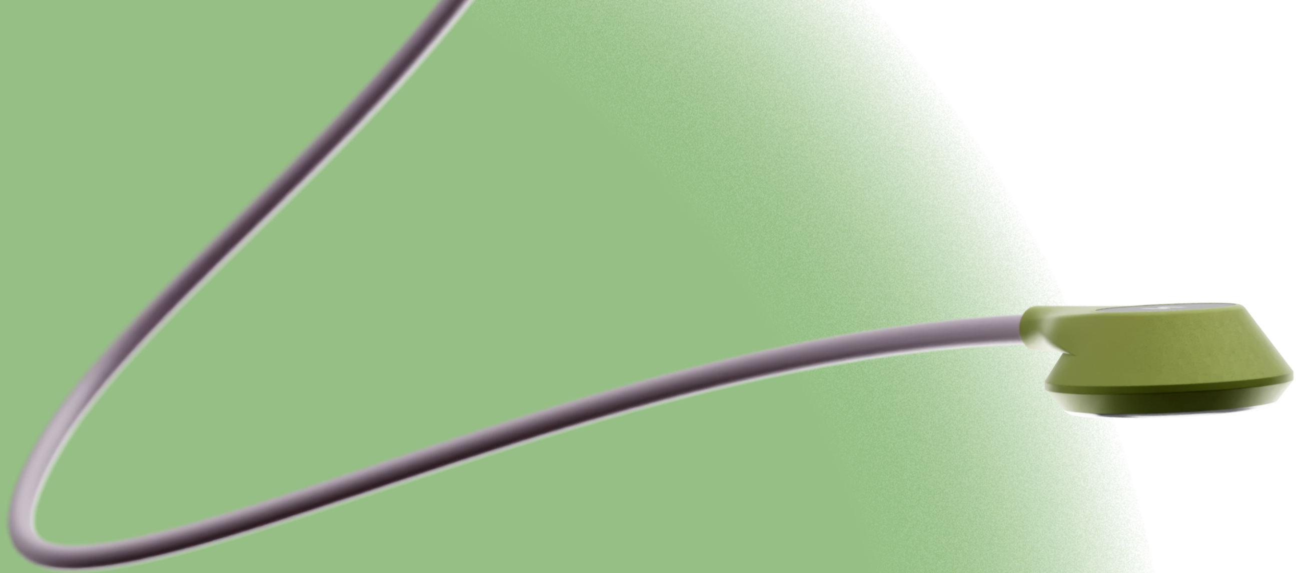
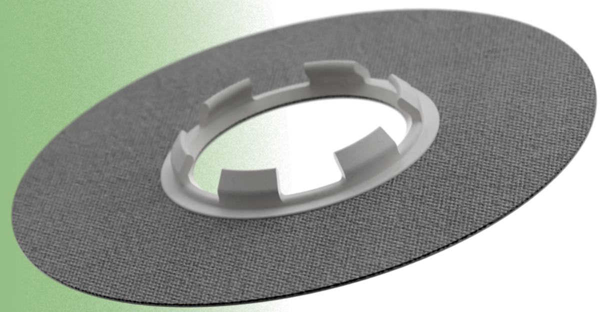


REWIRING FOR SUSTAINABILITY



A CIRCULAR APPROACH TO THE REDESIGN OF ECG LEAD SETS TO IMPROVE SUSTAINABILITY IN HEALTHCARE

REWIRING FOR SUSTAINABILITY

A circular approach to the redesign of ECG lead sets to improve sustainability in healthcare

Integrated Product Design
Industrial Design Engineering
Delft University of Technology

July 2025

By
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ESCH-R, creating circular hospitals together
Erasmus Medical Center

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PREFACE

While studying industrial design engineering, I have developed myself both professionally and on a personal level, discovering my true interests. I have come to the realization that creating tangible products, exploring innovative concepts, and evaluating various solutions bring me the most joy. Furthermore, I learned that I want to use design to make a difference, and contribute to something bigger, rather than just design a chair.

Balancing stakeholder needs becomes truly captivating to me when the interests are complex and rooted in a real-world context. When I was given the chance to work on this graduation project, I saw that it had this potential, and it surpassed my initial expectations.

I had the opportunity to work on a real-world project that addressed the critical issue of sustainability in a hospital setting. My strong personal interest in this topic, and this experience has shown me that, despite its extreme complexity, sustainable solutions are feasible. Working in the context of a large hospital such as Erasmus Medical Centre added an extra dimension to that challenge.

Ultimately, I am pleased with the research and design proposal I delivered. I hope, when reading this graduation report, it can inspire you and offer you something new.

Enjoy,

Tijmen

ACKNOWLEDGEMENTS

I would like to thank everyone who helped me within the project. Having had the chance to ask questions, share ideas, and have valuable conversations with many people throughout the process. I appreciated your openness and readiness to support me during this process.

I want to express a special thanks to Stefan Persaud and Jan-Carel Dhiel, my mentors. For their insightful advice, criticism, and coaching. Your advice has kept me on track and allowed me to produce meaningful work.

I would like to thank the people at Erasmus Medical Centre for providing me the project context, openness, and access I needed to fully explore the system of the ECG-lead sets. To the nurses and staff who kindly shared their time, opinions, and daily experiences with me, thank you, your input was extremely valuable for me.

I appreciate everyone at ESCH-R for creating a fun and effective working environment. I want to thank Jasper Klasen for sharing his knowledge and showing me so much of the Erasmus Medical Centre. Thank you, Ayşegül Özçelik, for the valuable sessions in which we discussed the project, the process, and reflected on everything around it.

To my fellow students and friends: I could not have made it through this project without your suggestions, laughs, and late-night brainstorming sessions.

Lastly, I would like to express my gratitude to my family and girlfriend for their consistent support, encouragement, and patience throughout this last stage of my education.

ABSTRACT

This graduation project, focussed on the environmental impact of the ECG-lead sets used at Erasmus Medical Centre (EMC). It explores how circular design techniques can help create a more sustainable healthcare system. Although ECG-lead sets are crucial for cardiac monitoring and diagnostics, they are frequently single-patient use (SPU), this greatly increases CO2 emissions and medical waste. Although there are multi-patient-use (MPU) alternatives, hygienic concerns, cleaning workload, and regulatory limitations limit their wider adoption. The project set out to redesign ECG-lead sets using an evidence-based and context-specific methodology, in order to evaluate theoretical sustainability strategies and their actual implications.

The research phase consisted of an in-depth exploration of the current ECG-lead set used across multiple EMC departments. Through interviews, direct observations, user journey mapping, and stakeholder analysis. The environmental impact of both SPU and MPU sets was measured using a Life Cycle Assessment (LCA), which revealed that MPU options become more sustainable after just four use cycles. Cable tangling, unclear ownership resulting from multiple department transfers, and inconsistent cleaning procedures were among the main obstacles found. The need for system-level thinking was highlighted by the frequent conflicting stakeholder interests, which ranged from procurement logistics to patient safety.

With a focus on co-creation, the design phase adhered to the triple diamond process: explore, ideate, implement. The concept for a modular, reusable ECG system with enhanced usability, durability, and lifecycle transparency was influenced by three co-creation sessions and multiple expert interviews.

Digital traceability to track usage cycles and maintenance, visible cleanliness indicators, and easy-to-use cable management were among the possible design interventions. In order to address user experience and operational viability, core concepts were validated through prototyping and testing with nurses and technical staff.

A reusable ECG-lead set that minimizes environmental impact and fits in the EMC context is the end result. Implementing dry electrode technology in the design, it reduces valuable material waste from conventional electrodes and keeps these in the loop of the circular economy. Embedding RFID tags to allow traceability, and lifecycle monitoring. The design enables individual part replacement and greatly reduces material waste by supporting circular strategies like reuse, repair, and refurbishment. This design shows how circular principles can be effectively translated into workable, scalable medical device solutions through co-created and context-specific design.

According to the project's findings, systemic knowledge and stakeholder involvement are both necessary for future healthcare transformation. In addition to producing better design, the project is an example that offers a scalable framework for implementing circular design in other medical product industries, making it a validated case study.

KEY TERMS AND ABBREVIATIONS

Key terms

Circular economy: A system where materials never become waste and nature is regenerated, with materials kept in circulation.
Circular strategies: Referring to the 9 R-Strategies explained in section
Electrodes: Single-use stickers with conductive gel and metal buttons for capturing heart ECG signals
Lead Set: Cables that connect electrodes to ECG to the patient monitor.
Digital Connector: The component that connects lead sets to the patient monitor.
Clip Connector: The connector that attaches the cable to the electrode.
"Het Broodje": Dutch nickname for the small patient monitoring computer used at EMC.
LCA: Life Cycle Assessment; used to measure environmental impact of products.
Green Deal 3.0: Dutch national program for sustainable healthcare.
Green Teams: Volunteer based sustainability teams within the EMC.
Alarm Fatigue: People become immune to frequent alarms.
Co-Creation: a collaborative design process involving multiple stakeholders.

Abbreviations

ECG = Electrocardiogram
EMC = Erasmus Medical Centre
ICU = Intensive Care Unit
OR = Operating Room
SPU = Single-Patient-Use
MPU = Multi-Patient-Use
RFID = Radio Frequency Identification
LCA = Life Cycle Assessment

CONTENT

1

INTRODUCTION

To measure the state of the heart, an electrocardiogram (ECG) is a common test. Frequently, it is the first test performed when a person has issues with his/her heart. The test records the electrical activity of the heart, and the recordings can be used to diagnose different conditions.

In a setting like the intensive care unit (ICU) or operating room (OR), it is also used to monitor patients over a long period of time. Approximately 200 million ECG's are performed globally each year (Reichlin et al., 2016). Using a so called ECG-lead set, a set of cables that gets attached to the patient using electrode stickers, to perform the test.

When it comes to ECG lead sets, the electrodes are only used once, and sometimes the complete lead set is used for only one patient. In general, single patient-use (SPU) medical devices have a significantly more negative environmental impact, compared to reusable alternatives (Keil et al., 2022). However, there are a number of issues with multi-patient-use (MPU) devices that make choosing the more sustainable route, not easy.
Issues like the potential for cross-infection, inability to clean, residue from chemicals, material corrosion, mechanical failure, and reactions to toxins are all associated with MPU medical devices and can lead to hospitals picking SPU devices (Medicines and Healthcare products Regulatory Agency, 2022).

Some of these concerns are directly applicable to ECG-lead sets, such as the heightened difficulty of cleaning and the decline in product quality of reusable ECG-lead sets (Albert et al., 2014) (Albert et al., 2010). To learn more about these factors and see how the practice works compared to the theory, this project was carried out.

1.1 PROBLEM DEFINITION

Problem

Without a clear specific study of the product, its use, system, and environment, ECG-lead sets remain poorly understood. Potential circular strategies should be selected for this product's specific context. Contributing to a more sustainable healthcare sector by addressing the environmental hotspots of the ECG-lead sets and improving the general product experience.

Gap

While the environmental impact of single patient-use (SPU) medical devices is well-recognized, there is limited in-depth research specifically targeting ECG-lead sets. Existing literature often generalizes across device categories or overlooks the specific practical challenges and behaviours associated with this product. As a result, the actual use, maintenance, and disposal of ECG-lead sets in everyday clinical settings remain poorly understood.

Importantly, only focused context-specific case studies can capture the nuances of real-world practice, including how staff interact with the product, how protocols are followed or adapted, and how institutional decisions are made. Without this level of detail, circular strategies risk being impractical or ineffective.

Why is this important?

Hospitals use a lot of ECG lead sets. The way they are currently disposed of adds a lot to medical waste. The environmental impact of healthcare could be significantly reduced by making this product more sustainable. However, evidence-based design with a practical application is necessary for significant change.

Therefore, thorough case studies are crucial for understanding what truly occurs in daily hospital practice as well as for identifying theoretical opportunities. Through a investigation of this particular case at Erasmus Medical Centre, the project produces useful insights that can guide workable, realistic circular solutions and act as a template for rethinking other medical devices.

Research goal

The goal of this project is to: investigate the use of ECG-lead sets in the Erasmus Medical Centre (EMC), mapping out, the current field, the patient, and product journey, identifying environmental hotspots and design opportunities. To develop a circular solution for the ECG to move to a more sustainable healthcare sector.

The goal of this report specifically is to; implement circular strategies to showcase the potential of rethinking medical devices. Creating a compelling case study that ends with a design proposal intended to highlight the practical opportunities and advantages of sustainable design.

Research questions

There are four main research questions, with sub-questions that specify the different themes.

» 1. What is the environmental impact of ECG-lead sets and electrodes at EMC, and what are the sustainability challenges?

1. How do single-patient-use (SPU), multi-patient-use (MPU) ECG-lead sets and electrodes compare in terms of sustainability?
2. How frequently are ECG tests conducted at EMC, in what volume and at which departments?
3. What are the core components of the ECG system, in what way do they contribute to the environmental impact?

» 2. What are the main barriers and opportunities for implementing circular strategies in the use of ECG-lead sets?

1. What practical challenges, such as staff workload or cleaning procedures, prevent the use of reusable ECG-lead sets?
2. How do concerns around hygiene, infection prevention, and patient safety limit the shift toward circular product strategies?

» 3. How do different stakeholders and systemic factors influence sustainable decision-making around ECG products?

1. What are the motivations and incentives of key stakeholders, such as suppliers, hospital departments, and regulatory bodies, regarding the use of SPU vs. MPU devices?
2. How do procurement policies at EMC support or hinder the adoption of sustainable and circular medical products?
3. In what ways do competing interests create friction between stakeholders, and which stakeholders can have the biggest impact?

» 4. What are the user experiences and needs of patients and nurses when interacting with ECG-lead sets?

1. How do patients perceive and experience ECG-lead sets in terms of comfort and trust?
2. What needs and preferences do nurses have regarding the usability, setup, and maintenance of ECG-lead sets in their daily workflow?
3. How do user issues affect both user experience and clinical outcomes?

1.2 DESIGN APPROACH

The process I followed for this project is described in this section, and shown in figure 1. It is based on a triple diamond framework, consisting of an exploration, ideation, and implementation phase. These three phases best describe the iterative process that I followed, continuously diverging and converging. The green areas describe my process best, as an alternative to the perfectly symmetric original triple diamond framework, in grey.

Exploration
In order to completely analyze the current use and difficulties associated with ECG-lead sets at EMC, I first immersed myself in the hospital setting during the exploration phase of the process. Due to the environment's complexity and different types of functional, technical, and user aspects, this was a time intensive process. Diverging a lot, seeing a lot, and learning about the complete hospital in general. To finally bring this back, to relevant insights for the project itself.

During this phase, I observed procedures and interviewed a total of 15 different hospital employees, ranging from nurses, a sustainability manger to procurement staff. Gaining a good insight into the real-world use cases of the ECG system, practical problems, and potential sustainability opportunities.

Ideate
The ideation phase doubled as a moment to reflect and a link between the analysis done and the start of implementation. I compiled the main insights of the research and stakeholder insights into areas of opportunity. Ideating about possible direction to go in, with brainstorm sessions, co-creation and sketches. Doing this in collaboration with others was time-consuming, but very valuable. Converging to the final design direction, all ideas were evaluated to strike a good balance of different stakeholder values, and user issues to design for.

This phase involved a great amount of collaboration, I held one and participated in two co-creation sessions. Furthermore, I talked with external experts, such as a Philips employee, an IDE graduate, and my project coaches. These moments opened up discussions about systemic and behavioural issues, guiding the project in a well-rounded direction. Interviews and observations again were utilized to confirm findings and evaluate design directions, speaking to the same people to share new insights.

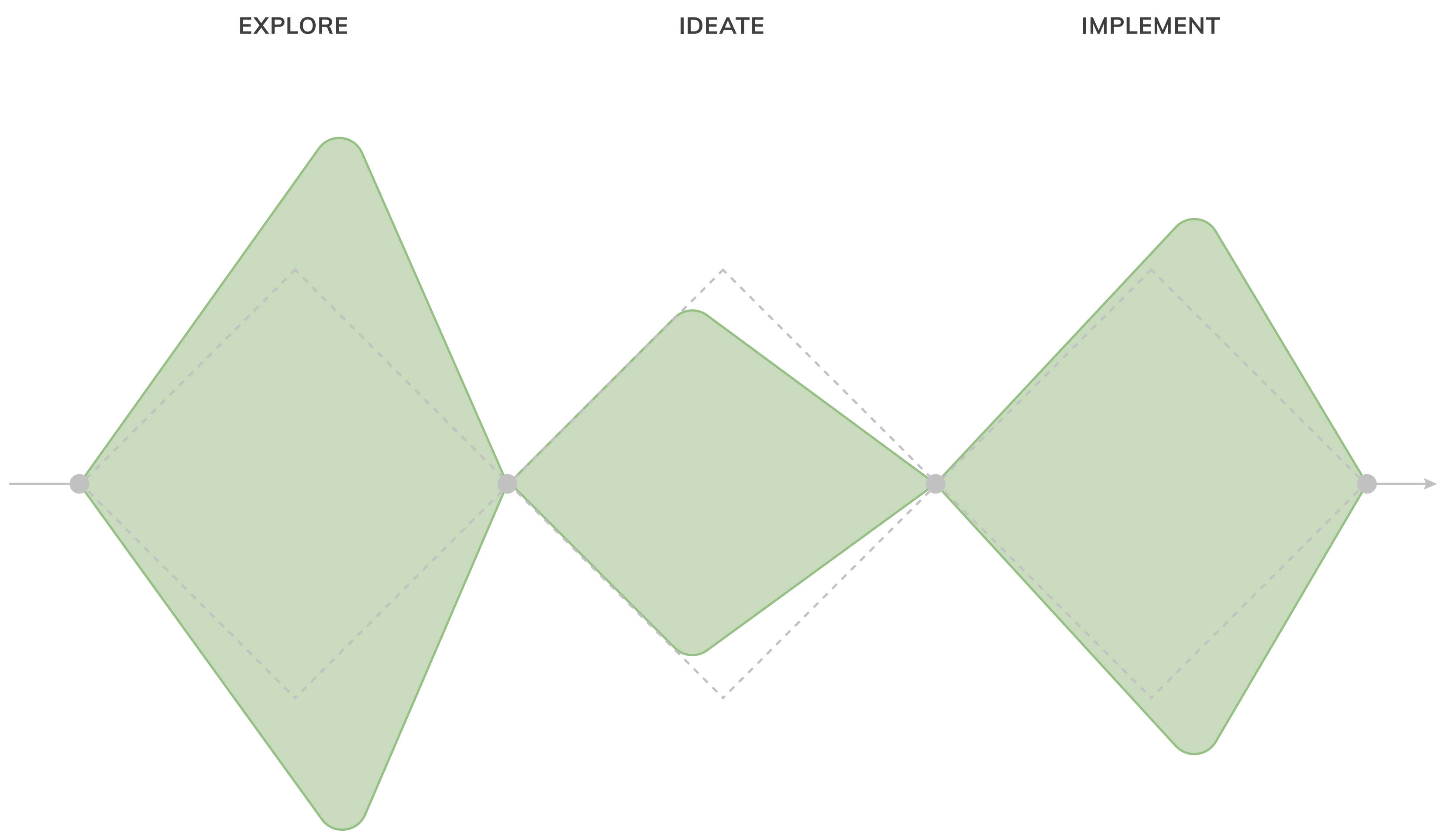


Figure1.Triple diamond framework project structure

Implementation
Starting with a design direction, the transition between ideation and implementation phase was smooth and because of the iterative qualities very similar. However, this phase evolved around the end goal, a design proposal. Meaning, everything quickly needed to converge to one end result. This was very much the design phase of the project, working quickly between sketching, prototyping, testing and back to sketching.

I created and tested a number of prototypes while taking professional and fellow student input into consideration to evaluate the feasibility of the design. Even after I came up with a main idea, there were continuous cycles of improvement. In the end, the design was definitive, and the focus shifted to delivering results, a prototype, validating the results in the report, and thoroughly explaining the final design proposal.

To sum up, the process was chaotic at some points, but generally the flow of the different phases addressed the needs at that time. Collaboration was crucial throughout this process, not only for brainstorming but also for analyzing the hospital system, and keeping the project on track. The final proposal is the outcome of a process that was also circular in different ways, a design approach that delivered an end result.

1.3 PROJECT TEAM

The project team was composed of multiple stakeholders, each bringing their own incentives and roles to the initiative.

As part of this project, I worked within the ESCH-R project, an interdisciplinary program funded by the Dutch Research Council under the Dutch Research Agenda. The project's overarching goal is to contribute to a more sustainable healthcare sector, as is the same for my project.

Although Erasmus Medical Centre in Rotterdam was not an active stakeholder in this team, the project was set within the context of their healthcare system. As such, their environment, practices, and infrastructure have played a significant role in shaping the project's relevance and applicability.

Additionally, as I a have completed this project as part of my graduation at TU Delft, the university played key role to ensure that the project meets academic standards and contributes meaningfully to my educational development.

2

BACKGROUND

This section offers a review of the background, difficulties, and prospects related to the use of ECG-lead sets in Dutch healthcare, emphasizing sustainability. It presents the concepts of a circular economy and explains their applicability to the medical industry, especially when viewed through the scope of the 9 R-strategies. The impact of healthcare on the environment in the Netherlands and the obstacles to adopting more sustainable practices are then reviewed. Before wrapping up with recent trends and advancements that point to a move toward more inventive and sustainable ECG solutions. A thorough review of ECG technology is given, covering its elements, applications, and user requirements.

2.1 CIRCULAR STRATEGIES

In an effort to create a circular economy and become more sustainable, different strategies have been developed. These strategies can be implemented to create a product that fits into the circular economy. The definition of a circular economy is (Circular Economy Introduction, n.d.):

> “ A system where materials never become waste and nature is regenerated. In a circular economy, products and materials are kept in circulation instead of linearly. ”

This principle of a circular economy aligns with the goals of the healthcare sector and therefore plays a central role in this project. The 9 R-strategies are strategies that are implemented in practice to facilitate change towards a circular economy. (R-Strategies for a Circular Economy, n.d.)

Refuse (R0)
This strategy focuses on preventing waste at its source by refusing the use of unnecessary or harmful materials.

Rethink (R1)
Rethinking involves making product use more efficient, whether by product design or adopting new business models like product sharing.

Reduce (R2)
Reducing means using fewer raw materials and energy in production, consumption, and everyday activities.

Reuse (R3)
Instead of discarding products after a single use, reuse strategies extend their lifespan by keeping them in circulation.

Repair (R4)
Repairing extends the life of products by fixing broken or malfunctioning parts rather than replacing the entire item.

Refurbish (R5)
Refurbishment involves restoring old products to a good working condition, often with upgrades or modern features.

Remanufacture (R6)
Remanufacturing takes discarded products and rebuilds them to match the quality and function of new ones.

Repurpose (R7)
Rather than discarding products that no longer serve their original function, repurposing finds new ways to use them.

Recycle (R8)
Recycling breaks down used materials into raw components that can be reprocessed into new products
.

Recover (R9)
Recovery is the final step when all other strategies have been exhausted. It involves converting waste into energy through incineration or other waste-to-energy processes.

These strategies can be seen as the backbone of the circular economy and also this project. As they provide direction, inspiration, and validation for future stages. The strategies, in combination with the value hill (Achterberg et al., 2016), nicely represents how circular strategies not only contribute to a more sustainable world, it also provides value for businesses, see figure 2.

The value of a product increases in production, different steps in the pre-use, add value. Eventually the product is used, and after that value can be retained. Implementing an R-strategy that is higher up at the hill retains more value than a product that is only recycled (R8). Value can be money, but also the resources that are put into the product like raw materials, production processes, research, and marketing are different forms of value. It shows that the R-strategies are viable for businesses to implement in order to become sustainable, both environmentally and economically.

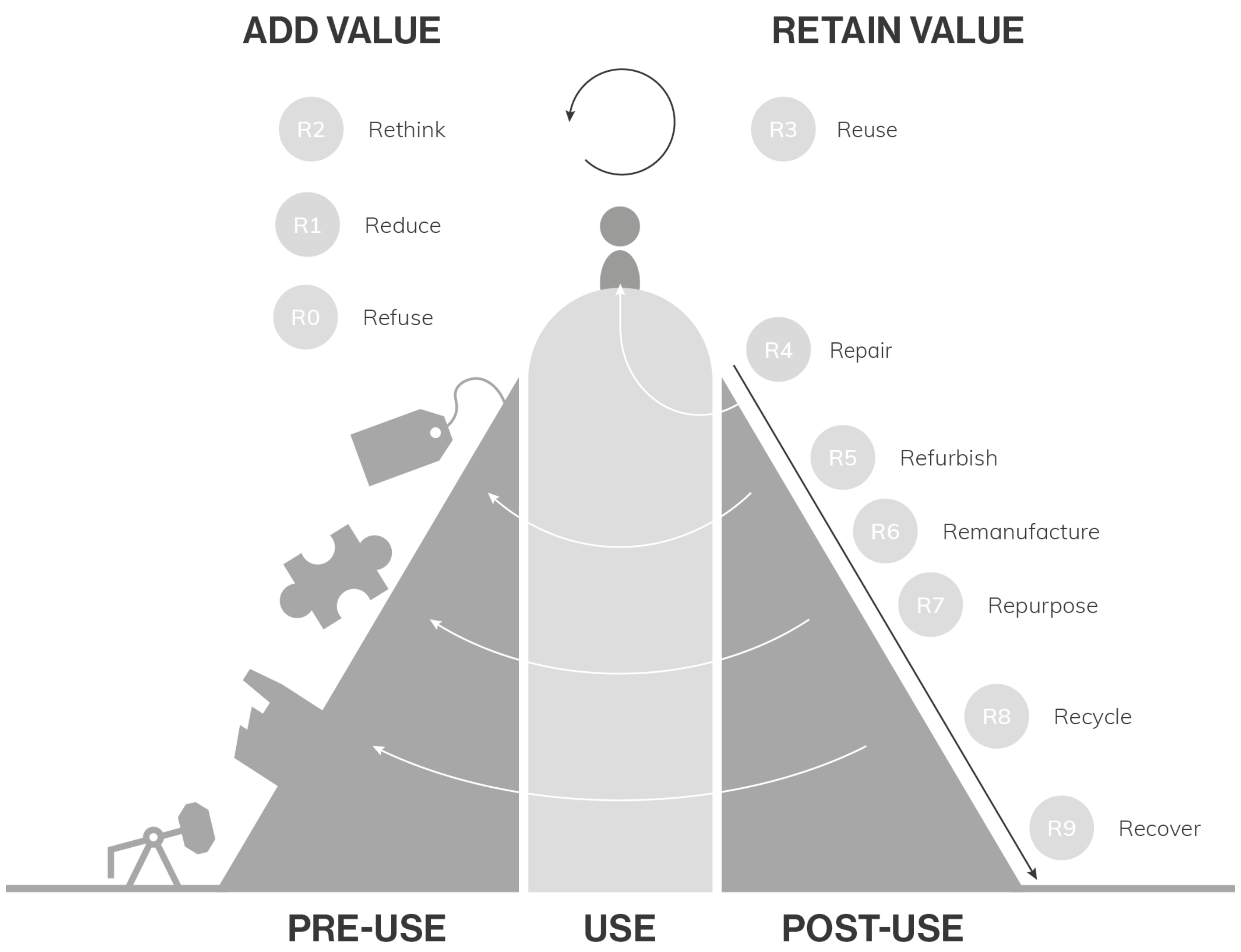


Figure2.Value hill

2.2 SUSTAINABILITY IN DUTCH HEALTHCARE

The environmental impact of the healthcare sector is significant. A national study has estimated that the Dutch healthcare system is responsible for 7% of the country's total carbon footprint (Steenmeijer et al., 2022). Erasmus Medical Centre (EMC) is the biggest medical centre in the Netherlands. In 2021, they produced 209.5 kilotons of CO2-equivalent (Lau et al., 2024).

The majority of these emissions were driven by purchased goods and services (72.1%). Of this percentage, 10.9% was due to the purchase of medical products. A direct link to these purchased products is the generated waste, this was another 6.2% of the total emissions in 2021 (Lau et al., 2024). Therefore, the use of medical products and their waste management are critical factors to becoming more sustainable.

The Dutch healthcare sector is now taking action, trough the Green Deal: Sustainable Healthcare 3.0. This is a collaborative initiative, based on previous versions, that promotes stronger commitments and broader participation across the healthcare sector. (Green Deal Duurzame Zorg 3.0, n.d.)

The three main goals are:

- Working towards a green and climate-neutral healthcare sector.

- Increased focus on prevention and attention on people's health.

- Reducing the negative impact that healthcare has on the climate and environment.

Green Deal 3.0 provides a critical approach towards aligning individual healthcare organizations with national climate goals. But these goals are not easy to reach and different lie ahead.

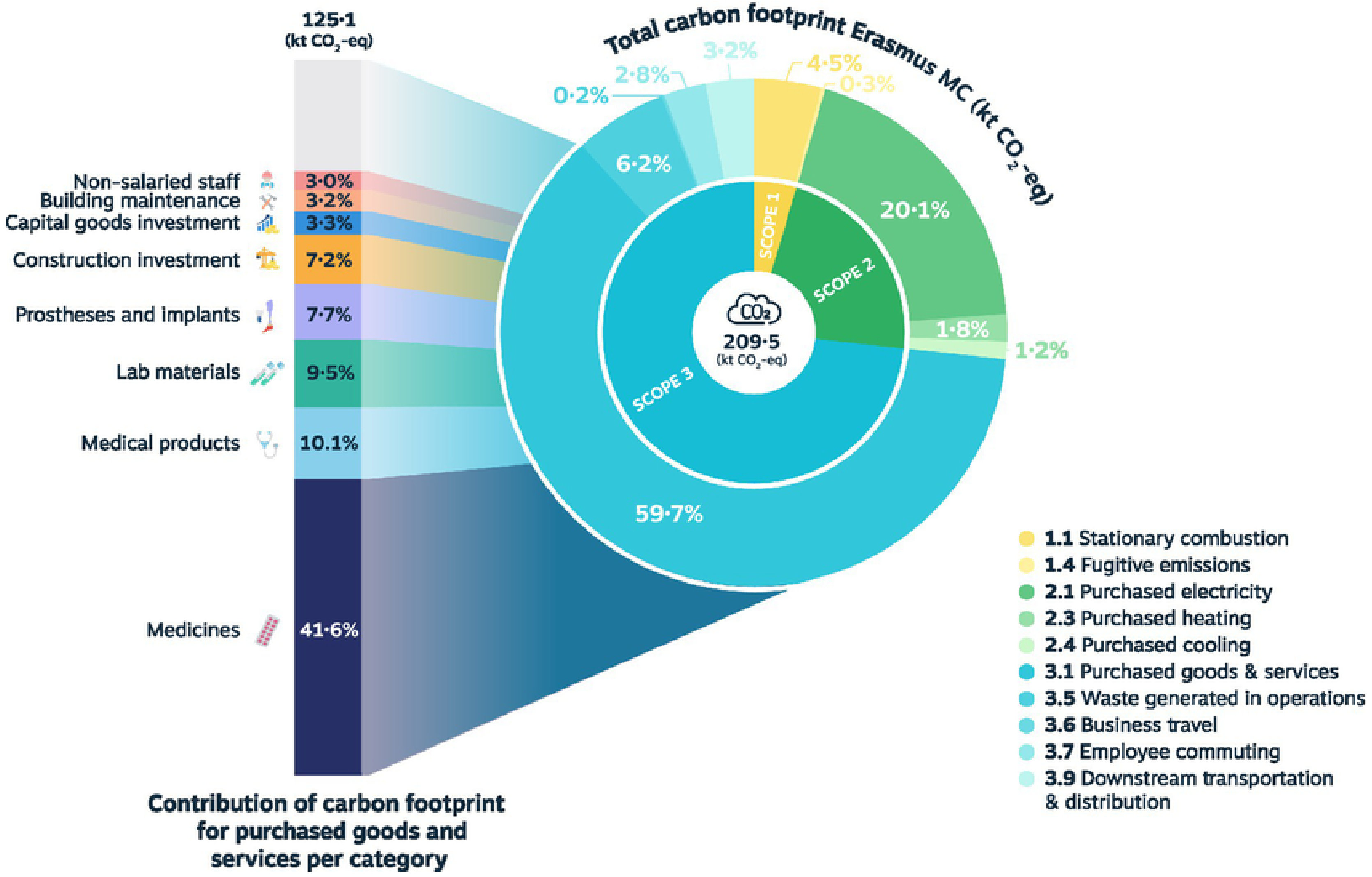


Figure3.Carbon Footprint EMC (Lau et al., 2024)

2.3 BARRIERS TO IMPLEMENTING R-STRATEGIES IN HEALTHCARE

The healthcare sector, has a lot of different challenges in becoming more sustainable . On top of that, there are already different problems within the healthcare system itself. These big and complex issues make it difficult for new developments to take place.

Increasing workload
It is broadly known and accepted that the workload in the healthcare is very demanding. Meanwhile, there is a gap between the demand and the supply of care, and this gap is widening, due to the ageing of the population. (Ministerie van Volksgezondheid, Welzijn en Sport, 2024). This limiting the growth and innovation of the sector and will continue to hold back new developments. Also, for improving sustainability within the healthcare.

In reality, this means that, nurses, doctors and other staff do not have time to spend an extra minute cleaning a MPU device or that they do not have the time to learn a new procedure. Change needs time and energy in order for it to work, and this will be the same for new sustainable initiatives.

Regulatory
Currently, regulatory policies prioritize patient safety and hygiene. This was relevant for a long time, as these two challenges required the most attention. Now we find ourselves at a place in time where the policies are not up-to-date with the sustainability goals. Rules about SPU medical devices, energy-intensive equipment, and complex waste disposal protocols are making it difficult to implement more sustainable solutions. In addition, regulatory frameworks are slow to adapt, requiring a lot of resources to be changed and pushed in the right direction. As a result, the healthcare sector has become extremely complex to navigate and find a balance between sustainability and following the law. (Health Council of the Netherlands, 2022) (Kalapos, 2024)

Product
From a product perspective, transitioning from single-use to multiple-use medical devices offers notable environmental benefits. However, the environmental and financial advantages of multiple-use devices are highly context-dependent. Despite potential sustainability gains, challenges persist in ensuring consistent product quality, preventing contamination, and meeting strict sterilization standards. Organizational preferences for single-use devices often stem from concerns over safety, maintenance, and human error. Moreover, the financial viability of reusable medical devices hinges on balancing upfront costs, reprocessing expenses, and device durability.(Health Council of the Netherlands, 2022) (Helping Hospitals Become More Circular, n.d.).

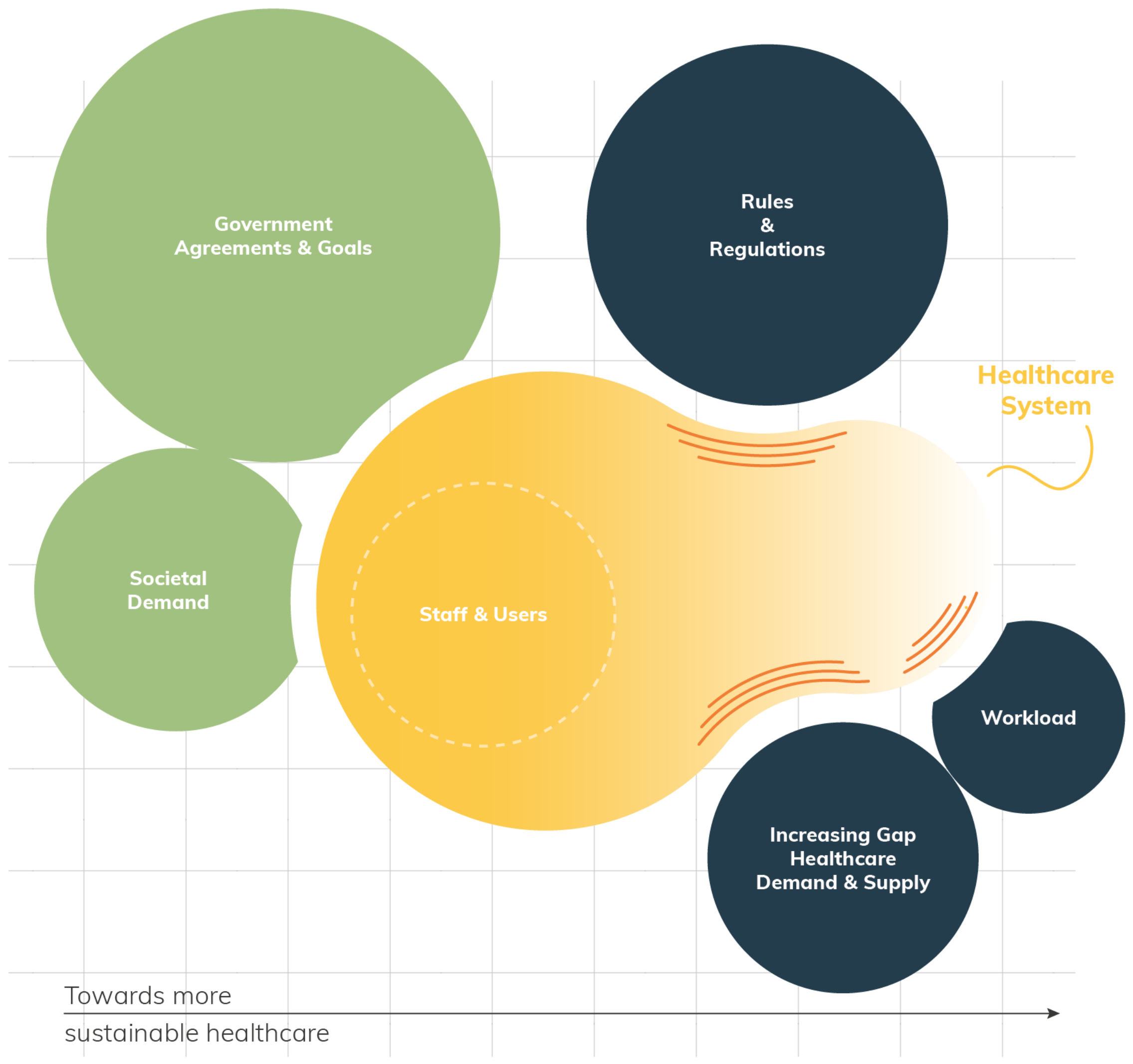


Figure4.Systemic barriers in Dutch healthcare

Illustrated here in figure 4, the change of the healthcare sector toward more sustainability is being slowed down by the factors that were just discussed.

It illustrates how there are some factors pushing us in the right direction (in green), yet it is difficult to navigate due to the other factors (in blue). The change creates stress on the healthcare sector and shows that currently it costs a lot of resources to take a step in the right direction.

2.4 WHAT IS AN ECG

The electrocardiogram (ECG) has become the most commonly conducted cardiovascular test, with around 200 million ECG's performed globally each year (Reichlin et al., 2016). In the Netherlands, there were 235,884 hospital admissions related to cardiovascular diseases, in 2023. That is, 646 admissions a day and most likely, they involved an ECG test at some point (Jaarcijfers Hart- En Vaatziekten 2023 : Hart & Vaatcijfers, 2025.).

An ECG is a type of test, not a product itself, and it is the very first test performed at a hospital to diagnose a patient with a cardiovascular condition. Besides that, it is the golden standard in patient monitoring, to record the patient's heart rate whilst unconscious in the OR or in the ICU.

Basic working principles of an ECG

The working principles of the heart are well understood, this description is based on the book: Rapid interpretation of EKG's by Fritz (2001). The basic principles of ECG are based on an electric current that is produced in our hearts. In order for the heart muscles to contract and pump blood, an electric signal is sent. This happens in the upper part of the heart. Then the current travels further through the heart and a second current is sent. When measured with the technology of the ECG, these different phases result in the so called the P wave, QRS complex and T wave. These phases are represented in a graph, which forms the basis of diagnosing cardiovascular conditions.

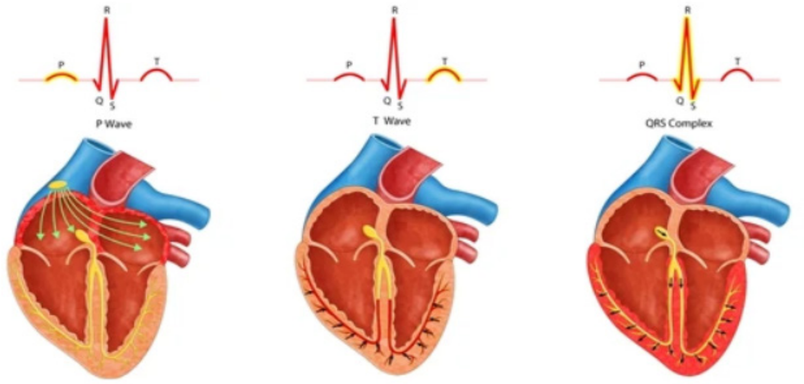
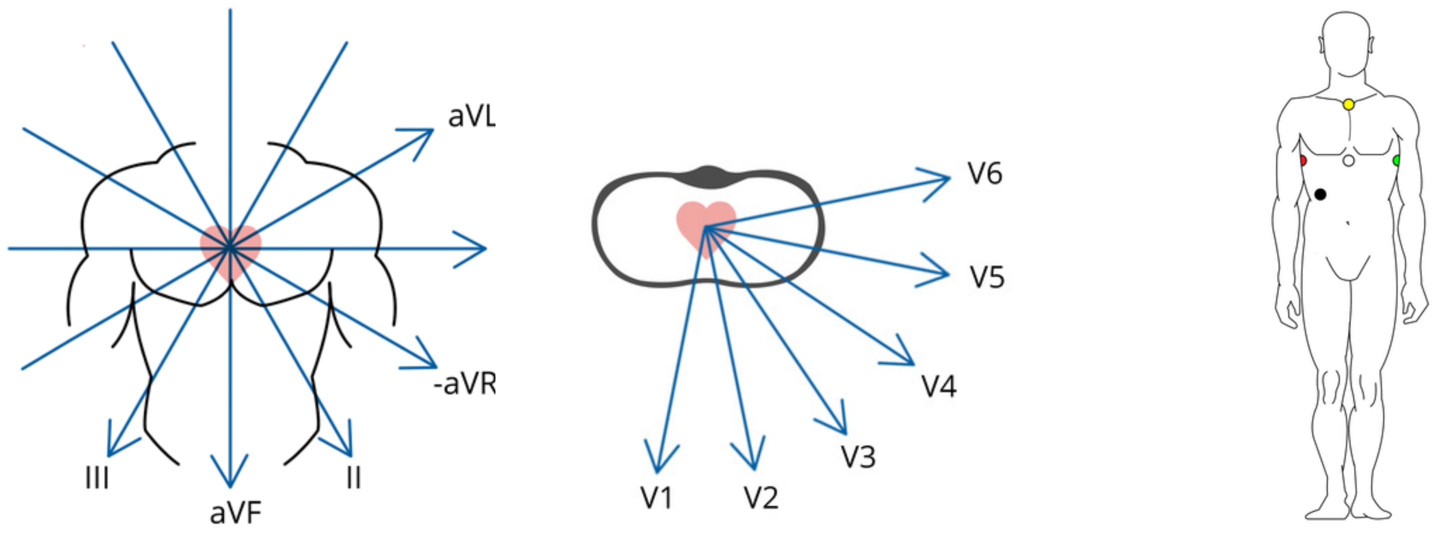


Figure5. ECG wave form explained

Figure6. ECG leads explained
(Lead Systems – How an ECG Works | CardioSecur, n.d.)



By connecting different leads, a different level of detail can be recorded, and each additional lead generates a new perspective on the heart. The standard 12-lead ECG uses 10 electrodes: four limb electrodes (RA, LA, RL, LL) and six chest electrodes (V1 to V6). This configuration allows for comprehensive assessment of 12 leads or 12 perspectives so to say. The definition of a lead refers to the measurement, but in practice is often used to indicate the amount of cables used. The limb leads record in the frontal plane, whilst the chest leads provide the horizontal one. Measuring the potential difference between the electrodes gives the ECG measurements, that is why you always need at least three leads, one positive, one negative and a reference (ground) lead. The reference lead is to filter out other electrical activities in the body, like other muscles contracting.

Because the measurements are done in two different planes, together these measurements can form a "3D" view of the heart. The output still remains the ECG graph, but measuring the 12-leads, gives 12 graphs that tell a lot about the heart's condition and allow cardiologists to diagnose patients.

ECG user profiles & needs

There are a lot of different users that interact with the ECG-lead sets, even just within the EMC. For the design process, it is important to understand each user and their respective needs. Also, a clear distinction between the patient and nurse is made, they are both end-user, but in a different way. These findings mostly come from interviews and visits to the departments.

The patient: passive user
For the patient in a hospital bed, connected to an ECG, the experience is very different and is more of a passive user. They are often in a vulnerable state, either recovering from surgery, under observation after a cardiac event, or simply too weak to be fully aware of the equipment surrounding them.
The ECG, with its sticky electrodes and tangle of wires, can feel intrusive, especially when it interferes with comfort, sleep, or mobility. Although it is typically not the only medical device attached to the patient, it adds on everything that is already going on.

Most patients don't fully understand how the ECG works, only that it helps monitoring their heart. But frequent, unexplained alarms can cause anxiety. They might assume something is wrong every time a beep goes off, even if the alarm is just an accident or lead disconnect. Some may also find the repeated placement and removal of electrodes uncomfortable, particularly elderly or long-term patients with sensitive skin. Patients need reassurance. They benefit from brief, clear explanations of what the ECG is doing and what the alarms mean. For them, ease of use isn't about operating the device, it's about comfort, clarity, and trust in the system and the staff managing it. Which are different product values than the active user, but still super important as it evolves around the patients and their experience.

The nurse: active user
The nurse is the active user of the device, they handle and work with the product on a daily basis across multiple patients. For them there are different needs compared to the patient.
Nurses are responsible for ensuring correct electrode placement and maintaining signal quality, even as patients move or are repositioned. Nurses know how to handle the product and massively value ease of use for the ECG lead sets. Changing the product would therefore also impact them the most, as they will need to adapt and learn the new way of handling the product.
Just like the patient, unnecessary alarms are annoying for nurses, and repositioning electrodes takes valuable time out of their day.

All nurses have a passion for caring and want what is best for the patient, but they also have to perform other tasks. Devices that can be trusted are therefore the main priority for nurses, although they do not decide which product gets bought, their opinion is most important.

Literature: Challenges in ECG use

In a large study by Hadjiantoni et al. (2021) they systematically reviewed the impact of incorrect 12-lead ECG electrode placement on clinical diagnosis, prognosis, and patient outcomes. The most insightful findings from this study prove the difficulty of placing electrodes correctly and its effects.

Misplacement of electrodes
One of the studies found that, incorrect positioning significantly altered ECG quality, leading to misdiagnosis and misclassification of different cardiovascular conditions. A small shift of just 2 cm in electrode placement, already affected the ECG interpretation in 17–24% of cases.

A very early study found (A Method for the Accurate Placement of Chest Electrodes in the Taking of Serial Electrocardiographic Tracings, 1960), that correct placement with an error less than 1 cm were achieved by trained technicians only in case of 50 % of studied men and 20 % of studied women. They found that electrode placement error typically was in the range of 2–3 cm, but occasionally reached even 6 cm. They identified the anatomical differences between men and women as a challenge in correct placement, particularly due to breast tissue and obesity, which obscure bony landmarks. More recent studies, still find that there is more inaccurate placement for woman (McCann et al., 2007).

Alarm fatigue
A systematic review by Lewandowska et al. (2020), highlights the significant impact of alarm fatigue in specifically intensive care units (ICUs), where 85–99% of alarms are false or clinically insignificant. Nurses face an overwhelming number of alarms with up to 150 to 400 per patient per shift, leading to stress, cognitive overload, and reduced trust in alarm systems. Despite recognizing the importance of personal alarm settings, many nurses hesitate to adjust alarms set by colleagues.

Alarm fatigue has been linked to patient safety risks, including delayed responses and unexpected events, some resulting in death. The study highlights the urgent need for improved alarm management strategies and better differentiation between alarm priorities. The ECG can is part of this system and should not contribute to a lot of these alarms going off.

Besides these two topics, there are not a lot of studies done on the ECG regarding the use. However, these studies show what is relevant to think about when improving the user experience.

The ECG-lead set & electrodes

To understand the ECG test better and also the ECG-lead set as a product system, it is important to know what it consists of. In figure 7, the product system is explained, part by part.
In the complete product system, the ECG-lead set, refers to the cables and the two types of connectors at the respective ends. The electrodes are a separate product that connect to the ECG-lead set, but when talking about the ECG product system it is included.

The electrode is the connection to the patient and is the only real part of the product system that interacts with the patient. It is a sticker with a small metal button that conducts the electricity from the patient's skin.
The clip connector is the connection from the electrode to the cable. Depending on the lead set it has a different shape.

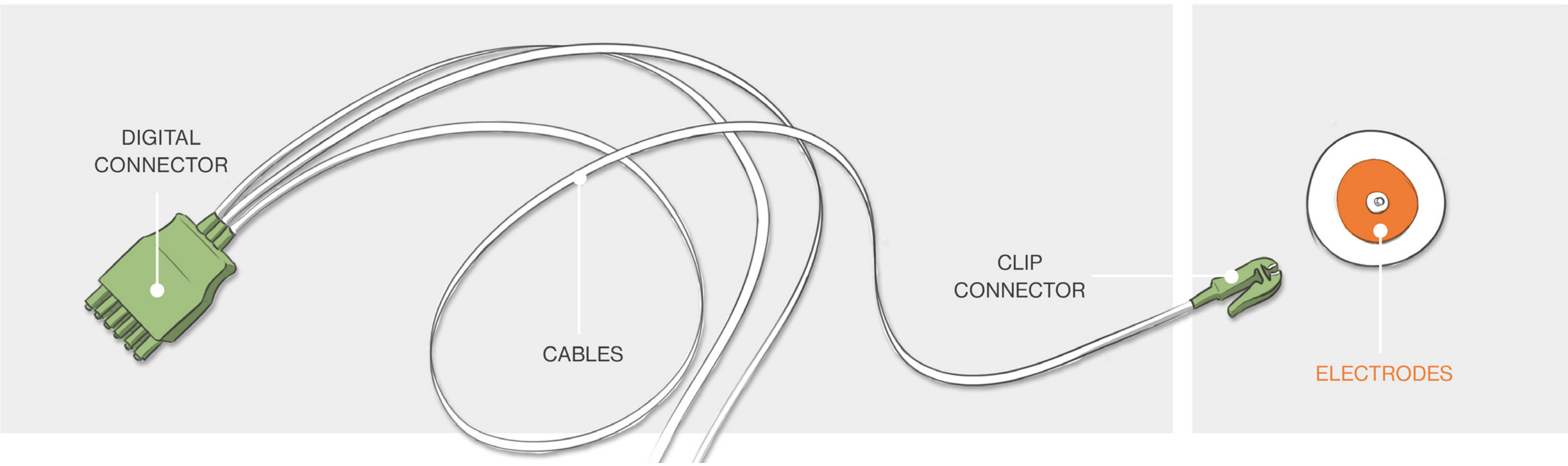


Figure7. Conventional ECG-lead set and electrode

The cable is the connection from the clip connector to the digital connector. This makes up the majority of the product, but itself is fairly simple.
The digital connector is a 6-pin connector that connects the number of leads/cables to the patient monitoring computer.

The product is basically a cable, it just transfers a signal from point A to B. Point A being the patient's skin and point B is the patient computer. This is where the signal gets corrected, calculated and interpreted. “Het broodje ” as it is often called, is a small computer that can be part of a larger system and the ECG is always attached here. There are two other vital measurements, blood pressure and oxygen saturation, that are measured continuously. Because of this continuous measuring, het broodje travels with the patient. When travelling from ICU to the OR for example, the vital measurements can be checked at all times. Upon arrival, het broodje gets plugged in to the bigger system, without loss of vital measurements.

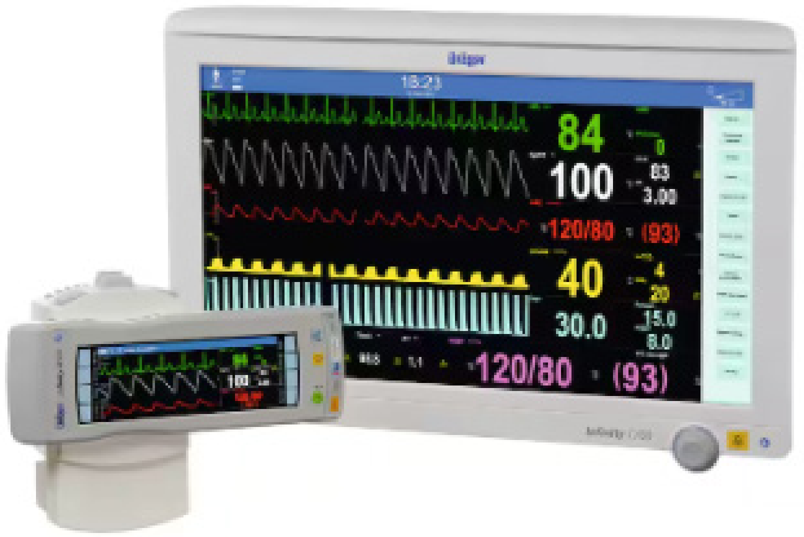


Figure8. Dräger patient monitoring system

Single-use and reusable ECG-lead sets

There are of course different types of ECG-lead sets, the most notable difference is the MPU ECG lead sets and SPU ones. The SPU sets are only used once and after that they are thrown away. The MPU sets get cleaned after they are used on a patient. Both products are classed as a Ia, which means they are low risk and do not for example have to be sterile.

In product features they are almost identical: they look mostly the same and work the same. The only notable difference from the outside is the build quality, the MPU set is made to last longer. More durable and high-end materials are used, whereas the SPU set is optimized to be as cheap as possible. This results in less material used and overall worse durability, which is fine for its purpose.

Why are there two types? Using a product multiple time is cheaper and also easy in a sense. The SPU ECG set is made and used because it is hygienic, and even easier to use. Because it gets thrown away a hospital does not have to worry about cross contamination, it also does not need to be cleaned which saves time for the nurses. The SPU ECG lead sets get mostly used in scenarios where the risk of contamination needs to be zero, patient that are in isolation for example.

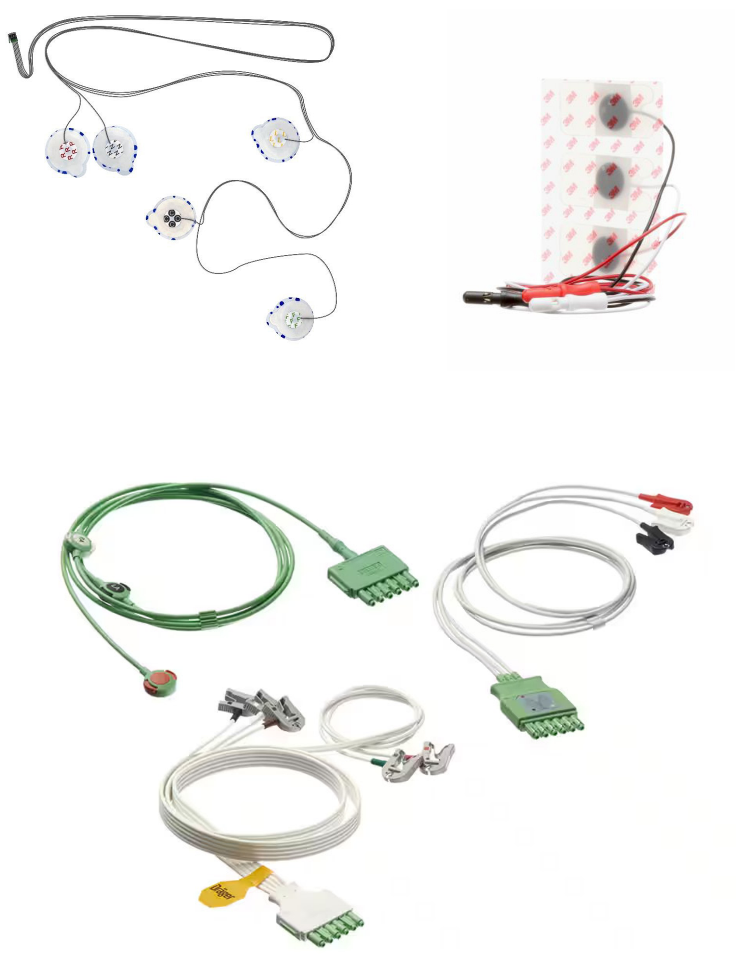


Figure9. Dräger MPU lead set (completely green) and on SPU lead sets

The ECG products technology

The product's technical principles seem not super complex, yet the product features can get quite complex. To truly understand the product, the mechanisms, and variations of each part, they are discussed here.

The electrode
There are different types of electrode used in practice. They differ in material, size, and shape. They all have a slightly different purpose, yet their working principles remain the same. The function of the electrode is to provide a stable connection from the skin of the patient, to the ECG-leads. Starting from the bottom, these are the elements which it consists of this is what is consists of.

The sticker film, is a layer to protect the sticky layer before it is used. The gel, is a substance and sometimes solid material, that is moist and soft. This makes it perfect to adapt to the skin and create a large contact area to the skin. It conducts the signal produced by the heart and is very important to make a stable connection to the skin. The sticker is the layer of the electrode that sticks to the skin. It supports a stable connection by making sure it stays in place, it does not conduct the signal itself. This layer is often textile material. The metal button is the connection point for the cable connector, besides that it bridges the sticker layer and conducts the signal from the gel. The shape of this connection is universal across all types of electrodes.

Different variations are mostly in the shape and size, this is mostly related to the different types of patients. Regarding the shape, they are always symmetrical, this is because otherwise it distorted the signal too much.

Besides these variations, there are also ones that use other materials. The two main reasons for that are allergies and interference. Because most of the other electrodes use a metal button, this can interfere with equipment like a röntgen machine or CT scan. Sometimes these types of test are done whilst a patient is hooked up to the ECG, for those cases there are other electrodes that are made of a conductive material that does not interfere. For allergy's sake, there are also electrodes that use a different material than the most common ones.

Figure10. 3M reddot electrode
(3M Electrodes | 3M Hong Kong, n.d.)

The clip connector
The connector is a simple part of the ECG-lead set that has only one function: to hold on to the electrodes. Different brands of ECG-lead sets, have different types of connectors, yet their goal is always the same.

The connector always consists of a moving part to clamp onto the electrode. Taking the clip connector for example: this one works by pushing down on the two ends; the material gives some resistance and ultimately wants to go back to its original shape. This is how the clamp force is applied, and the result is a strong and stable connection.

On the right in figure 11, there are two other types of connectors that work with a similar principle, but are slightly different. All types have a small bit of metal connected to them at the ends, on the right in figure 12, you can see this. This allows the signal to be transferred to the cable connection inside the clip itself, well protected.

The cable
The most straightforward part of the product is the cable, although there are still some differences here. In general the cables are made of some different layers, the core transfers the signal and is usually copper. This insulated with a layer of plastic and around this there is again a layer, that is called the shielding. Cable shielding is designed to protect against electromagnetic interference, ensuring reliable results. This is again insulated with the final layer, a TPU type of plastic that is flexible and durable.

The way the cable is configured is also different, a good example is the Monolead from Dräger. This cable places all the connector after each other, all on a “single” cable. It claims to be more user-friendly and result in less tangling of the cables. In other cases the different lead cables differ in length, the leads that are closer are then shorter and the ones further way longer.

The next component, in most cases, is an extension cable.. This connects to ECG-lead sets, and simply allows for more distance to be bridged by the cable, and only differ in length.

Digital connector
The last part is the digital connector, just like the electrode connection, universal (figure 13). Most of the patient computers, use the same 6 pin connection, but there are also connection with a smaller amount of pins. In total 12 pins are available at “het broodje”. Besides that, it is designed to only fit one way and makes the use quite easy.

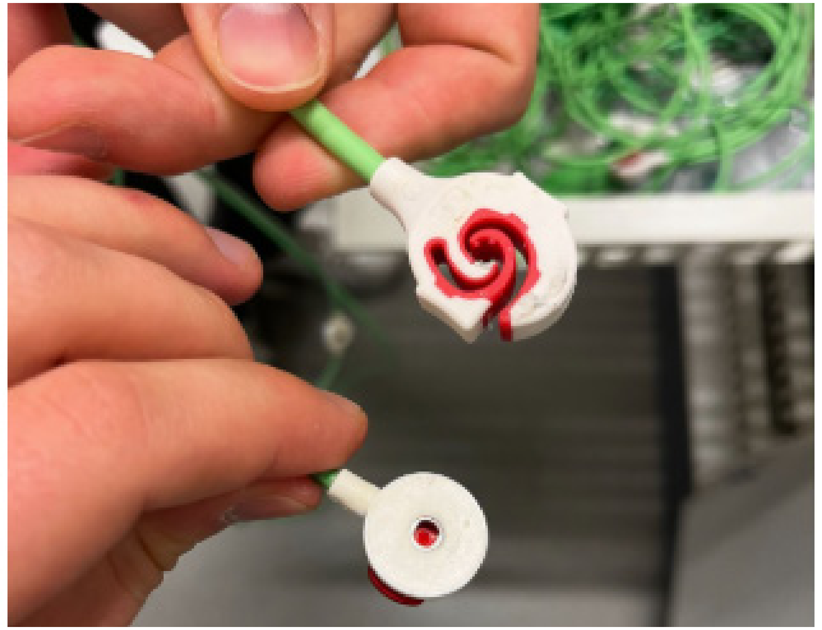


Figure11. Dräger MPU lead set, two types of clip connectors

Figure12. Dräger MPU lead set, clip connector

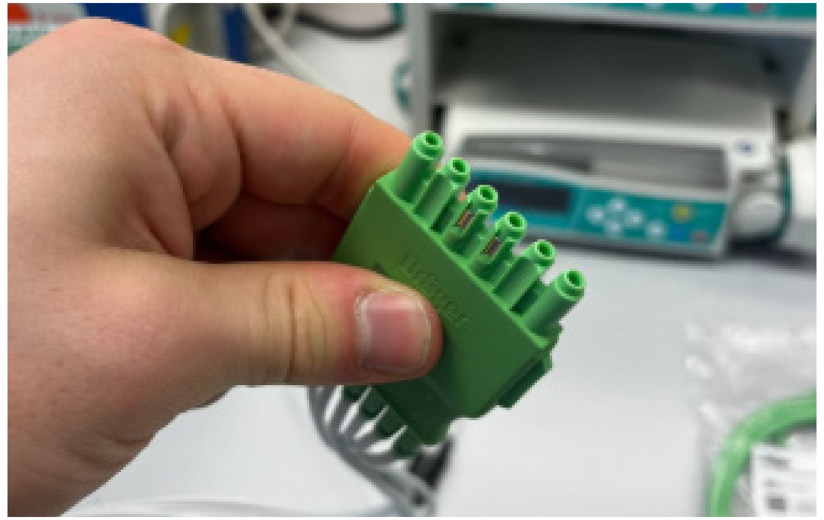


Figure13. Dräger MPU lead set, digital connector

The ECG field: Past and Future

In this section, we will look back at what has shaped the application landscape of the ECG-lead sets and electrodes which exist today, and look at where the trend is going. This broad overview helps to understand the bigger picture and can help to place this project in perspective.

This short time line sketches a good understanding of what has happened so far in the ECG field. Different positive developments got us to where we are now, but widely adopted breakthroughs can obstruct change and innovation (Vincent, 2022) & (Friedman, 2024).

Early 20th Century – The birth of medical ECG
In 1902, Willem Einthoven developed the first electrocardiograph. The following year, he recorded the first human ECG and introduced the PQRST wave. He also established the standard limb leads (I, II, III), laying the foundations of medical ECG interpretation.

Mid-20th Century – Advancements in technology and lead Systems
Advancements in ECG technology focussed mostly on new lead systems (new electrode placements). The precordial chest leads (V1-V6) and the unipolar limb leads (aVR, aVL, aVF) were developed, creating the modern 12-lead ECG. By the 1950s and 1960s, the first computerized ECG analyses were introduced, as well as disposable gel electrodes.

Late 20th Century – Digital and Portable ECG's
With advancements in electronics and computing, the ECG machines became smaller, making them portable and more accessible for clinical use. By the 1990s, ECG interpretation had become computerized, improving accuracy and enabling better decision-making.

Early 21st Century – Wireless and Wearable ECG's
In the 2000s, wireless ECG systems became more common, and we saw the integration of ECG technology into consumer devices like the Apple Watch. Making heart monitoring widely accessible, as we know it now.

Another, development that is relevant to discuss is the rise of plastics. Previously medical devices were all MPU, they were valuable and difficult to make. However, with the rise of plastic, the market for SPU medical devices rose. Single-use was viewed as good and the solution to a lot of problems. This view still affects us, it results in good product, but for the sustainable healthcare sector it proves to be very frustrating.

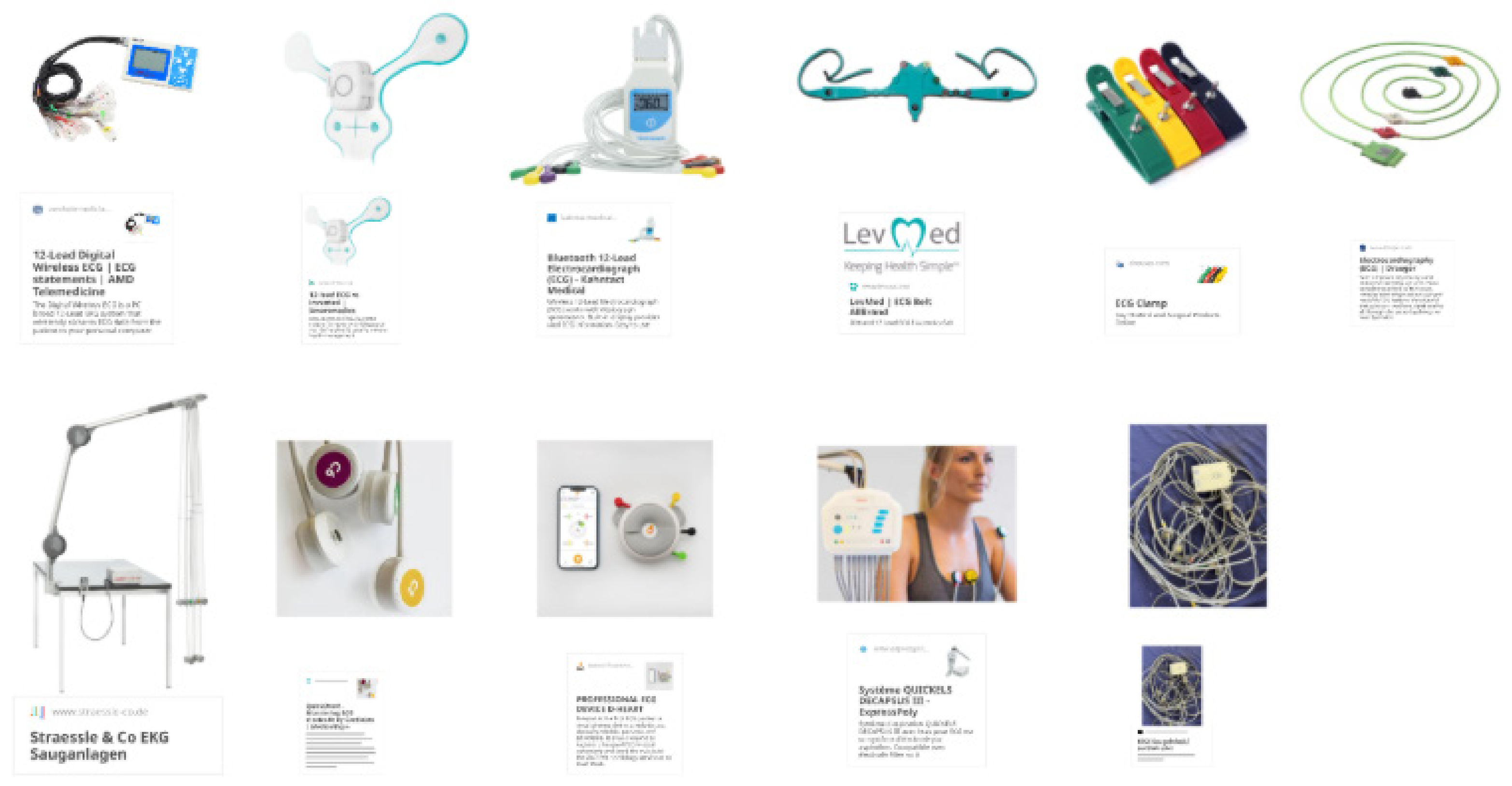


Figure14. Overview of different ECG products

This brings us to today, where there are still new developments taking place and new technologies explored in relation to the ECG. Throughout the years, the ECG has played a vital role in the medical world and solidified its place as the number one tool to diagnose heart related conditions. Interesting to see is that there are a lot of different variations in ECG products currently.

We have already seen what has shaped the field up until now, in this overview (figure 14) it becomes clear what this has meant for the products itself. There are also some products that already give us a hint to where we might be going.

The first three products (from the top left), show that ECG product market is moving toward more portable, easy-to-use, and connected devices. This is oriented to smart healthcare and trying to improve patient care from a distance. This is relevant, because the increasing demand for care can be relieved when prioritizing prevention, and postpone the moment for care. Newer ECG devices are now also becoming wireless, use Bluetooth, and can connect to smartphones or tablets. Some are even wearable, like ECG belts, making them easier and faster to use. These are again a great fit for home use or telemedicine, where patients can be monitored from a distance.

While many hospitals still use traditional wired systems with electrodes, there are also alternatives for these systems. For example, there are systems that use suction cups or clamps, from a sustainability perspective this is also interesting. Because there is no waste involved in these systems, except cleaning. These systems also try to rethink the way the product is used and adapt more to the patient.

The current products are interesting to observe, however it is also clear that the traditional product of the ECG-lead set is still the standard. The examples above are on the market but do not have a large market share yet.

Advancements towards sustainability

Technology moves quick, and there are two obvious drivers that pop in many places: sustainability and machine learning. In the field of the ECG new; research, initiatives and technical innovations this no different. This section discusses the advancements and trends that are relevant for the ECG, and tries to envision the future of the field.

Lead Reduction & Optimization
Since the standard 12-lead placement, there has always been a certain obsession to new placement standards. In research the new placements are compared to the standard, also research on which leads are important to keep is relevant. With the introduction of AI, this area became more relevant and the search to reduce the amount of leads has received renewed attention. There is a focus on reducing the number of ECG leads while maintaining or improving accuracy.

AI Integration in ECG Analysis
There is already an FDA-approved AI 12-lead product on the market, claiming to be accurate and use less leads to still perform a detailed “12-lead” recording. AI, is also used to interpret results better, recognizing patterns and diagnose automatically. Lastly, there are models that try to detect misplacement of electrodes, improving the quality of the reading by providing feedback for the users. AI is being leveraged for both lead optimization and automated interpretation of ECG data.

Sustainability & Reusability
Advancements in the electrode patches mostly focus on sustainability. Research for new materials and alternatives, like a biodegradable patch and a reusable patch, are relevant for this sub-product of the ECG. Besides that, reusability is being researched, not only the dilemma of using either SPU or MPU cables. These are also initiatives like the reprocessing SPU lead sets. There is an increasing emphasis on sustainability, including biodegradable patches and reusable components.

Wearable ECG Monitoring
Some new technologies strongly relate to the world of wearables. To reduce pressure on the healthcare sector, people are stimulated to do more from their own home. The Philips home monitoring product, for example, purely focusses on this and uses a specially designed patch for wearable electronics. Innovations in wearable and home-based ECG solutions are emerging.

Although not all these trends directly contribute to sustainability, they might indirectly do. Besides that, it is good to see the way the industry is going and understand where new opportunities might lie for sustainable solutions.

3

ERASMUS MC CONTEXT

The organizational background of Erasmus Medical Centre (EMC) is described in this chapter, providing details about the internal and external structure and influence of sustainability initiatives. An outline of EMC's organizational structure and its specific sustainability programs, like the Green Teams, are given at the outset. The chapter looks at the larger network of outside parties, such as partners, suppliers, and governmental organizations, which influence or shape sustainability goals. Lastly, it talks about competing interests among stakeholders, especially in the argument between reusable and single-use medical devices, emphasizing the intricate decision-making environment that sustainability solutions must function in.

3.1 ORGANIZATION STRUCTURE

The Erasmus medical centre has almost 18 000 employees, comparable to a small village. This requires a clear structure to allow for different disciplines to come together and work on their core tasks, patient care, education, and research. In figure 15, the structure of the EMC is shown.

In Dark blue, the organizational departments are indicated, they fully focus on controlling the EMC and steering the organization in the right direction. They do not directly contribute to the core tasks, but are very important to keep everything in line. The executive and supervisory board lead the organization, in the end everything has to go through them.

The orange branch, shows the different advice and participation councils. This is the main feedback loop for the boards, a way to get insight into how all processes are going on the work floor. Different types for different roles in the EMC, representing everyone that works for EMC.

The Themes, in light green, are the main themes of the hospital. Under a theme you still find different sub-departments, but at this level common services are managed for the whole theme. For example, the theme Sophia houses all the medical care related to children, departments like Paediatric surgery and Adolescent Psychiatry are housed under this theme.

In yellow the services, these are basically all the background tasks that need to be performed in order for a patient to be able to receive the care they need. These services often get arranged per theme, so the department of finance will service each theme separately.

Lastly, the programs, they focus on different developments that are taking place. Sustainability for instance is a topic that needs to become relevant in each department, theme and service, by having its own program it ensures these developments are clearly represented and get the attention they require.

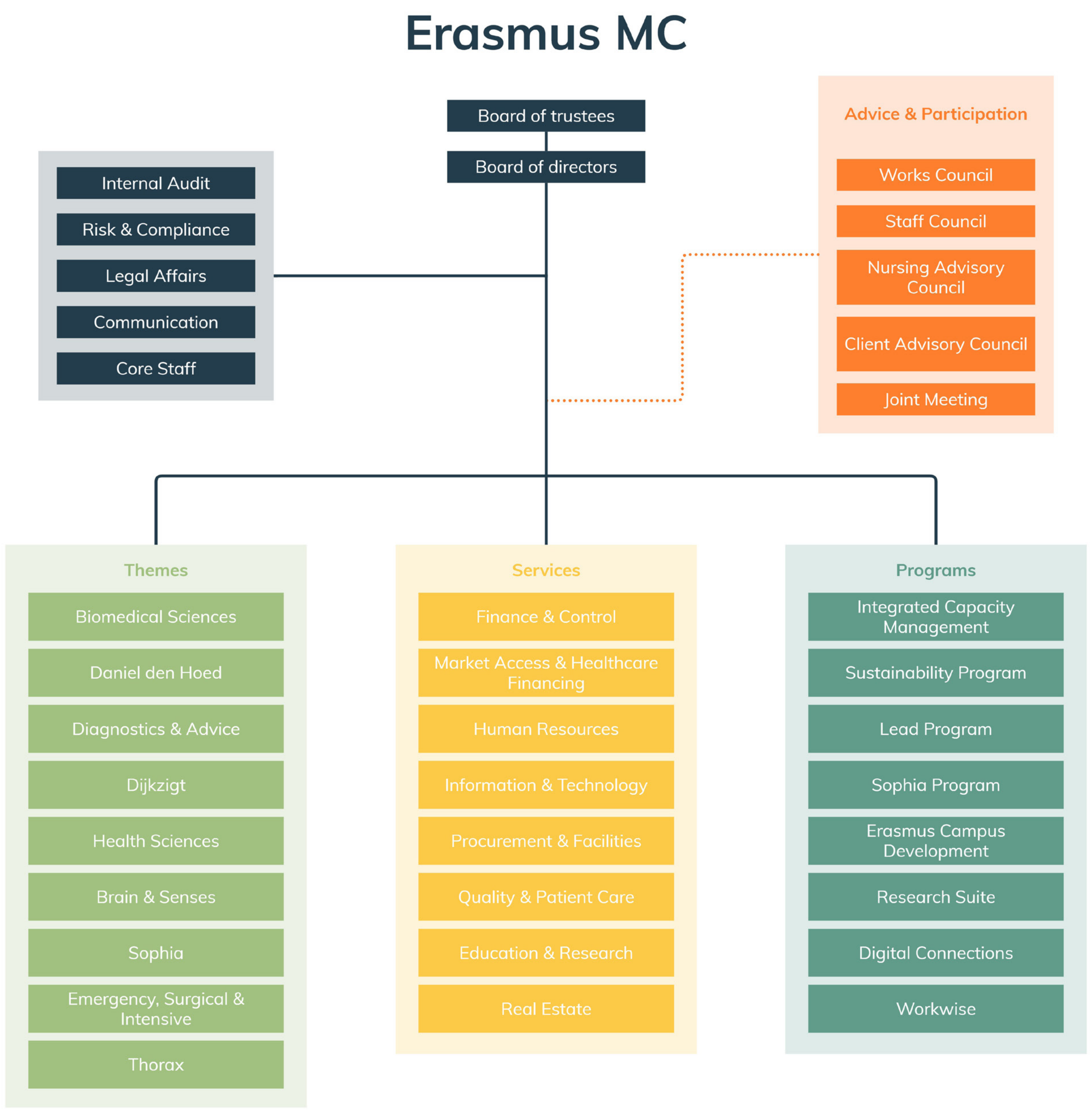


Figure15. Organization structure

3.2 SUSTAINABILITY INITIATIVES

The Green Deal 3.0 sets out five key goals: promoting health through better diets and lifestyle, raising awareness of the links between climate and health, cutting CO^2 emissions by 55% by 2030 and reaching climate neutrality by 2050, reducing the use of raw materials by half and maximizing circularity, and minimizing the environmental impact of medications. The sustainability program of the EMC is organized in such a way that these goals can be achieved (Green Deal Duurzame Zorg 3.0, n.d.).

Green Teams
The Green Teams and play a central role in promoting sustainability within the different themes, services, and programs of the EMC. Two full-time employees focus to coordinating the various Green Teams, the teams themselves consist of volunteers who, alongside their regular roles, dedicate their time to sustainable initiatives. The aim is to start from the ground up to reach out to people which are intrinsically motivated, subsequently together with their Green Team they can support, spread, and drive action within EMC.

Recently, the number of Green Teams at EMC has more than doubled to now 47, each comprising approximately four to eight colleagues who work self-directively on projects aimed at enhancing sustainability within their respective departments or sectors. (Erasmus MC, n.d.)

The focus is on achievable, short-term improvements that are relevant now. It is not so much about concrete solution, more so about awareness and recognition of the sustainability issue (up until now at least).

Figure16. Picture green deal 3.0

3.3 EXTERNAL STAKEHOLDERS

Since, the organization's structure and goals are clear of the EMC, it is time to look at the external stakeholders that impact the overall context in which this project is positioned. This is relevant to be able to know the limits for the design phase.

The stakeholder map (figure 17), shows the different parties involved within EMC. There are endless stakeholders, this map shows the most relevant ones that contribute to sustainability and are related to the ECG field.

For this project the ECG companies are the most interesting to look at, there are a few that have sold their products to EMC. Currently, most of the ECG-lead sets are supplied by Dräger and the electrodes mostly by 3M. These parties are leaders in their industry and can offer EMC good quality products.

The bigger stakeholders such as, the government and the municipality of Rotterdam, directly influence the EMC in their organizational goals. Although they work together, it is mostly EMC that has to decide what they deem necessary. Besides that, a lot of the EMC is funded by the government, because they are a hospital, but also because they provide education. This makes them very important stakeholders to the EMC, where a good relation is crucial.

Because the EMC is a academic hospital, relations to other research institutes are important. There are a lot of these institutes, also within the EMC. Sharing knowledge is the foundation of innovation and allows for the EMC to be a fore runner in academic research. The Erasmus university is the strongest relation to the EMC, but TU Delft also is becoming more relevant. Initiatives like Convergence, and plans to create a campus together indicate the technical and medical field are coming together.

Lastly, the other hospitals and academic medical centres are highlighted here. When promoting sustainability, the only way to achieve the goals is to work together. Sharing knowledge insights and common understandings help to show each other what is possible. A project like this one, in a way, is an example of how other hospitals can take inspiration of the EMC and this project specifically.

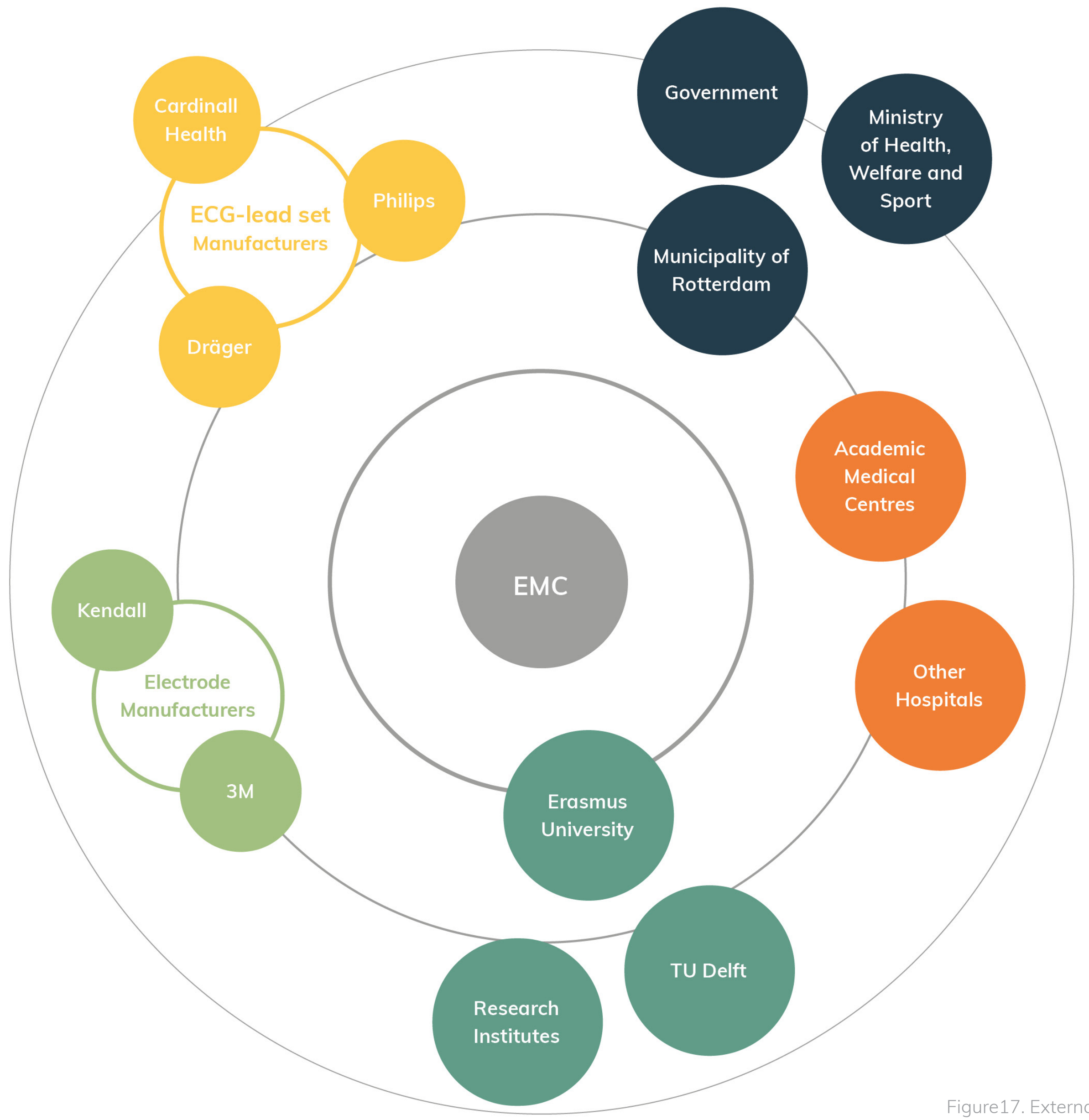


Figure17. External stakeholder map

1

3.4 CLASHING INCENTIVES

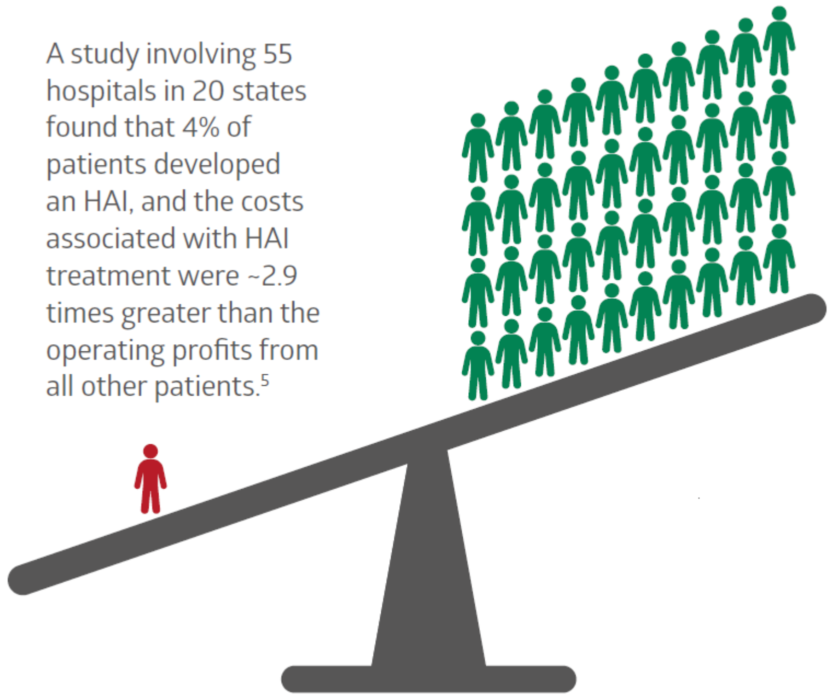
In the stakeholder map everything seems peaceful, yet in reality every stakeholder has their own agenda. Unfortunately, sustainability is especially difficult to work on together, because of everyone's own interests. Some of these relations are mentioned here to demonstrate the difficult field and keep an eye on whether there are some opportunities.

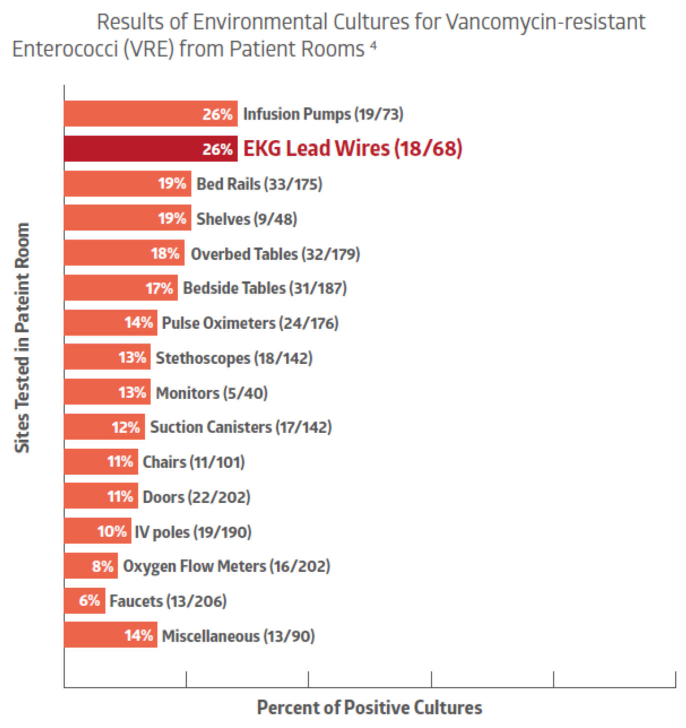
The main arguments in favour of SPU revolve around infection prevention, with key concerns being cross-contamination and the financial impact of healthcare-associated infections (HAIs). Companies like Dräger are actively promoting SPU, emphasizing these safety and cost-related points. The push seems to be strongly driven by financial incentives, and research is done in a way to make MPU devices look bad. In figure 18 there is an example of this, where the costs of a HAI are depicted as the worst possible outcome (Centers for Disease Control and Prevention, 2021).

It has to be said that it is good to consider the risks of MPU devices, yet research that is not independent should be looked at critically. Because this argument heavily supports the companies case and their financial benefits.

On the other hand, MPU lead sets are also supported for their sustainability and cost-effectiveness in the long run, especially when proper cleaning protocols are followed. They're also considered better for comfort and ease of use, likely due to more refined, reusable designs. This highlights a growing tension between clinical safety priorities and environmental and economic concerns, showing that the direction of development may depend heavily on policy, infection risk, and budget constraints. Understanding these contrasting arguments helps to map where the field might be heading and to understand where to fit in.
In favour of sustainability, the relation of the EMC to the market is also interesting to highlight. In the Netherlands, we have the Procurement Act that ensures that public contracts are awarded fairly and transparently. It gives all suppliers equal opportunities, and the goal is to prevent corruption and use public funds efficiently. It allows EMC when negotiating the best contract, to also ask companies to contribute to their sustainability goals. This is a relatively new requirement for companies and lets EMC leverage their position, as these types of contracts are substantial for these suppliers.

Figure18.Two figures from this report: (Centers for Disease Control and Prevention, 2021)





4

UNDERSTANDING ECG AT EMC

To design a more sustainable ECG lead set, it is essential to first understand how the product is currently used. This chapter provides an in-depth exploration of the use of ECG systems at EMC, focusing on practices and user experiences. Through a combination of observations, interviews, and data analysis, this section maps out the entire product lifecycle of ECG lead sets.

By examining these different factors in the daily practice of departments such as the ICU, cardiology, and OR. The goal is to identify environmental hotspots, user needs, and process-related barriers in order to start designing. Overall, this chapter lays the foundation for ideating and implementing more sustainable ECG products based on the practices at EMC.

The use of ECG's in EMC: How much?

Identifying and understanding how ECG-lead sets are used in the EMC creates a clear understanding and places it in the right context. Analysing and conducting research on the system resulted in this context specific insights.

Product lifecycles

The different types of lead sets have a different product lifecycle, in this overview (figure 19) the aim is to show the different routes this product can take.

The SPU and MPU ECG lead set are the two main different types that are relevant to discuss. They share identical first few steps in the product life cycle, first they are taken from storage and taken out of their packaging for use. When this has happened the setting up of the test is the same, they first place a number of electrodes and after that connect the cables to them. The product is used for a certain amount of time, depending on the context this can be up to 48 hours, but also as short as 5 minutes.

Then, when the recording finishes, the electrodes get thrown away in both of the use cases. However, the SPU lead set also get thrown away in the general waste. For the MPU lead set, it gets reprocessed through cleaning. This is done with a micro fibre cloth, first it is inspected visually and depending on how dirty it is some extra water gets used. The cleaning takes approximately 30 seconds. After this, the cable is wounded up in a bundle and hung underneath the patient computer. This shows to the other nurses that it is clean and ready to bemused again, and so it can get used again.

The SPU lead set, gets used for only one time and after that becomes general waste. There is no recycling done for the product. The MPU lead set, gets used for multiple cycles and is thrown away only after it has broken. When it is broken, the nurse bring is it to the technical support department, they can do a double check. They are not allowed to fix the product, they can only ensure that it is broken and not thrown away unnecessarily. From observation, the longest a lead set has been used is 10 years, but it is difficult to say what the average lifespan is. This is because the product are not tracked at all, so they are just bought and thrown away when broken, for now there has been no interested in tracking this data.

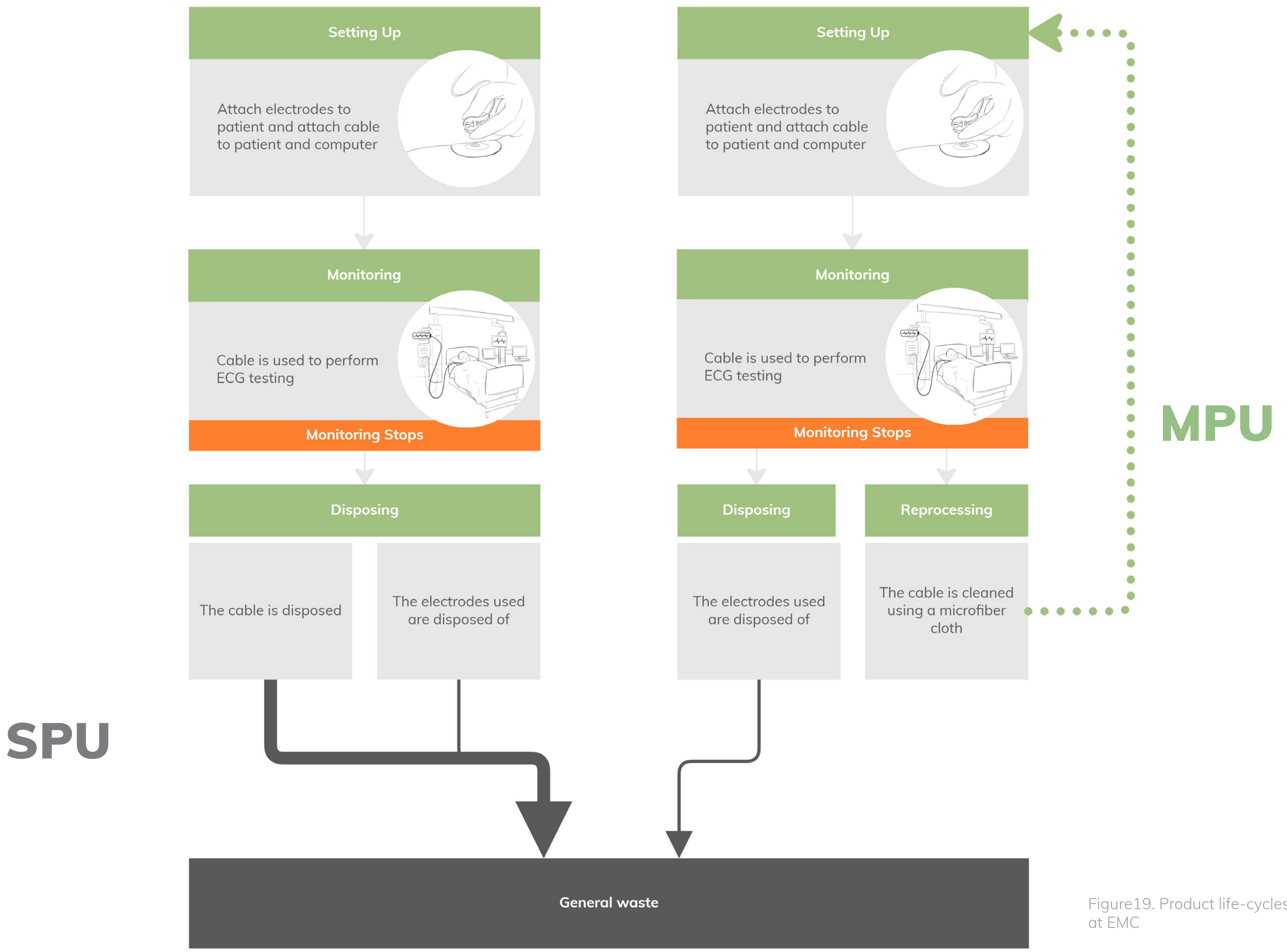


Figure19. Product life-cycles at EMC

Product use 2024

Disclaimer: the numbers used in this section and in sections following this one. These numbers are fictive and the real numbers can be found in appendix A.

It is difficult to find the exact amount of ECG-lead sets in the EMC because of the different product lifecycles. To still understand the scale at which the ECG gets used in the EMC, the purchasing records of 2024 (appendix A) helped to gain perspective.

The data shows the number of electrodes purchased in one year, and since the electrodes are only used once and thrown away it helps us to give insight into roughly how many ECG's are used at the EMC.

In figure 20, the amount of use is shown. On average 2400 electrodes per day are used. The cost of one electrode is on average only 0.11 euros, still it accumulates to 350 euro a day spend. It is an estimation, but if we say that there are 8 electrodes used on average per ECG test. Then there are roughly 300 ECG performed per day.

The total number of electrodes used was 880000, in figure 21 the distribution of these electrodes is shown per theme, the same themes as discussed in the organization structure.

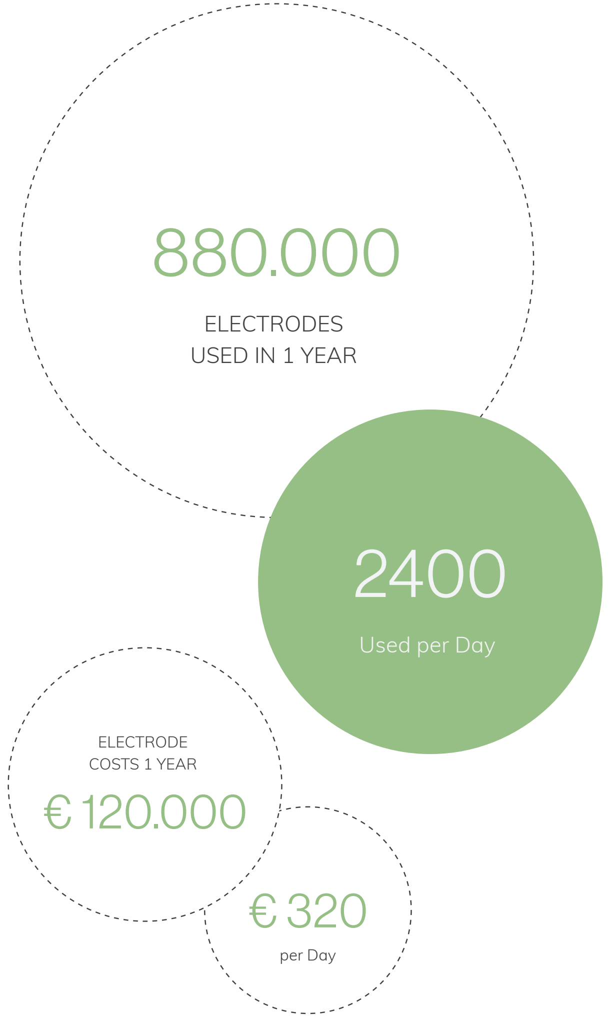


Figure20. Product life-cycles at EMC

As becomes apparent, most of the electrodes are used on the Thorax and the Emergency, Surgical & Intensive. Together they form 76% of the total use, with runner-up being Sophia. Sophia has shown to have the most different types of ECG products used. This is mostly due to the fact that they need a lot of different sizes and types of product because of the large range of patients.

A total of 200 new cables are bought in a year, the prize of these are a lot higher than the electrodes. The average purchase cost was 180 euros for the cables. This gives a good impression of the price range, but because the ECG lead sets are not tracked during their lifecycle it is difficult to use this data for anything else.

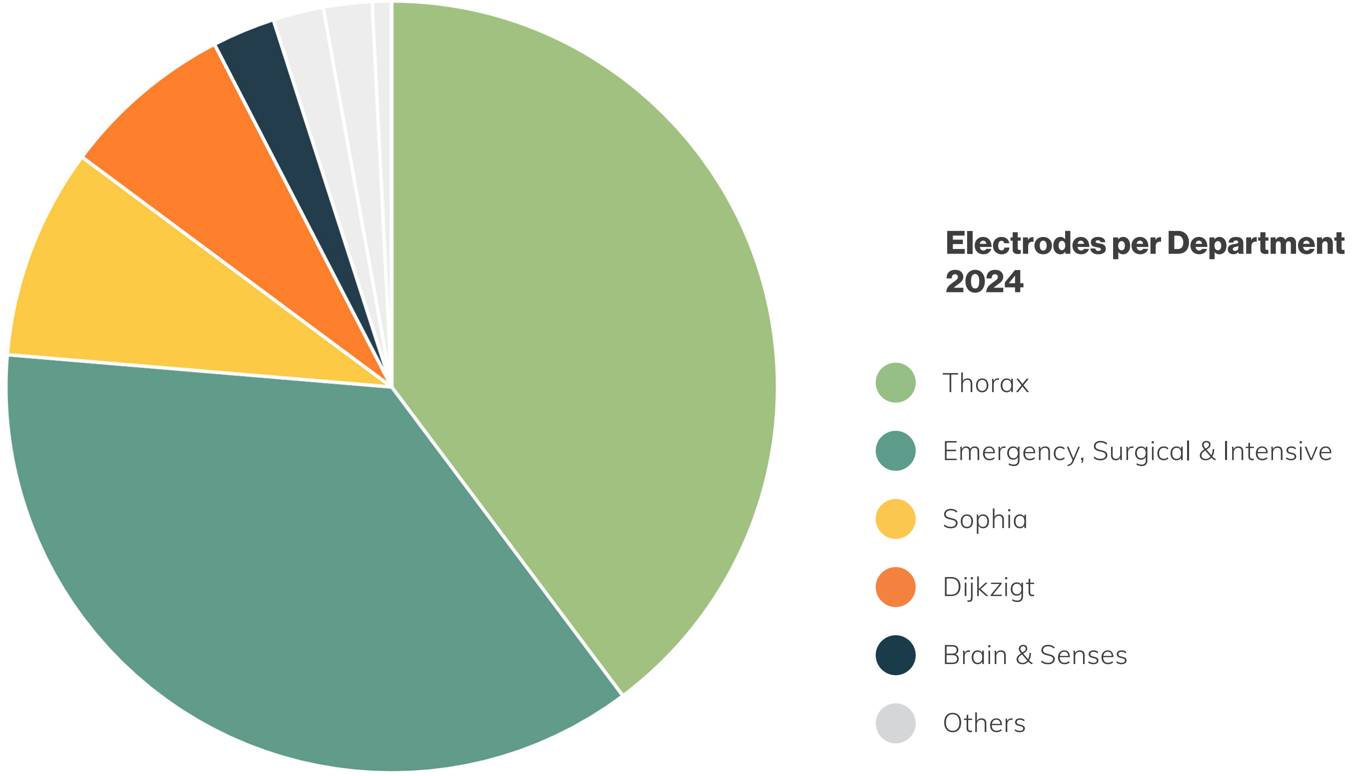


Figure21. Electrodes er department

4.1 THE ECG BEING USED IN PRACTICE

To discuss the different processes of use, these user journeys were made. After collecting data at the respective departments by interviewing and doing observations, this overview was made. It highlights the fact that although if you look from a far all the procedures look the same, there are still a lot of details that are different and should be taken into account.

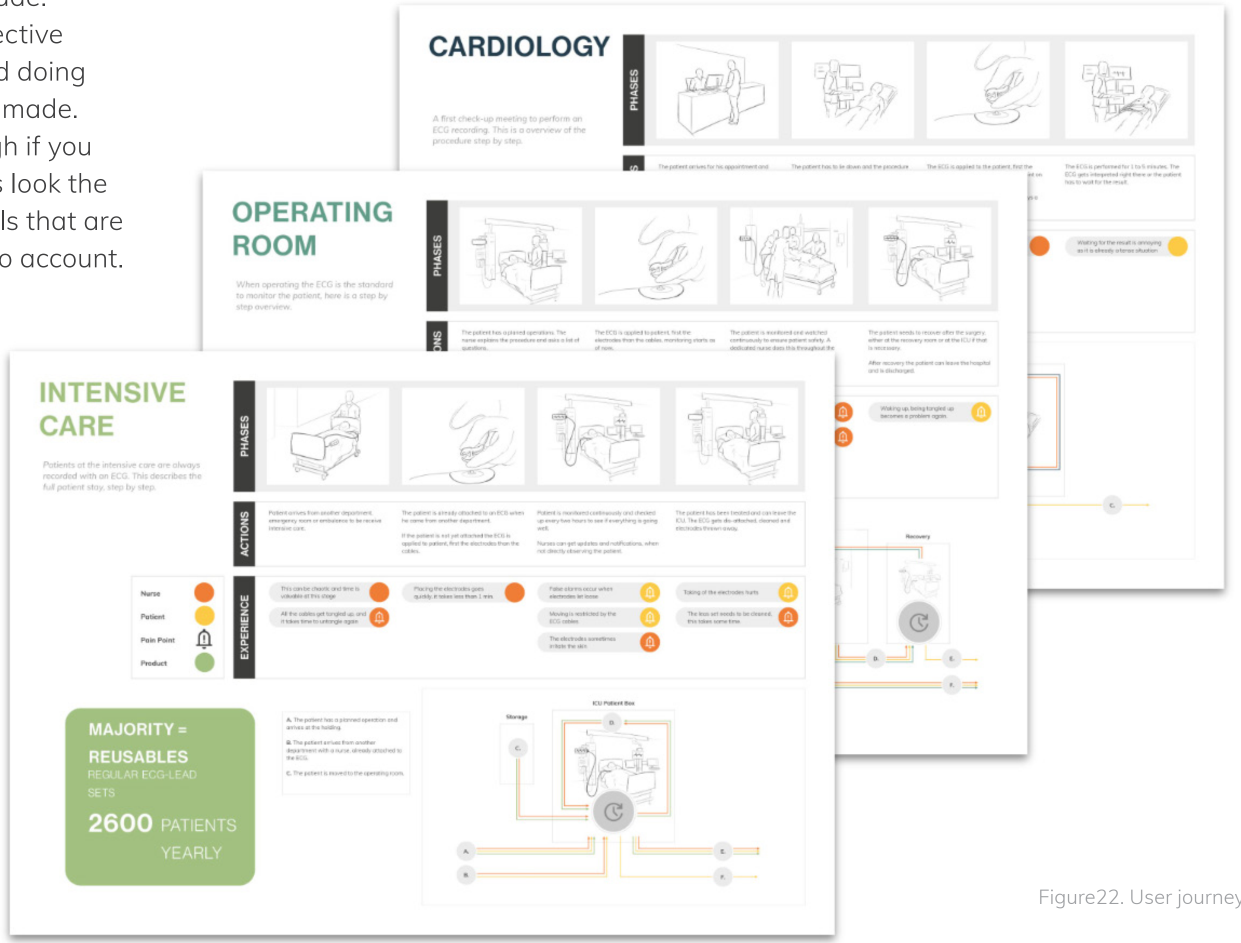
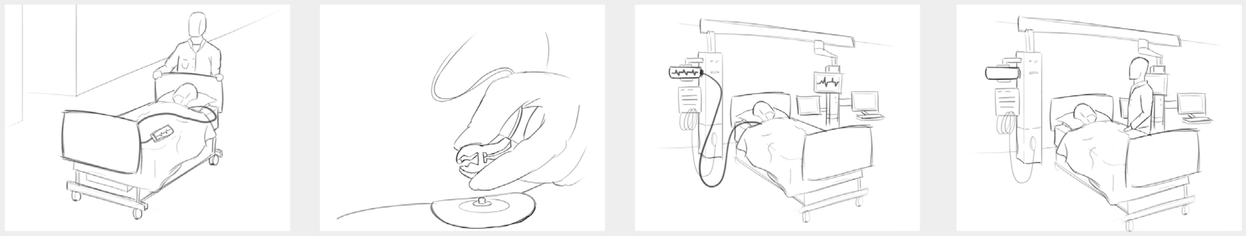


Figure22. User journeys

INTENSIVE CARE

Patients at the intensive care are always recorded with an ECG. This describes the full patient stay, step by step.

PHASES



ACTIONS

Patient arrives from another department, emergency room or ambulance to be receive intensive care.	The patient is already attached to an ECG when he came from another department. If the patient is not yet attached the ECG is applied to patient, first the electrodes than the cables.	Patient is monitored continuously and checked up every two hours to see if everything is going well. Nurses can get updates and notifications, when not directly observing the patient.	The patient has been treated and can leave the ICU. The ECG gets dis-attached, cleaned and electrodes thrown away.

EXPERIENCE

Nurse
Patient
Pain Point
Product

This can be chaotic and time is valuable at this stage (Nurse)	Placing the electrodes goes quickly, it takes less than 1 min. (Nurse)	False alarms occur when electrodes let loose (Pain Point)	Taking of the electrodes hurts (Pain Point)
All the cables get tangled up, and it takes time to untangle again (Pain Point)		Moving is restricted by the ECG cables (Pain Point)	The leas set needs to be cleaned, this takes some time. (Pain Point)
		The electrodes sometimes irritate the skin (Pain Point)	

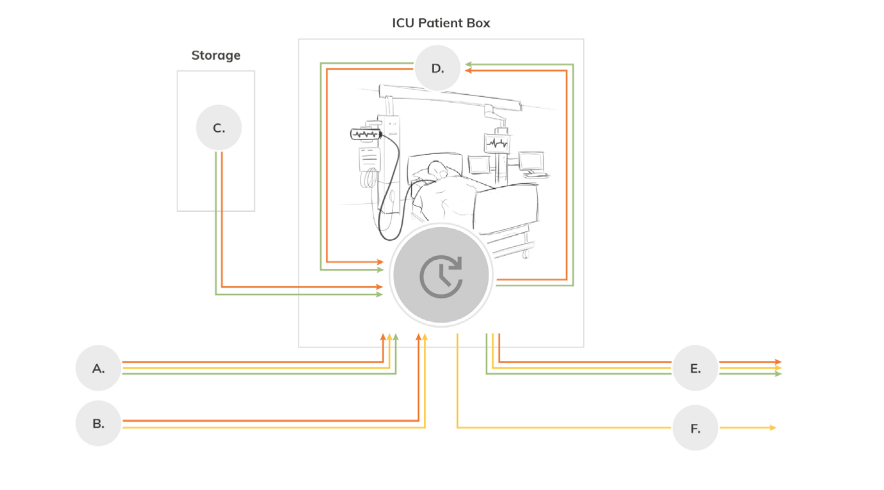
MAJORITY =
REUSABLES
REGULAR ECG-LEAD SETS

2600 PATIENTS YEARLY

A. The patient has a planned operation and arrives at the holding.

B. The patient arrives from another department with a nurse, already attached to the ECG.

C. The patient is moved to the operating room.



CARDIOLOGY

A first check-up meeting to perform an ECG recording. This is a overview of the procedure step by step.

PHASES

ACTIONS

The patient arrives for his appointment and registers at the front desk. After that the patient waits in the waiting room for a bit.

The patient has to lie down and the procedure is explained by the nurse or doctor. After this intake procedure the test can start.

The ECG is applied to the patient, first the electrodes than the cables. From this point on the recording starts.

At this the department it is almost always a 12-lead ECG.

The ECG is performed for 1 to 5 minutes. The ECG gets interpreted right there or the patient has to wait for the result.

EXPERIENCE

Nurse
Patient
Pain Point
Product

The patient might be a bit tense for the test.

Explaining the procedure helps the patient to relax

Explaining takes some time and is repetitive, but part of the job

Placing the electrodes goes quickly, it takes less than 1 min.

Waiting for the result is annoying as it is already a tense situation

100 % =

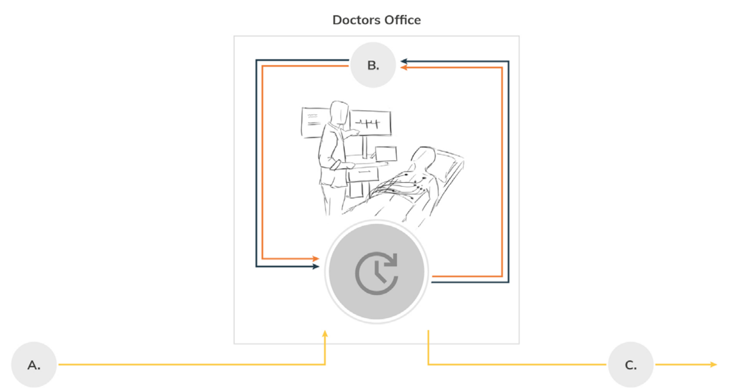
REUSABLE

A DEDICATED ECG MACHINE THAT STAYS ON THE DEPARTMENT

A. The patient arrives from the waiting room and enters the doctors office.

B. After the procedure the ECG cables are cleaned by the nurse or doctor. Because it is a stationary machine it does not leave the department.

C. The patient can leave straight away after the procedure and go home.



OPERATING ROOM

When operating the ECG is the standard to monitor the patient, here is a step by step overview.

PHASES

ACTIONS

The patient has a planed operations. The nurse explains the procedure and asks a list of questions.

The patient arrives from another department, than it is often a emergency.

The ECG is applied to patient, first the electrodes than the cables, monitoring starts as of now.

The patient is already attached to an ECG, the patient computer is transferred.

The patient is monitored and watched continuously to ensure patient safety. A dedicated nurse does this throughout the procedure.

The patient needs to recover after the surgery, either at the recovery room or at the ICU if that is necessary.

After recovery the patient can leave the hospital and is discharged.

EXPERIENCE

Nurse
Patient
Pain Point
Product

This can be chaotic and time is valuable at this stage

All the cables get tangled up, and it takes time to untangle again

A operation is scary and overwhelming

Placing the electrodes goes quickly, it takes less than 1 min.

Depending on the operation, electrodes are placed creatively

Electrodes let loose and interrupt the operation.

All different cables get tangled up when working on the patient

Waking up, being tangled up becomes a problem again.

MAJORITY =

REUSABLES

REGULAR ECG-LEAD SETS

SINGEL-USE

SETS ALLOW FOR RONTGEN & CT SCANS

A. The patient has a planned operation and arrives at the holding.

B. The patient arrives from another department with a nurse, already attached to the ECG.

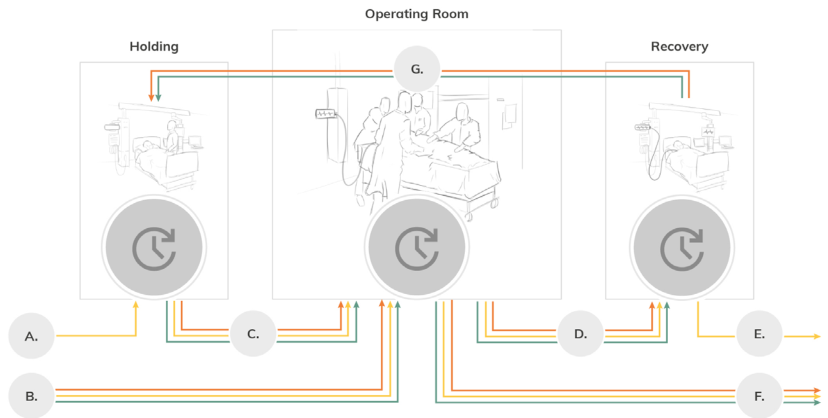
C. The patient is moved to the operating room.

D. The patient is moved to the recovery room.

E. After fully recovering the patient is discharged from the hospital.

F. The patient needs intensive care after the operation to recover fully and is moved to the department.

G. The ECG lead set is detached from the patient, cleaned and moved back to the holding.



The patient and nurse
Noticeable is that most of the user issues are both annoying for the nurse and patient at the same time. They experience the problems differently, like the tangling of cables, is uncomfortable for the patient but for the nurse more annoying in their work. The most occurring issues come from the ECG-lead set being tangled, not perceived as clean, and electrodes letting loose. In the grand scheme, all these issues are quite small, yet they can accumulate into bigger concerns and consequences.

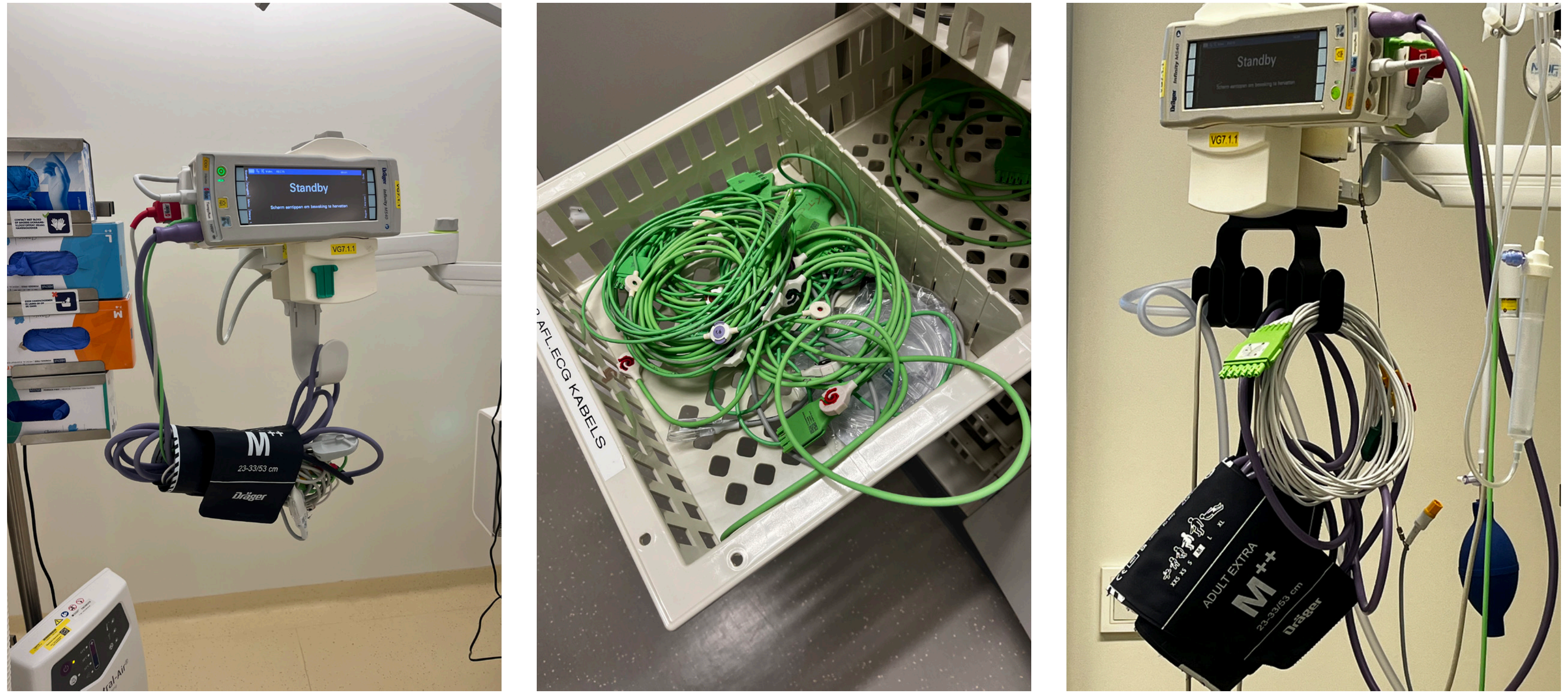
The cardiology department
The cardiology department uses a quite different type of ECG-leads. The machine is often stationary, or at least one big trolley, that houses a computer and ECG-leads. The procedure takes only a couple of minutes and is a very short procedure compared to the other departments.

Interestingly, there are still single-use products being used here, the electrodes get thrown away after each patient. Which is remarkable to see, when you consider they might not be used for more than 5 minutes.

Movement of the ECG
Due to its importance in patient monitoring, the ECG-lead sets travel between departments whilst continuously monitoring. This changes the scenarios in some cases, because a patient can either arrive with an ECG already applied, but also without. For the product, this means it roams around in the hospital.

A consequence is that departments like to keep them in stock, and hoard the sets so they always have enough. They perceive an ECG lead set that goes to another department as lost. It begs the question if this is desirable and indicates a user issue.

Figure23. Pictures of ECG-lead set storage at different departments



Cleaning the ECG lead set in practice

Since ECG lead sets are categorized as Class I medical devices, they don't need to be thoroughly cleaned or sterilized. This is due to the fact that they are regarded as low-risk devices that only come into contact with healthy skin. Therefore, rather than adhering to stringent clinical hygiene standards, their cleanliness primarily serves utilitarian and aesthetic purposes.

Cleaning is done after every patient recording when utilizing a Multi-Patient Use (MPU) lead set. In both single-patient and multi-patient use scenarios, the electrodes are discarded after the ECG recording is finished. But there are some notable differences in how the lead set is handled:

SPU Lead Set: The electrodes and the complete lead set are disposed of in the general waste stream. There is no reprocessing or cleaning.

Multi-Patient Use MPU Lead Set: The lead set goes through a reprocessing step following electrode removal.

Visual Inspection: First, the cable is inspected for any obvious contamination or dirt.

Cleaning Procedure: The lead set is cleaned with a microfibre cloth. To help remove the debris, a small amount of water may be added to the cable if it looks noticeably dirty. There is no use of specialized cleaning products.

Duration: It takes about 30 seconds to complete the cleaning procedure.

Storage: The cable is hung beneath the patient computer after being cleaned and wound into a tidy bundle. Other employees can see that the lead set has been cleaned and is prepared for use thanks to this placement.

By utilizing the device's low classification and making sure it is properly maintained for safe ongoing use, this simplified cleaning technique strikes a balance between efficiency and basic hygiene.

In the figure 24, pictures are made of the MPU lead sets. They show cables not being cleaned properly and as well as broken points.

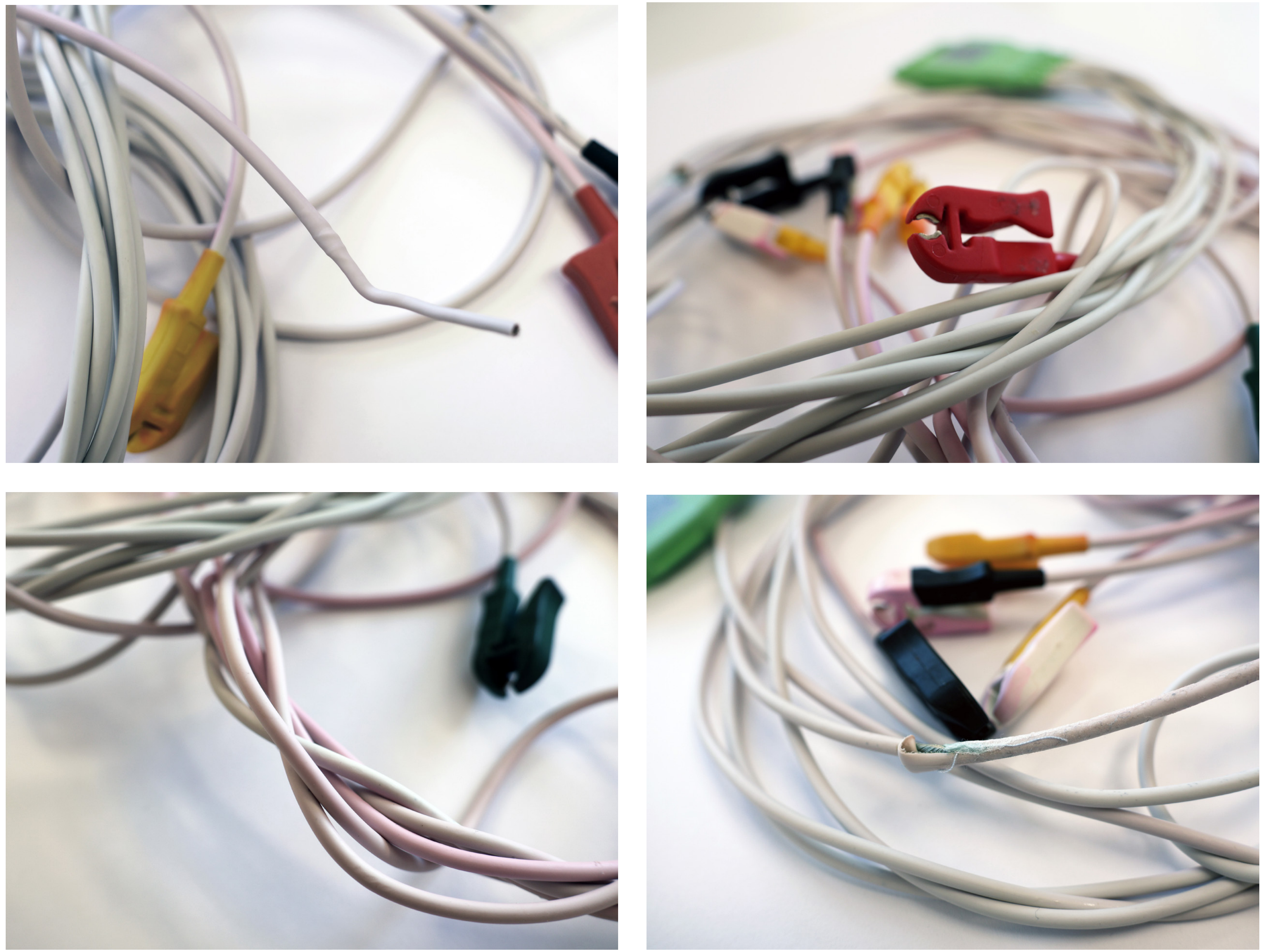


Figure24. Pictures of used and broken ECG-lead sets

4.2 LCA OF ECG-LEAD SETS USED IN EMC

As already been mentioned, the emission of CO^2 of a MPU medical device against a SPU one has been found to be less than the SPU version. However, it depends on the context, to see how the ECG-lead sets compares in the context of the EMC a Life cycle assessment (LCA), was performed. The method and results are discussed in this chapter, for the full detailed description see appendix B. The calculation were made using the Idemat 2024 database used commonly in the education at TU Delft (Eco Costs Value, 2025).

Method
For this comparison two types of ECG-lead sets were compared, both are used in the EMC. The lead sets both are from Dräger and by taking apart each version, the materials were weighed and evaluated. For the cables, a section was weighed and then used to calculate the full length of the cable.

The process of selecting the right materials was done by more desk research, this results in an estimation of the lifecycle impact and not a definitive answer. Trough deduction the materials were estimated, the same goes for the transport and use cycles. Besides the cables, a separate LCA for the electrodes was performed to use as reference for the use cycles of the products.

Results & Conclusions
The results after following the method, in figure 26, the SPU and MPU ECG-lead set are displayed. The results show that the MPU one is clearly worse from an environmental perspective. Yet because it is only based on one cycle it interesting to see that the difference is not that big. For the SPU one, it even shows how the transport of the product has a bigger burden than any other aspect.

Figure25. Taken apart lead sets for the LCA

Seeing the total scores side by side (figure 26), gives a clear overview. The MPU ECG-lead set is equivalent to two times more kg CO^2 emission. However, that is not a massive difference when considering the fact that this shows only one use cycle.

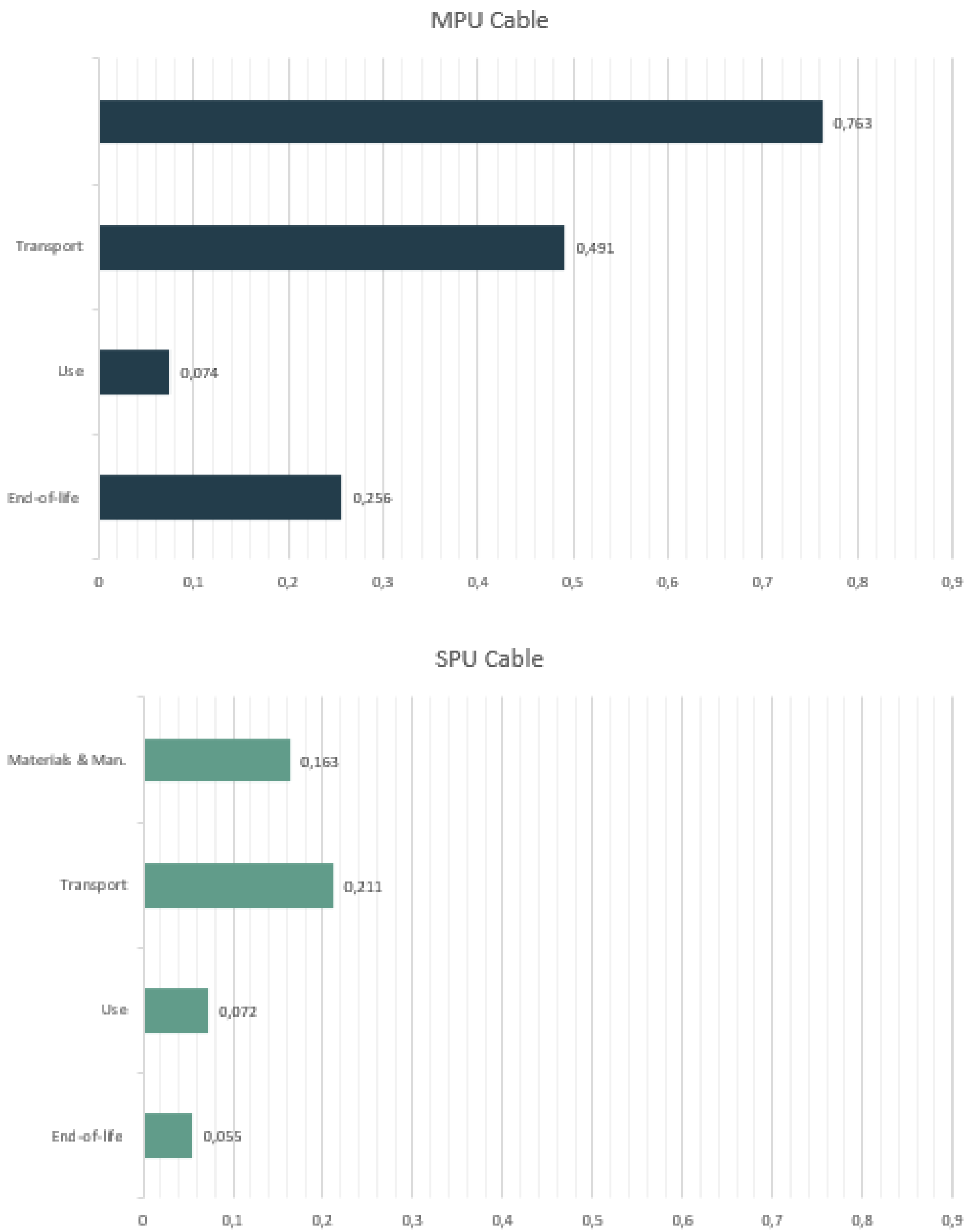


Figure26. MPU vs SPU LCA comparison

Plotting the use of the two types of lead-sets makes apparent that using MPU lead sets, is way better than throwing away the whole product each time (SPU). In this figure 27, it is shown how after already two cycles, it becomes more sustainable to use a MPU ECG-lead set. The cleaning cycle of the MPU adds a bit more emission each cycle, this amount is almost the same as the electrodes used per cycle. For the SPU cable, the amount added per cycle is the total, as it totally thrown away each time.

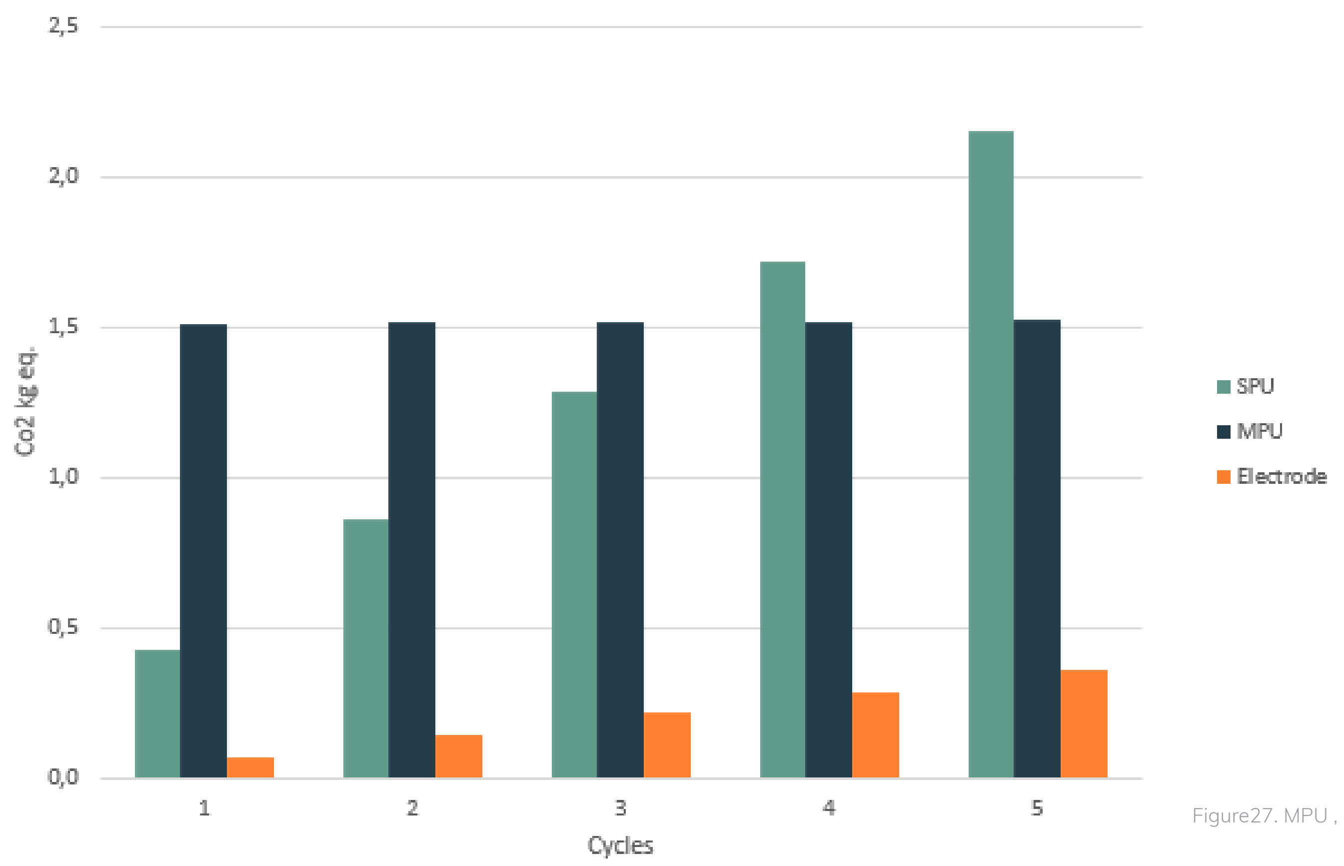


Figure27. MPU , SPU and Electrodes compared over multiple cycles

In this figure, 28 shows how the different products used at Erasmus MC affect the environment over a one-year period. Single-use products must be used in some clinical situations because of hygienic requirements, patient safety, or the absence of practical reusable substitutes. It is clear that single-use items are the main source of emissions and are responsible for the vast majority of the environmental impact.

An important insight is revealed by comparing SPU lead sets and electrodes in greater detail. Despite the relatively small carbon footprint of each individual electrode, the sheer volume of electrodes used year-round creates a significantly large impact. However, because SPU lead sets are used much less frequently, and as already identified they have a higher emission per unit.

This analysis emphasizes how crucial it is to take into account both the frequency of use and the emissions per unit when assessing the environmental impact of medical supplies. It also draws attention to the possibility of significant emissions reductions through focused interventions, such as maximizing use, locating less harmful substitutes, or putting reuse plans into place where practical.

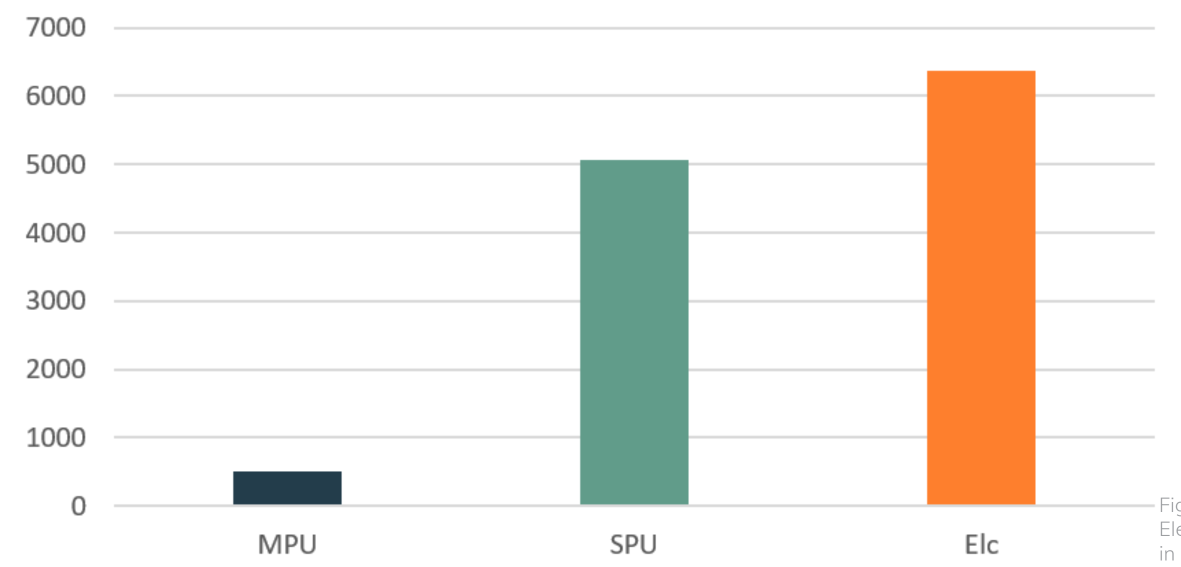


Figure28. MPU , SPU and Electrodes compared: Total in 2024

5

CO-CREATION

Co-creation is a practice in which multiple individuals work together to create something. It goes beyond traditional collaboration, because all stakeholders have an influence on the end result. Co-creation recognizes the value of input from all participants and strives for a jointly developed solution.

In this case, a collaboration between the designer and different staff members of the Erasmus MC, resulted in a common understanding of the ECG-lead sets in the EMC. This chapter explains the approach of the session, the results, and reflects on co-creation as a tool in the healthcare context. The value of shared input and validation of ideas on this specific context is what has contributed to the project to solidify its existence.

5.1 PREPARATION

The goal of the Erasmus MC co-creation session was to learn about the systemic and practical issues related to the sustainable use of reusable ECG-lead sets. Its goal was to bring together a wide range of hospital stakeholders, including those in nursing, technical services, procurement, and sustainability, to confirm current knowledge. But also to exchange new ideas and work together to think about possible future directions. There were two main elements envisioned for the session.

The first step was to present and test the findings collected during the research phase of the project, focused on the reusable ECG-lead sets.

Secondly, it created space for the group learning and brainstorming, allowing participants to exchange knowledge. Collectively coming to new ideas to tackle current problems.

To ensure a conversation, participants were selected for their distinct roles in the ECG-lead sets lifecycle. Their combined knowledge covered clinical use, technical servicing, organizational policy, and systems-level sustainability.

Nurse in intervention cardiology:
Frequent ECG cable use, often encounters tangling and frustration.

UX Designer:
Works on a sustainability dashboard for the hospital to support departments driven by data. Has an Industrial Design background.

Two Medical technicians:
Works at ICU, frequently tests ECG cables and familiar with cable issues

Person from procurement:
Strategic buyer for multiple product categories, including monitoring and anaesthesia, including ECG-lead sets.

The materials used during the session included visual posters (appendix C) depicting common problems with ECG cables: tangling and storage issues, broken connectors, visibly dirty cables, and challenges around interdepartmental loss or hoarding. Sticky notes and pens were provided to support collaborative idea capture during discussion phases.

The session was structured to last 60 minutes, with roughly 45 minutes dedicated to focused group work. It was divided into three phases. The first focused on identifying and prioritizing key issues experienced with ECG cables. The second explored the underlying causes of these issues, including behavioural, procedural, and systemic factors. The third invited participants to brainstorm possible solutions — not only product innovations, but also process improvements, policy changes, and shifts in daily practice.

Although guided by this structure, the session allowed for open dialogue and encouraged deviation when participants' insights led in new or productive directions. The aim throughout was to support collaborative reflection and to build a shared foundation for more sustainable approaches to ECG cable use in clinical care.

Figure29. Co-creation materials

5.2 RESULTS

1. Tangled cables and work flow disruption
The most common and disruptive problem in routine clinical practice was found to be cable entanglement, especially when patients need to be moved or monitored immediately or during patient handovers. Significant delays and operational stress can result from the disarray of lines, which include respiratory circuits, arterial lines, infusion tubes, and ECG cables.

"You then spend 10 minutes taking everything apart... and only then can you actually do what you intended to do" *(Nurse)*

While certain departments have implemented organizing tools like labelled hooks for different cable types, participants noted these solutions depend heavily on behavioural consistency.

"Every accessory of the patient monitor has its own hook... that already prevents a lot of spaghetti." *(Medical technician)*

"How often is a department well-trained? :)" *(UX Designer)*

Everyone agreed that although there are organizational tools, their effectiveness depends on time, discipline, and training, all of which are frequently lacking. The group came to the conclusion that tangling is more regularly a process issue than a defect in the final product.

2. Cleaning inconsistency and time-intensive
According to protocol, reusable ECG cables should be cleaned after every patient contact using disinfectant wipes. However, staff under time pressure often skip this step.

"It definitely gets skipped." *(Nurse)*

Improper cleaning leads to visible dirt, unpleasant aesthetics, and possibly even patient risk. Furthermore, repeated disinfection can degrade cable materials.

The group generally felt that the cleaning burden is unrealistic for high-pressure clinical environments, and contributes to premature wear and inconsistent hygiene. Everyone agreed this issue affects not just cable longevity, but also patient perception and professional standards.

3. Cables breaking and lack of usage tracking
Breakage was reported as a moderately common issue, but more problematic is the lack of insight into cable lifespan and usage history. Most cables show no visible sign of age or damage, leading to guesswork about when to discard or replace them.

"You also don't know how old a cable is... you can't tell just by looking at it." *(Medical technician)*

Without traceability, reusable cables might be discarded too early, or too late, undermining both economic and environmental goals.

Participants supported the idea of integrating traceability through RFID or similar solutions to understand usage patterns and optimize replacement cycles. The lack of this visibility was seen as a gap in both procurement logic and sustainability strategy.

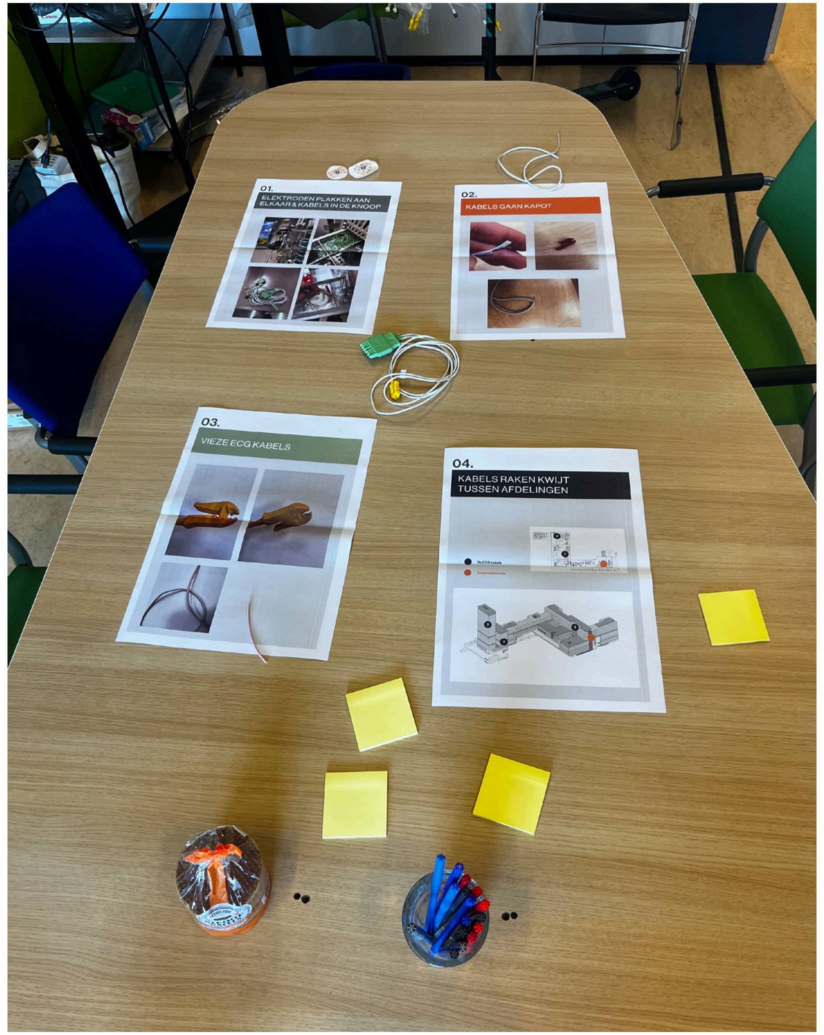
4. Sustainability across the system
Much of the discussion circled back to one core theme: most problems aren't about the ECG cable design itself, but how cables are used, stored, cleaned, and tracked.

"It doesn't so much seem like a design flaw of the product, but rather a process flaw in which the product is involved."
(Person from procurement)

Participants agreed that even a perfectly engineered reusable cable cannot succeed in a flawed environment. Real gains must come from better behaviour, smarter workflows, and more integrated systems.

The group emphasized the need for a system-wide approach. Product innovation alone won't solve waste, tangling, or loss—especially when behavioural and operational conditions remain unchanged.

Before



After

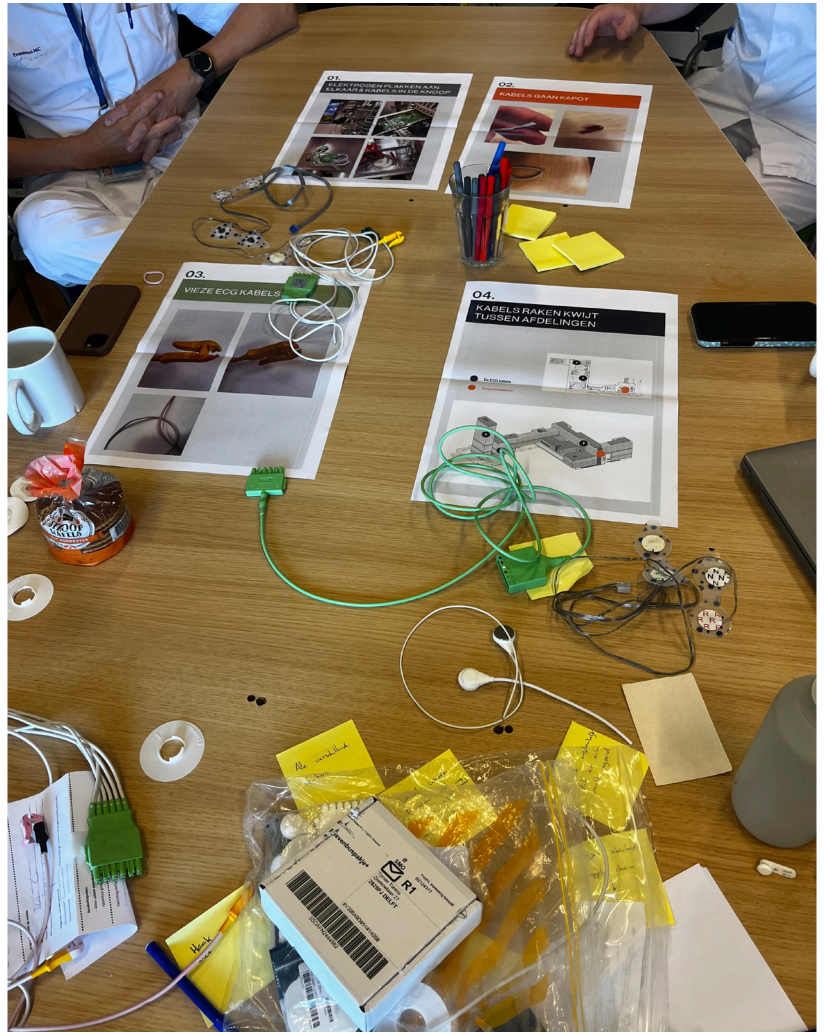


Figure30.Co-creation set-up, before & after

5.3 CONCLUSION

The discussion showed that although technically sound, ECG cables are part of a disjointed system with poor traceability, inconsistent behavior, and inefficient processes. Daily practice varies from ideal protocols, as demonstrated by tangled cables and neglected cleaning procedures. Participants agreed that these problems are signs of larger systemic problems that cannot be resolved by simply redesigning the product.

Digital traceability, such as RFID tagging, was highly sought after in order to learn more about wear, replacement cycles, and real-world usage patterns. A number of participants underlined that sustainability claims are merely conjectural in the absence of trustworthy data.

Additionally, the conflict between reusable and single-use solutions was examined. Reusable cables have obvious theoretical advantages, but poor handling, cleaning, and storage compromise their usefulness in real-world applications. Single-use cables, on the other hand, provide hygiene and predictability in certain high-risk situations despite their apparent wastefulness.

In the end, the discussion reaffirmed a crucial realization: sustainability is a characteristic of the system in which the cable functions, not of the cable itself. Even the best-designed product will not reach its full potential until procedures, behaviours, and procurement models are in harmony.

Besides this, it showed that even for "just a cable" things get complicated very quickly in the hospital setting. That maybe, it is not just a cable and to solve sustainability issues we should not overlook these types of products.

Reflection

Reflecting on the session, there are a few different takeaways for a future session. Looking at the preparation and intended structure of the session, it went in a different direction.
Although the discussions flowed organically, linking issues like entanglement to training, storage, and time pressure, correctly. The session got stuck at the point of discussing problems, whereas the intention was to think about solutions.
Facilitating a session requires taking a strong lead, within this session the advantage of a good flowing discussion became a weak point. Where steering away from the conversation became difficult, even after multiple attempts. The preparation for the session therefore should focus more on facilitating, and practicing or preparing this instead of the structure.
The tools used were minimal, and served some purpose in the session. But overall they did not massively contribute to the final insights, taking more time in preparing these could be valuable. However, just like the preparation of a session structure, this can backfire as well. Overall, the session has created very valuable insights but not go fully as planned.

6

DESIGN PROCESS

The design process explains how the final design proposal was reached, from ideating and choosing a design direction, to prototypes to test ideas. The process is described in this section to elaborate and show the importance of the design process. Most importantly, the final design direction is explained, discussing the choice for this particular direction and formulating clear goals and a vision, to be fulfilled.

The previous sections showed the research done, providing a strong foundation to continue from. Enabling the start of the designing phase, this process was an iterative cycle between ideation, prototyping and validation. Therefore, it is important to highlight that, although it might seem this happened in chronological order, this is not exactly the case. As often when designing it can become a chaotic process, but as it is structured here it presents the value of the process.

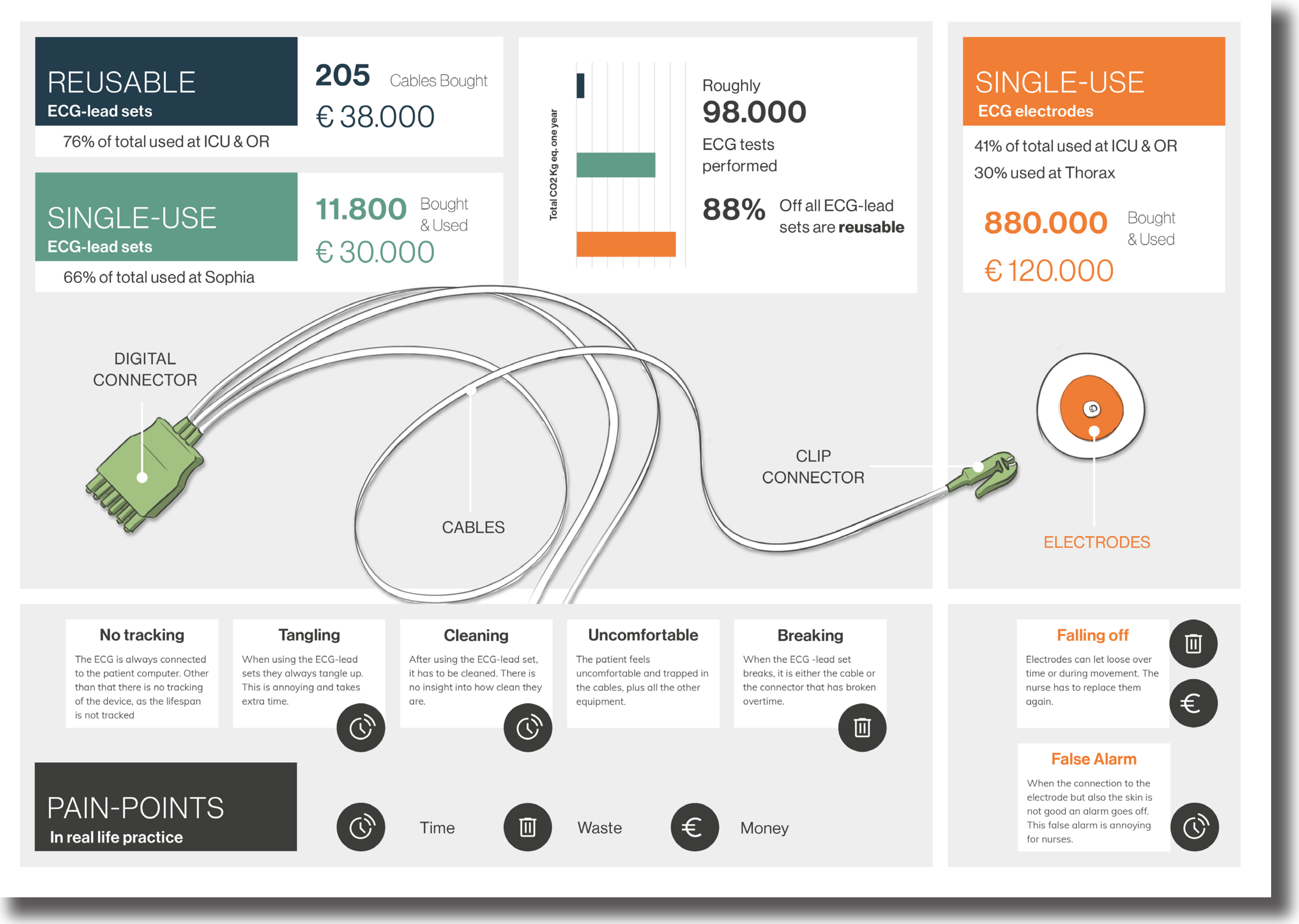


Figure31. Visual of the main findings

6.1 DESIGN BRIEF

The design brief is explained in chronological order, first shortly summarizing the different insights gained from the research phase. After this, different possible directions are presented to show the different potentials, and finally the final design brief is discussed and explained. This gives an insight into the thought process behind the design vision, and also depicts different other insights that might be useful to explore further in the future.

Reusable

Reusable ECG-lead sets are used most frequently in hospitals. Roughly 88% of all ECG tests performed in a year use a reusable ECG lead set. While this makes them an interesting design opportunity, the reusable lead sets, as the name suggests, are already reusable and therefore quite high up the value chain.

Most user issues relate to reusable lead sets: tangling, lack of traceability and cleaning are all associated with negative perceptions of the product. Designing to solve these issues seems relevant for the user, but for improving sustainability, it might not be as impactful. Since the product already incorporates a reuse strategy, only a few interventions could be relevant.

Single-use

The single-use lead sets are unfavourable for the environment when you look at their one-time use. However, it is important to note that the EMC already uses as little as possible single-use products. The total amount is only a small margin, roughly 12%, of all the ECG tests performed. Regarding the user experience, some points are less relevant, like traceability, cleaning and tangling, as the use is simply a very short period.

They are used specifically in the OR and at Sophia, this is because they are mostly used when mitigating the risk of cross contamination is a priority. With small children, isolated patients and special procedures these are required. The single-use products therefore makes more difficult to improve sustainability wise, simply due to the amount of requirements.

Electrode

The electrodes are a sub-part of the product system and have their own user issues and usage levels. The most critical insight from the electrodes is that they are used extensively across the hospital. Even a small change to the design could have a significant impact across the entire EMC.

User issues with the electrodes are caused by them malfunctioning over a longer period of time. This results in false alarms being triggered, creating more stress for nurses at work. As the product is quite simple, there is not much potential for design freedom.

Problems & potential solutions

This section reviews a number of potential solutions. Categorized by the main problems found in the research, they present different possible solution space's. The concepts that are highlighted in green represent the design interventions that were eventually implemented into the final design, combining different solution space's and solving multiple problems.

The solution are presented based on the time it would take to implement. There are different solutions that could be relevant right away and others that would take more time to develop. Some of these "quick fixes" are especially promising for the EMC, whilst they are not included into the final design. They can be adopted quite easily, if the right professions look into it. However, this project has a focus on product design solutions, and therefore does not continue with these type of solutions.

NOW
5 YEARS
10+ YEARS

Problem 1. **Tangled cables and poor cable management**

Improve user experience.
R-strategy: Rethink / Reduce

- Introduce dedicated cable organizers with compartments or hooks
- Rethink the storage solutions
- See if materials can impact the tangling
- Design tangle-free or retractable cables
- Make a wireless ECG system

Problem 2. **Loss of lead sets due to no tracking and little insight**

Enables smart inventory control and tracking
R-strategy: Reduce / Reuse

- Manually log the use of the lead sets when purchased
- Use visual markers for different departments
- Improve logistics data collection
- Create awareness about hoarding
- Develop a smart rack&trace system
- Combine different sensors into one

Problem 3. **Lead sets perceived as and are not hygienic**

Improves hygiene and enable safe reuse
R-strategy: Reduce / Reuse

- Design visual cleanliness markers
- Create awareness about hygiene for staff
- Make a lead set that is easier to clean
- Design a specific cleaning tool
- Separate cleanable covers to fulfil regulations
- Create a ECG lead set that can withstand sterilization
- Work to improve regulations and allow more reuse

NOW — 5 YEARS — 10+ YEARS

Problem 4.
Incorrect placement of the electrodes reducing quality

Improves accuracy and reduces human error.
R-strategy: Rethink

- Design a teaching guide for staff
- Design a visual guide for during the placing
- Redesign the electrode to fit better
- Develop a system that recognizes correct placement

Problem 5.
Electrodes fall of causing false alarms and extra waste

Improve electrode quality and reduce failures & waste
R-strategy: Reduce / Rethink

- Improve packaging so they do not dry out
- Reduce valuable materials in the electrode waste
- Increase the stickiness of the electrodes
- Design a reusable electrode

Problem 6.
No system in place to recover broken lead sets

Closes the loop or extend product lifetime
R-strategy: Recover / Recycle / Repair

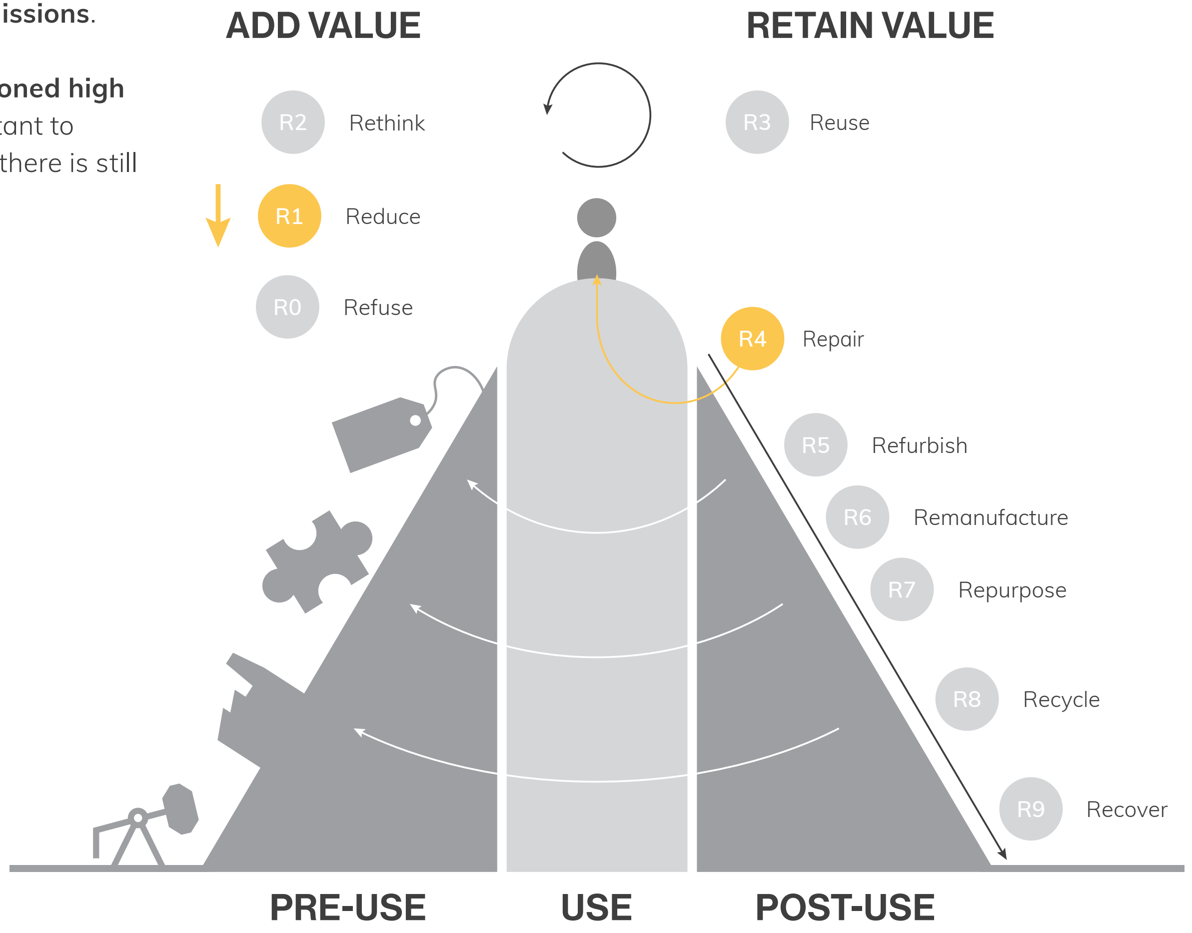
- Collect the lead sets to be recycled
- Create a system that allows upgrades
- Make the lead sets repairable
- Design the cable for disassembly and better recycling

REUSABLES
ECG-lead sets & Electrodes

The reusable product system emerges as the **most relevant** area for further focus. It is the most widely used and, combined with the electrodes, **contributes the highest emissions**.

Although it is already **positioned high on the value hill**, it is important to **reinforce this position** and there is still room for improvement.

Figure32.Value hill with highlighted with R-strategies



3 KEY OPPORTUNITIES

Traceability	Repairability	Valuable waste
The exact usage of the product is unknown, as critical information, such as lifespan, cleaning cycles, and the number of times it has been used in a department, is missing.	When the cable fails, it is often only one out of four individual cables that breaks, resulting in the disposal of the entire unit, including the three remaining functional cables.	The electrodes contain valuable materials used for signal conduction, yet they are discarded after each use, resulting in significant waste generated in high volumes.
Designing a system to trace the reusable lead sets, could collect valuable data.	Changing the design of the product could, improve repairability.	Redesigning the electrode and connector clip could reduce valuable waste.
This new data could improve product efficiency, potentially reducing the total number required in the hospital.	This strategy could extend the lifetime even further, retaining the value of the ECG-lead set.	Reducing the valuable materials could have significant impact, given the volume of electrodes used
R1	R4	R1

Design vision

"Design the next generation of reusable ECG-lead sets and electrodes, by improving user interaction, traceability, repairability and keeping valuable materials in the loop.

To show the potential of circular strategies being implemented, solidify the position of the reusable's and contribute to a more sustainable healthcare."

Design goal

The goal is to design a circular solution for ECG-lead sets that supports a more sustainable healthcare system. The design will be based on what was identified in the analysis phase and shaped by the needs and input of stakeholders. The final result of the project will be a tested concept that demonstrates at least one clear environmental benefit compared to existing ECG cables.

This design should also demonstrate that, even a straightforward component as a cable can, be redesigned to support sustainability goals and change the perception about medical products and their environmental impact.

Scope

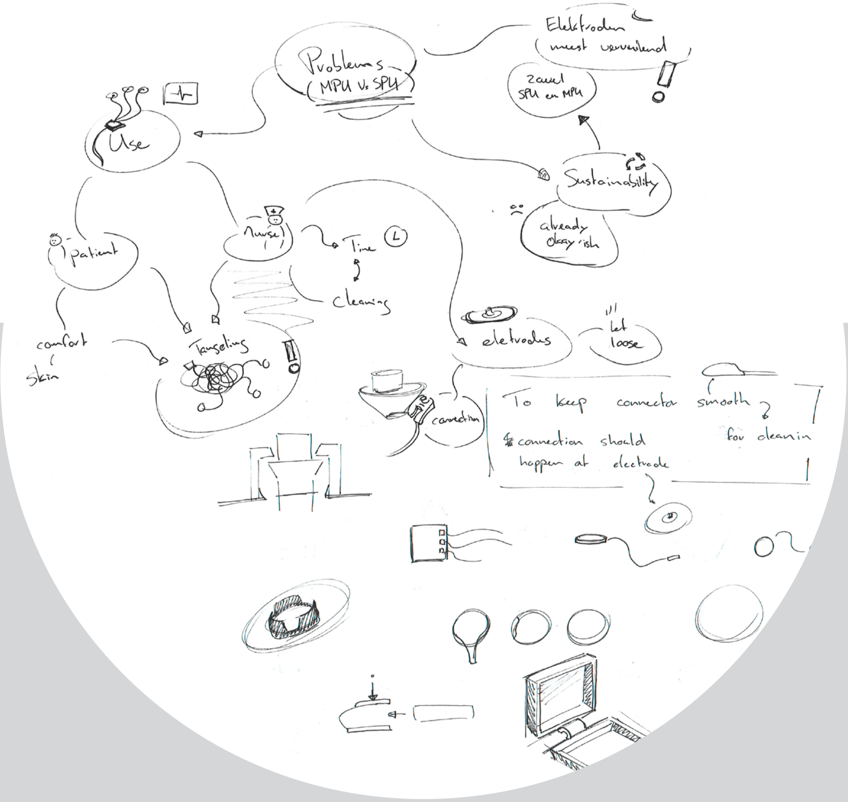
This project aims to design the next-generation ECG-lead set, trying to remain relevant five to ten years into the future. The analysis and research are based on the current healthcare system, technologies, and stakeholder needs. As a result, even though the design will be shaped towards the future, its components will be based on the world of today.

Since this is a design project, it focuses on exploring solutions related to physical products, product-service systems, and user interaction. Whilst maybe broader shifts such as policy changes, behavioural changes, or awareness are seen as important for long-term impact, they are not the main focus of this design project. Nevertheless, these topics will be addressed through recommendations and contextual insights when relevant.

Importantly, the design also aims to provoke thought, challenging people to reconsider how even a simple product like a cable can contribute to sustainability issues in healthcare. The project hopes to spark conversation, raise awareness, and inspire a shift in mindset towards more circular and thoughtful product development.

6.2 IDEATION

With the design brief set out, ideas were thought of using different methods. Dividing the problem into sub-problems and questions to be answered, a broad of variety of ideas was generated. Sketching, mind mapping and brainstorming with others kept track of the process and made it easy to compare ideas.



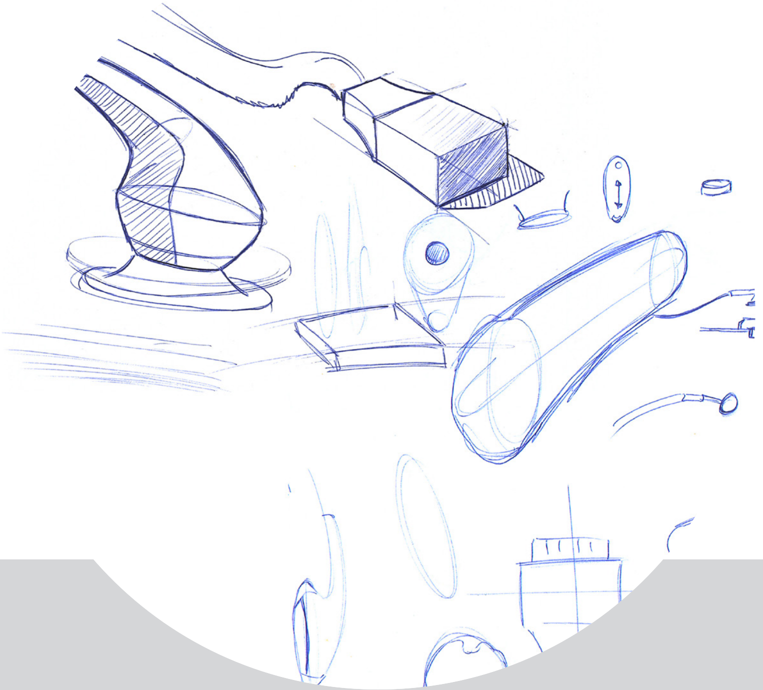


Figure33.Design sketches

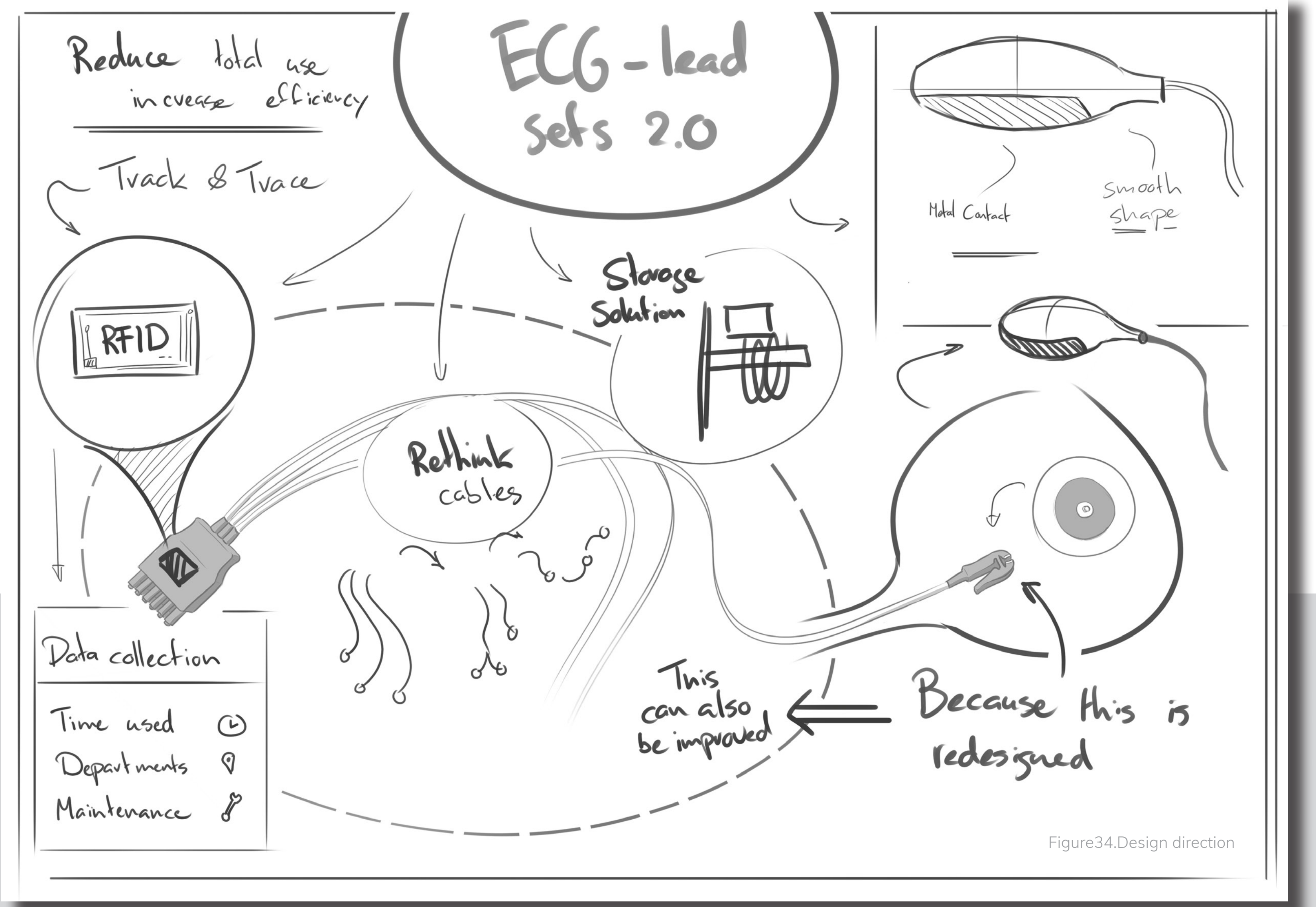
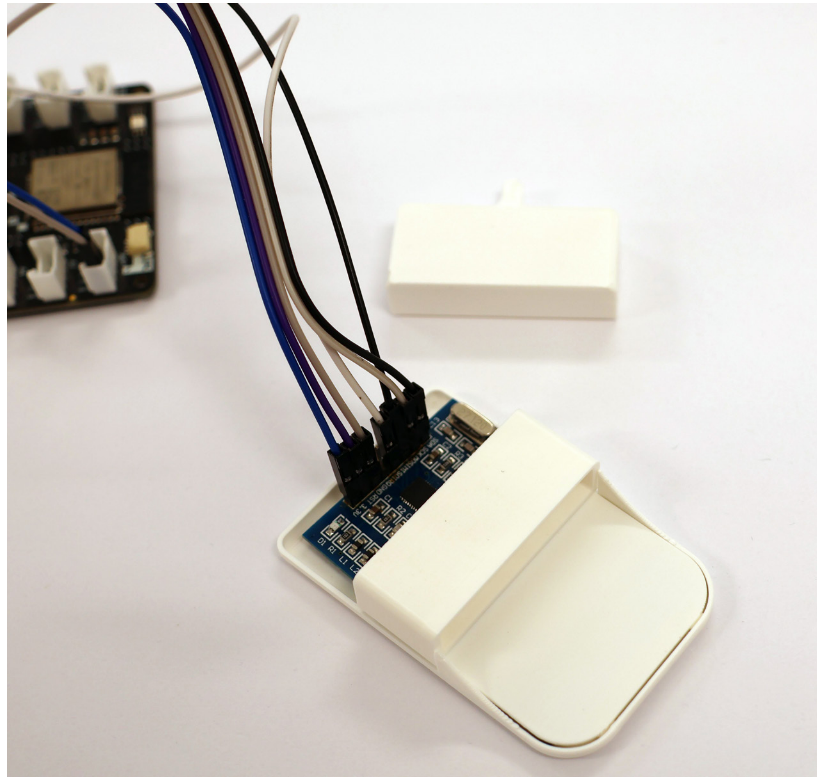


Figure34.Design direction

6.3 PROTOTYPING

The next step after coming up with an idea was to make it tangible and analyse its application. A lot of different prototypes were made for testing and evaluation during the process. The majority of these prototypes were 3D printed after first being created in SolidWorks. The small form factor of the patch resulted in a very quick cycle of making prototypes, tweaking and refining the design in great detail. The digital connector, extension cable, traceability adapter and dry electrode were all prototyped somewhere during the process.

Figure35. Extension cable (left) and gigital connector (right) prototypes



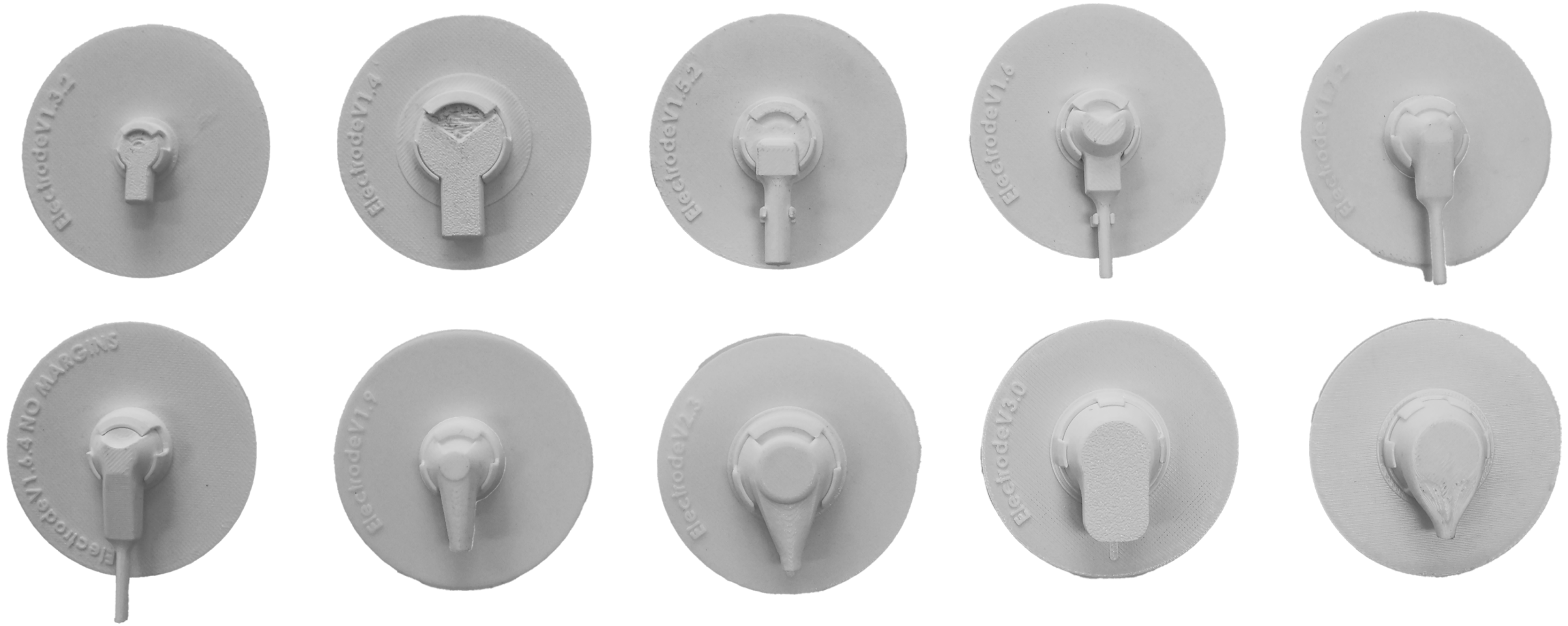


Figure36. Timeline different patch protypes

The progress toward the final design is clearly shown in the figure above (figure 36), which displays a number of prototypes lined up in order. Starting with a very small initial model, the process consistently explores the concept of working with minimal volume of material, to make a sustainable impact.

Whilst later also guaranteeing that the product can be handled and grasped with ease by the medical staff. Increasing the size and developing a way to add more body to the lead set ends.

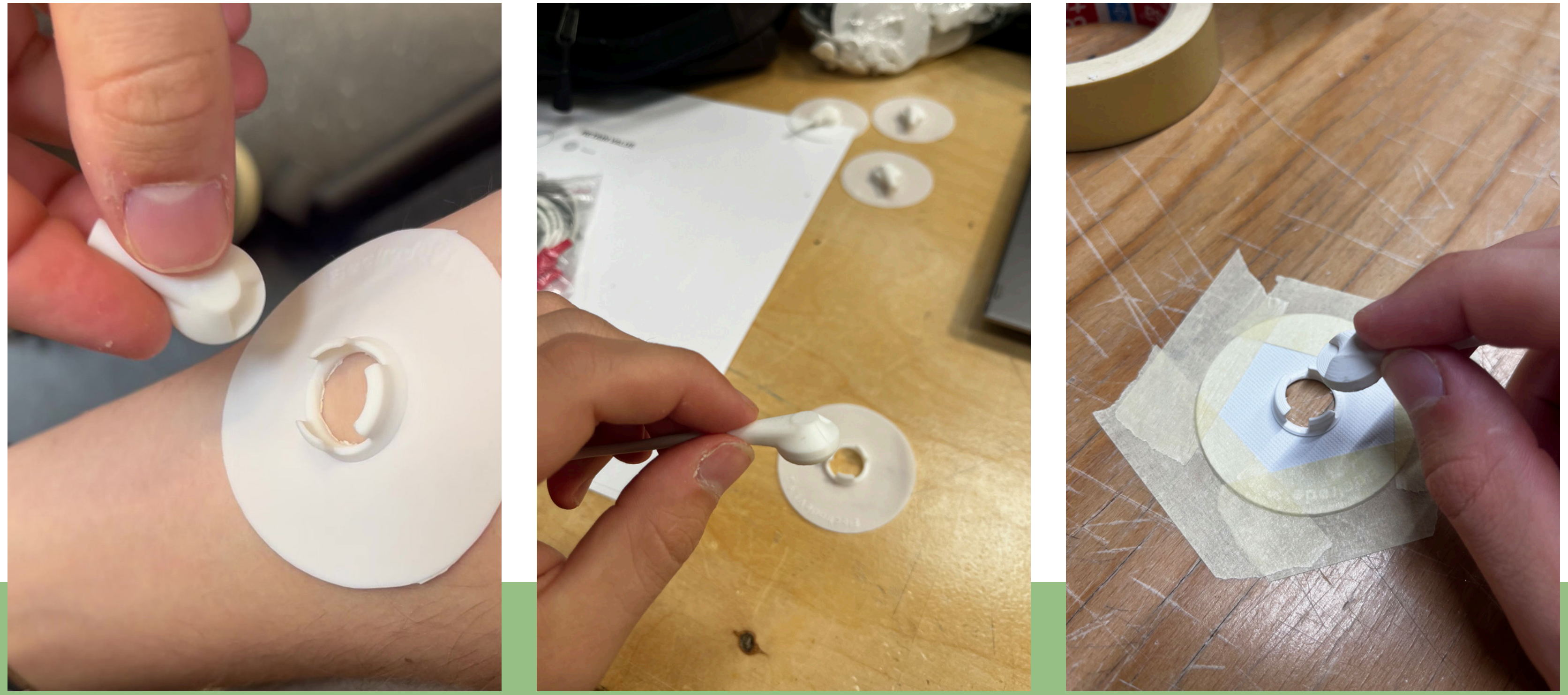
In the end, prototypes that were fixed and clipped in place eventually gave way to the ones that allow for free rotation. As this proved to be relevant for the medical staff.

6.4 TESTING

Prototypes and ideas were evaluated using different tests during the design phase, giving insightful outcomes that shaped the results and helped to move forward in the process. The tests described in this section helped to shape the final design, they were not meant to evaluate the actual final design proposal. These test and evaluations are discussed later in the report.

The tests depicted in figure 37 were initial tests of the lead set electrode and patch. In addition to facilitating discussion with others, they offered insights into connection stability and ease of use.

Figure37. Quick prototype testing of the patch



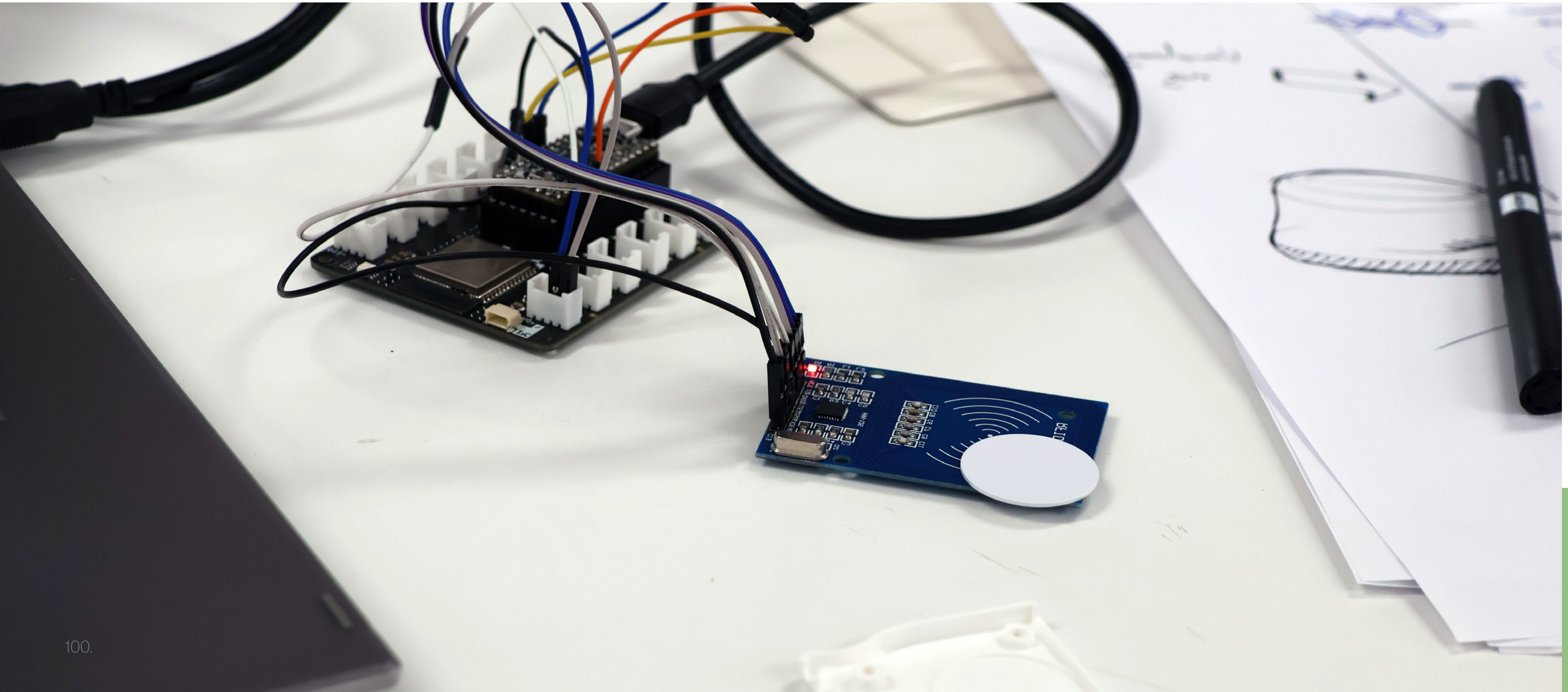
RFID testing

A working prototype was made in order to assess this custom use case. The prototype showed communication over a Wi-Fi network, tested the effective range of RFID tags, and confirmed that tracking the necessary data was feasible.

The testing procedure is depicted in the figures (see 37). The system was configured to connect to Blynk.Cloud using an ItsyBitsy microcontroller and an RC-522 RFID reader module. The prototype components were first tested separately, to eventually integrate them in one system.

Designing the prototype provided valuable real-world insights into how such a system would operate. Wi-Fi connectivity, provided valuable insights about the power consumption. During testing, the Wi-Fi connection was drawing enough power to run out the battery. Likewise, the RFID tags being read had more complications than expected.

Figure38. RFID test set up



Additional layers of plastic decreased the visible range of the RFID tags, when a tag was embedded in the prototype the reading distance decreased significantly. Reading without being embedded the range was 7 cm, embedded it decreased it to 3 cm. Whilst there was only an extra 2 mm of plastic in between the tag and the reader.

The RFID tag's performance was also impacted by its size and the orientation in which it held. Bigger tags are easier to detect, compared to a card tag, and the coin tags were more difficult to detect. The orientation of the tag needed to be more aligned and could not be at an angle.

Overall, the system performed well and proved to be reliable, the findings helped to establish the right design proposal in the end.

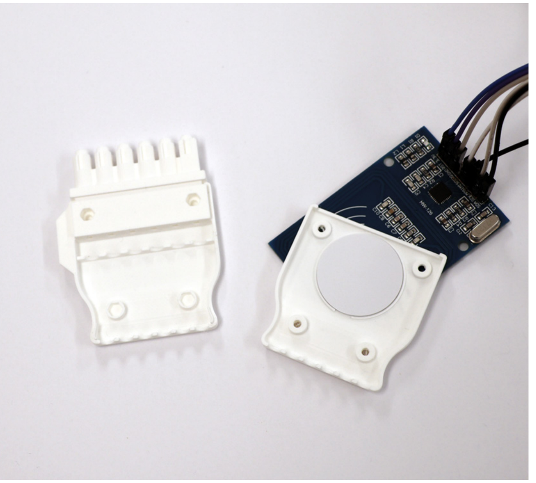


Figure39. Computer connector with embedded coin RFID tag

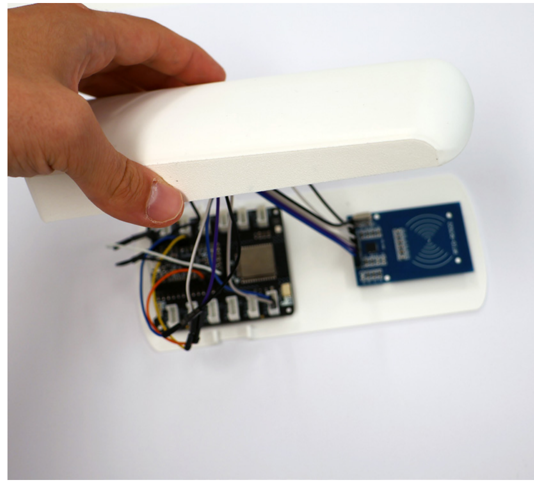


Figure40. Casing for the electronics

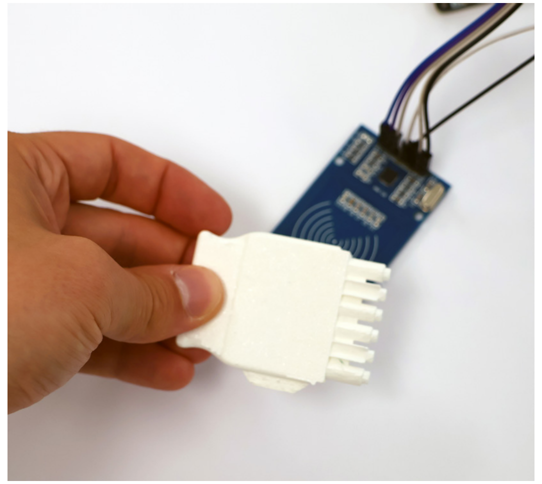


Figure41.Testing the range trough the plastic layer

Dry electrode tests

In order to see if dry electrodes are compatible for this specific design application, a prototype was made to test this. The test set up used a piece of 2 mm thick mm stainless steel disk, with a diameter of 20 mm. This was attached to a wire attached with soldering tin and the electrical wire was directly connected to a AD8232 ECG module. This small microcontroller amplifies the signal to be able to picked up by an itsy-bitsy. The first intentions of this set up were to validate different patches, to see which factors would impact the signal quality. However, upon testing this seemed less viable as it was very difficult to run a reliable test.

Here you can see the setup (figure 44), it was tested by first using three leads that were connected to the conventional electrodes. This baseline was used to compare the stainless steel electrode.

In the first test performed, the dry electrode performed reasonably good. The results showed that for the stainless steel electrode, the amplitude was smaller. This was most likely caused by the resinate of the electrode itself, it impedances the very small signals that need to be picked up. Also, the dry electrode it was quite sensitive to movement and the signal took a longer time to settle down, to a point there was not too much noise.

The second and final test showed unfortunately showed no result, different factors might have played a role in this. These are suggestions as to why this could have happened, yet none of them are definitive. Due to its simple and self-made design, the prototype is naturally less reliable than a professional setting. An issue related to this would be the most plausible cause for the failed second reading.

Oxidization: Over the period where the electrode was not used. Oxidation might have taken place, creating a small layer of less conductive material. Lower grade stainless steel can be prone to this.
Build up of dirt: due to different times used and handled, dirt might have built up. Also, the skin could be not properly cleaned.
Error with the module: the module used is a relatively simple amplifier, professional amplifiers can provide a more reliable reading. Also, the connection to the module could have deteriorated after not using it.
Broken cable: a simple wire was used to connect the electrode to the module and may have broken after some time. Besides, it was not a shielded cable, usually used for ECG measurements to reduce noise.
Soldering connection: the connection to the

It is a shame that the second test did not perform as the first one, and it remains uncertain as to why. Still, the prototype showed result at some point and together with supported literature shows the design is feasible and has potential.

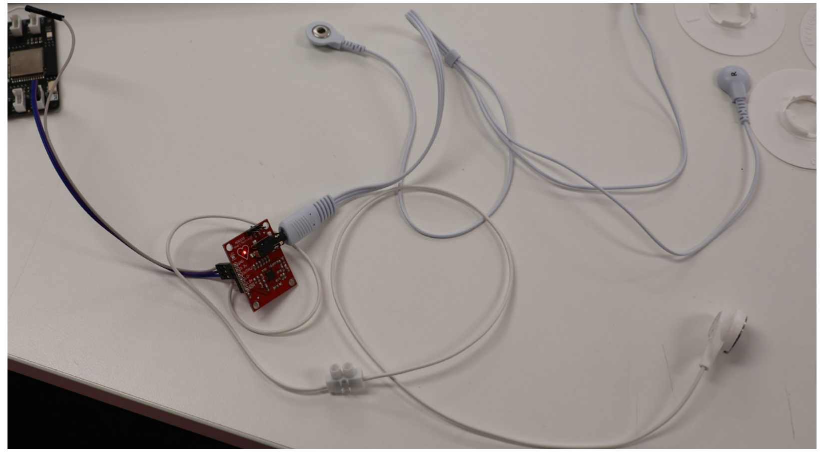


Figure44. Test set-up

Figure42.Test result in the first recording

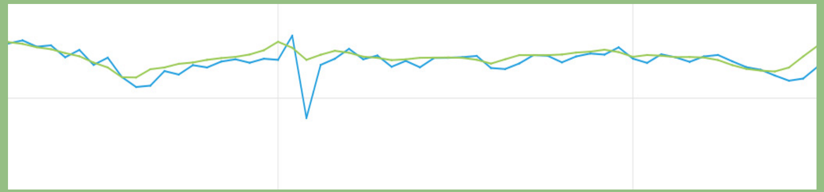
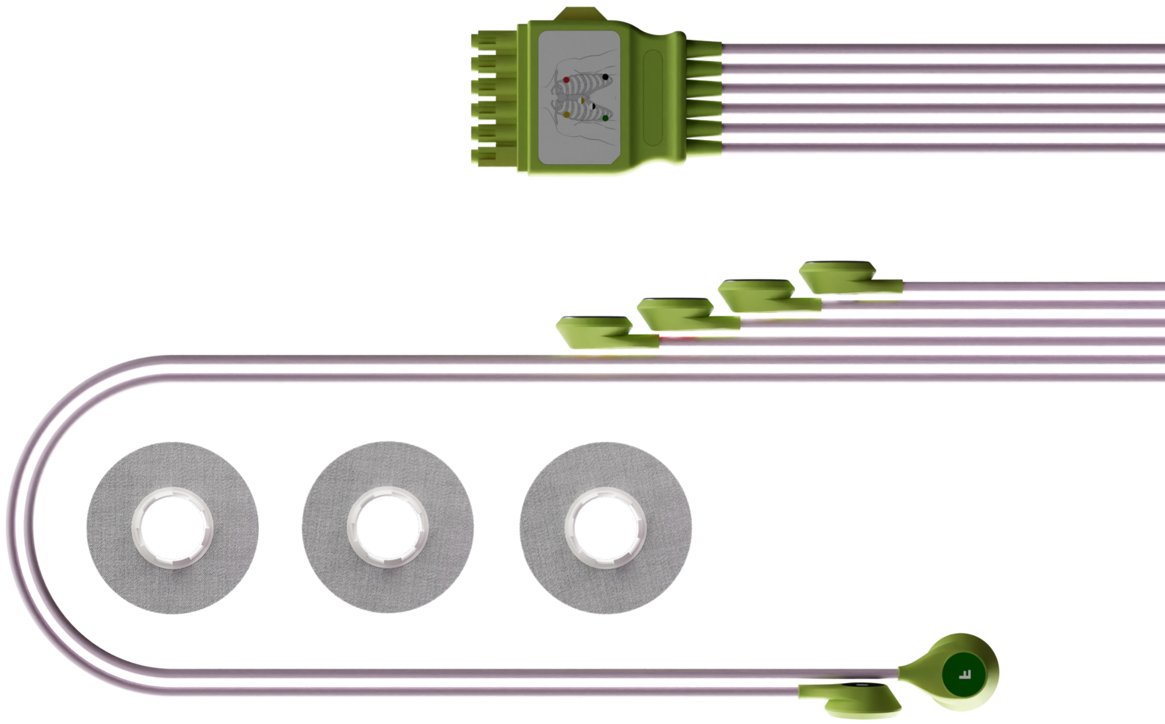


Figure43.Test result in the seconf (failed recording)

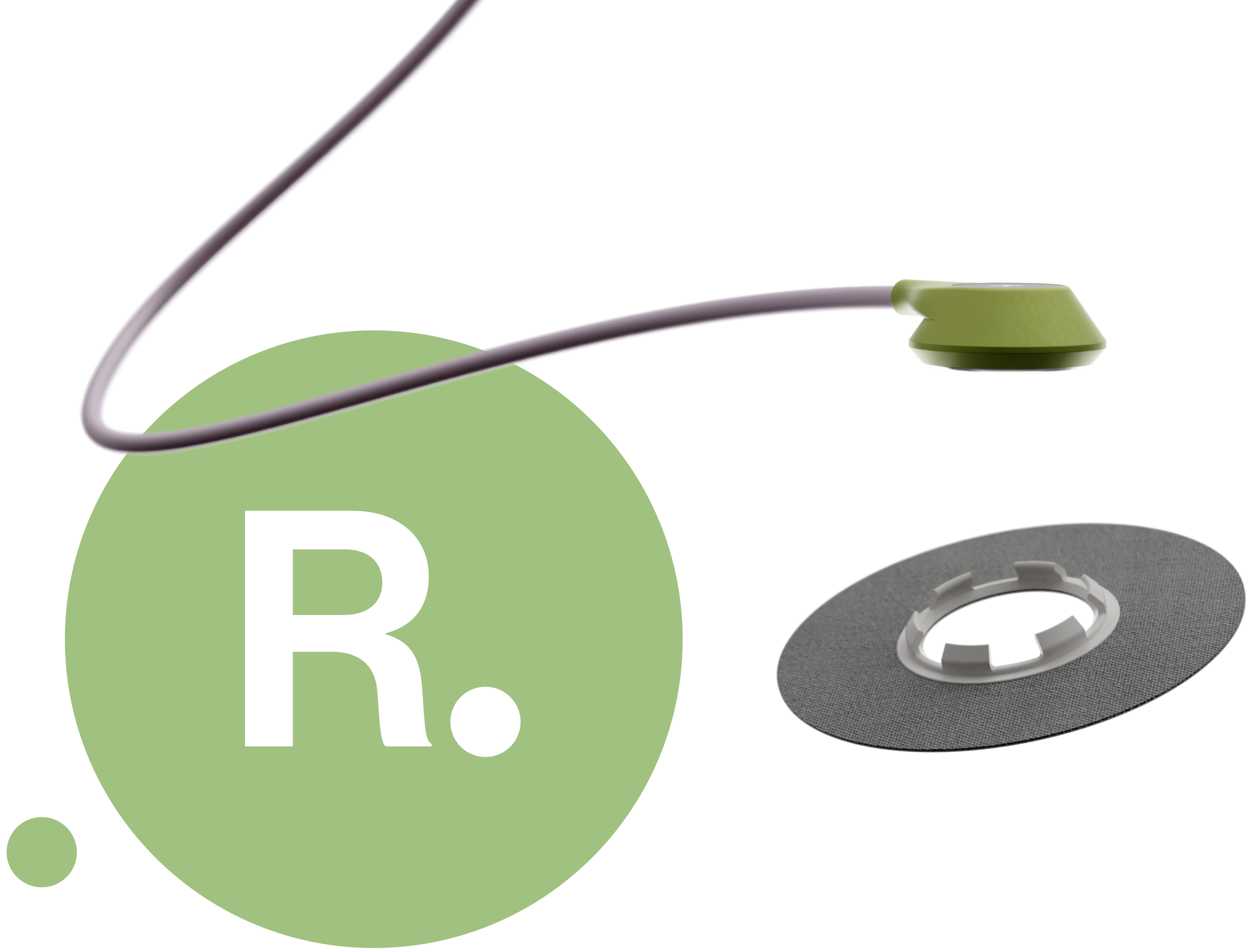
7

FINAL DESIGN



This chapter introduces ReLead, the redesign of the conventional ECG-lead system with a focus on medical practicality, sustainability, and circularity. By switching essential parts from single-use patches to reusable cables, ReLead decreases waste and increases product lifespan through reuse and repair. Using RFID technology to improve traceability and design for repair to increase product lifetime.

When combined, these developments produce an ECG-lead set that is more intelligent and sustainable, having a positive effect on the environment and clinical usability.



RELEAD

Rethinking ECG-lead sets to Reduce environmental impact

ReLead electrode moves the conductive connection from the disposable patch to a reusable cable with a stainless steel dry electrode.

To keep valuable materials in the loop, ReLead presents a new approach for the signal connection to the patient. By transferring the connection point, from the single-use electrode, to the reusable cable.

-48% CO^2

Figure45. ReLead dry electrode

ReLead patch
holds the ReLead electrode securely in place, guaranteeing a stable connection for every measurement.

The new electrode patch, is designed to purely hold the lead connector in place. It has been stripped from its valuable materials and uses a new small piece of plastic to hold the electrode stable.

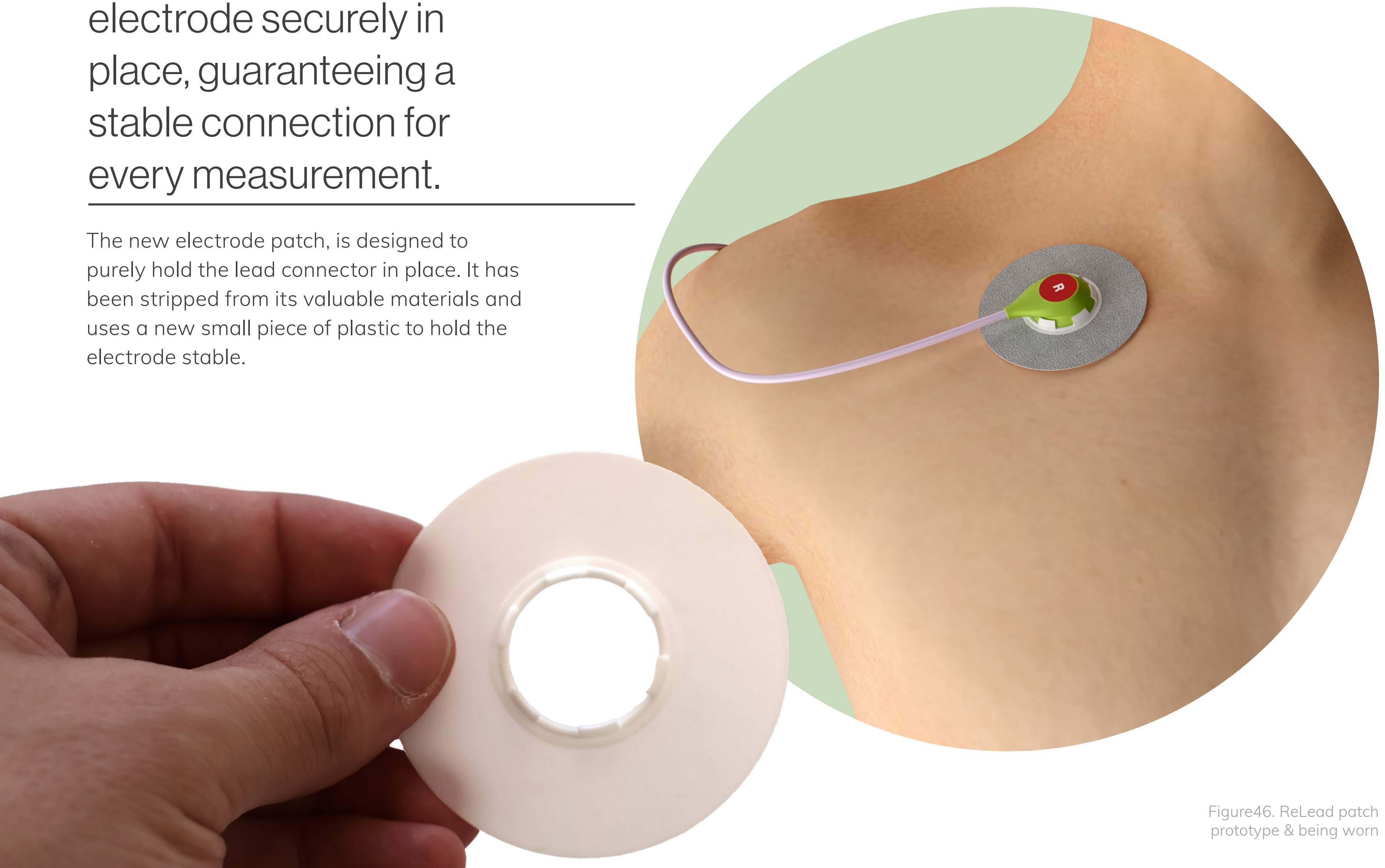


Figure46. ReLead patch prototype & being worn

ReLead track & trace
Uses RFID and a digital platform to monitor and optimize ECG-lead set usage, improving efficiency

The traceability system was identified to be relevant to make an impact on the efficient use of the multiple ECG-lead sets in the hospital.

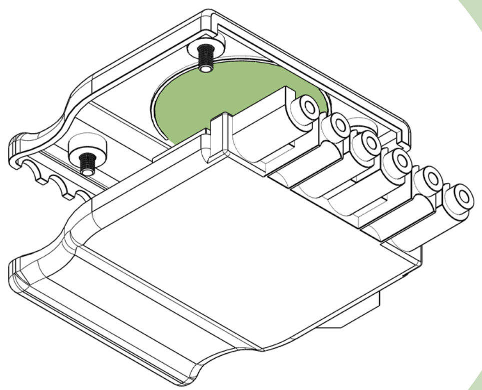
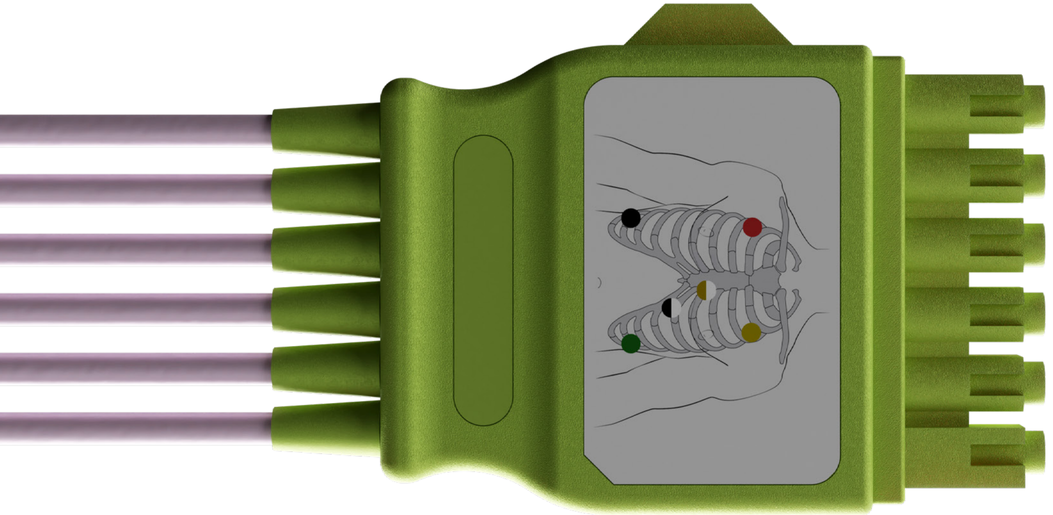


Figure47. ReLead computer connector



ReLead design for repair

To allow the repair of singular broken leads. The digital connector is designed for repair.

The design that allows the product lifetime to be extended. ReLead makes it possible for the ECG-lead set to be repaired by the manufacturer. The computer connector can be easily screwed open, and each individual lead can be replaced. The design thrives to maintains the same product quality, whilst making this possible.

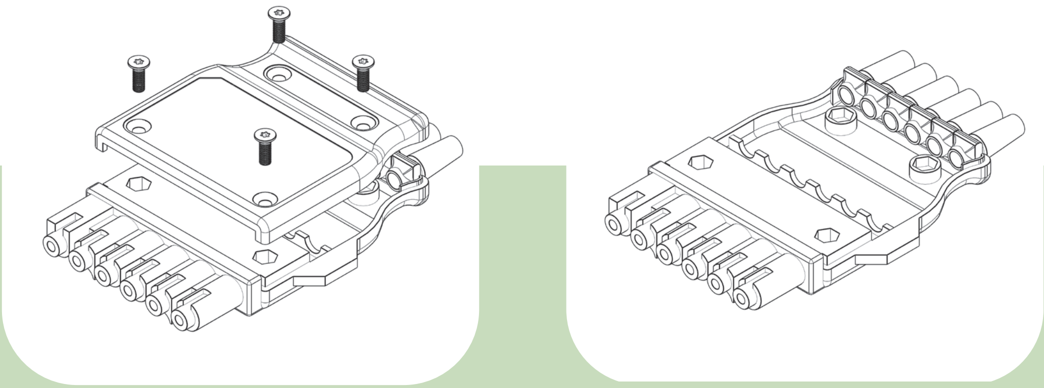


Figure48. Connector exploded view

Figure49.Prototype of the electrode and patch

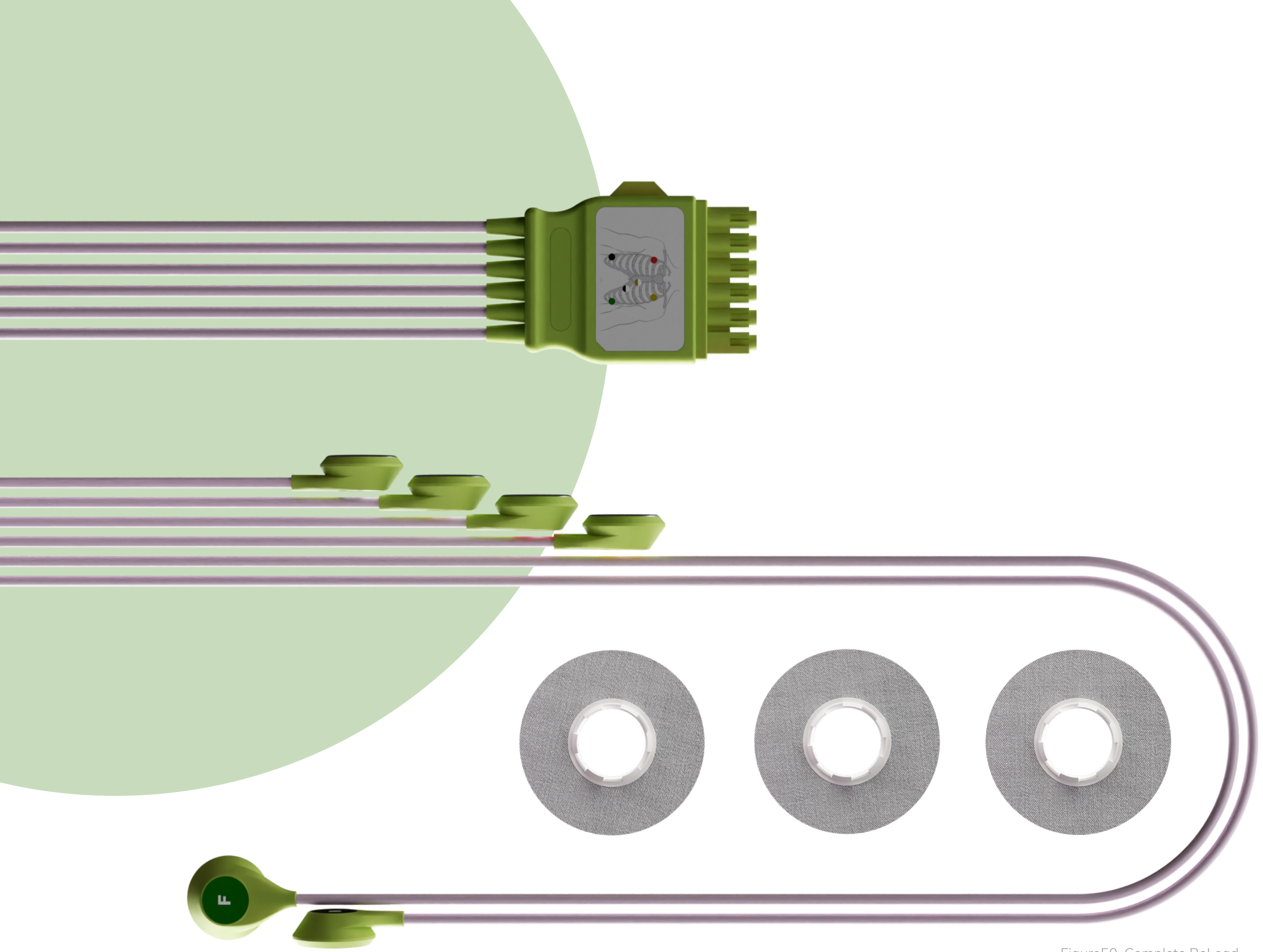


Figure50. Complete ReLead ECG lead set with patches

Summary design features

ReLead connector & electrode
To keep valuable materials in the loop, ReLead presents a new approach for the signal connection to the patient. By transferring the connection point, from the single-use electrode, to the reusable cable. The value of the conductive materials is kept in the loop of the ReLead ECG-lead set, whereas before these materials would go to waste after each use.

To achieve this, the lead connector was redesigned to incorporate a so-called dry electrode. This electrode is made of stainless steel and is housed in a new type of lead connector. The new electrode patch, is designed to purely hold the lead connector in place. It has been stripped from its conductive materials and uses a new small piece of plastic to hold the electrode stable.

The result is a new electrode patch and lead connector, that together reduce the impact of the single-use electrode patches.

ReLead track & trace
The traceability system was identified to be relevant to make an impact on the efficient use of the multiple ECG-lead sets in the hospital. Besides, this issue was also identified among employees of the EMC, more insight would improve the user experience. ReLead track & trace gives insight in the currently lacking visibility of the real use of the product.

The ReLead ECG-lead set has embedded RFID tags at the computer connector: passive RFID allows the system to operate without the ECG-lead set needing any electricity. The ReLead track & trace adapter and digital platform, completents the system and generate additional value. Value for stakeholders and to reduce inefficient use of lead sets.

ReLead repair by design
The last, main design feature, is an approach to the design that allows the product lifetime to be extended. ReLead makes it possible for the ECG-lead set to be repaired by the manufacturer. The computer connector can be easily screwed open, and each individual lead can be replaced. The design thrives to maintains the same product quality, whilst making this possible.

Current ECG-leads set break at the cable, this means the whole set is disposed when it is only a singular cable that does not work. With the new ReLead design this is no longer the case and more value is retained by extending the product's lifetime.

7.1 DESIGN DETAILS

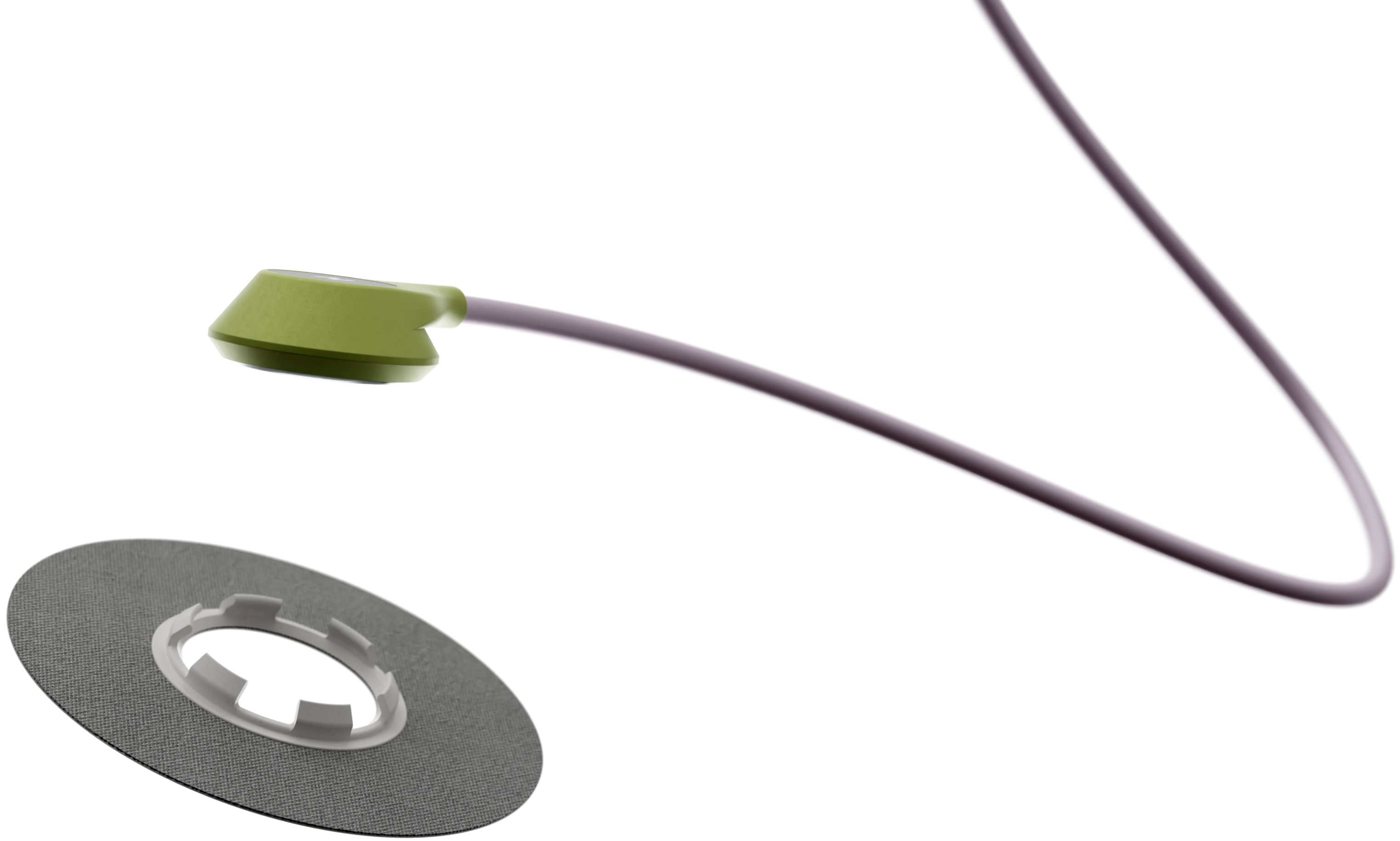
Dry electrode

The stainless steel electrode has a diameter of 20 mm, making it just large enough to pick up a good signal from the body. It is shaped with rounded of corners to minimize impedance of the signal. Stainless steel has great qualities related to cleanability and compared to other possible electrode materials is more durable. Because it is a dry electrode, no other steps are required, and the measurement can achieve similar qualities.

The housing of the stainless steel electrode was made with a few aspects in mind. The overall footprint is kept within a very similar size, to reduce unwanted issues in use and comfortability for the patient. Also, the overall shape has been kept smooth to make cleaning easy and quick. It reduces the amount of sharp corners and edges where dirt can accumulate.

The housing is made using encapsulation, this is a process where electronic components are enclosed in a solid material (like epoxy or resin) to protect them from moisture, dust, vibration, and damage. The material is poured over the part and hardens into a solid. This production method allows the stainless steel electrode to be embedded securely into place, and create a durable part.

Figure51.Dry electrode contact



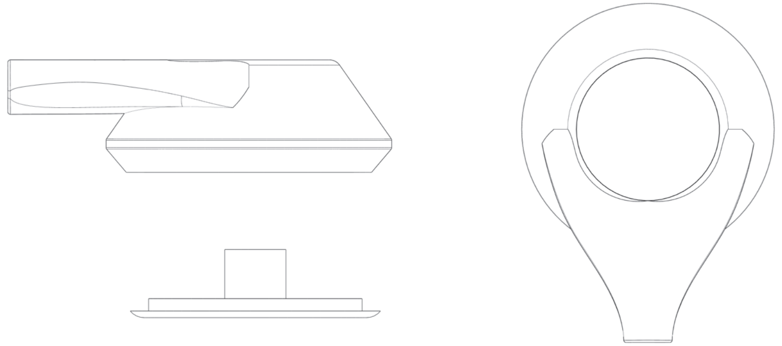


Figure52.Ecploded view housing and stainless steel electrode.

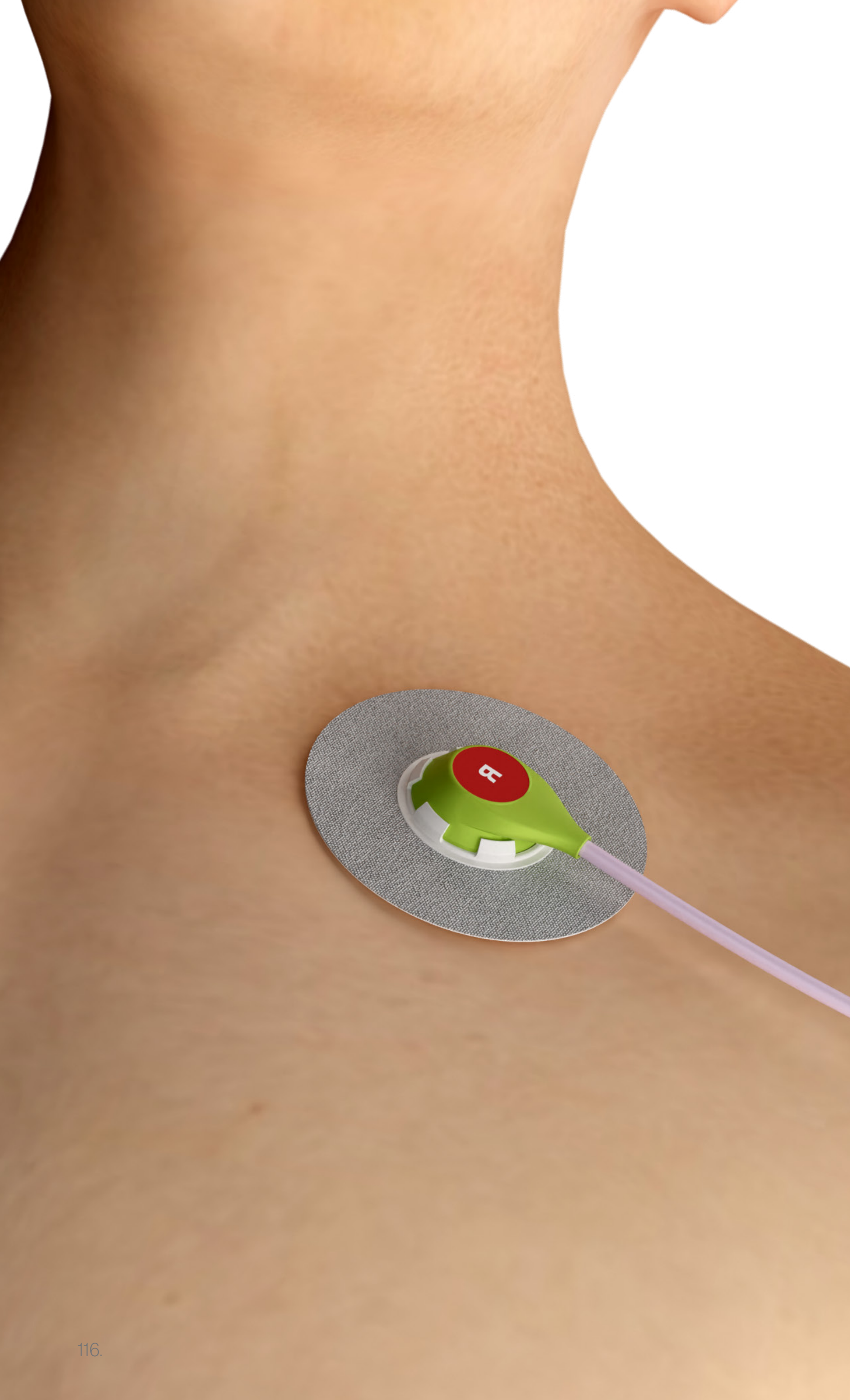


Figure53.New patch in use

ReLead Patch

The new patch has the function of holding the lead end in place, the design minimizes extra material use whilst ensuring a stable connection. The material and construction of the patch remains mostly the same as the traditional electrode.

Using six small plastic pins, it grabs onto the lead end, using a small offset in the angle of these pins. The lead end in pushed down onto the skin of the patient. Besides that, the lead end slightly protrudes on the other side of the patch, this ensures that there is a decent amount of pressure on the skin.

The use of this patch is the same as the traditional electrode, first peeling off the sticker film to apply the patch to the chosen location on the body, and attach the lead set. Important to note is that in the new design, this order of action will always be required, because it is designed to snap in place, when the patch is already attached to the patient.

In total the holder is good for 0.3 grams of plastic, however compared to the normal electrode this is a small amount. Especially considering the fact that because of this change, there is no metal, no gel, and no extra plastic cover. This change in the design is where the big sustainability advantages comes in.

Figure54.Conventional patch with valuable metal

Design for repair

The computer connector has become a more important part of the product, it houses part of the tracking system and is designed to be repaired. Besides a lot of changes to the design, the overall shape, function, and configuration is kept in the same. This ensures compatibility with the current systems, and keep the design relevant.

The RFID tag is placed closely to the surface of the connector, the passive RFID tag has an encrypted product ID. This ID can be read out by the adapter that will be discussed in the other section. RFID tags come in a lot of different configurations, shapes, and sizes and can be fitted to the design.

The repairability of the computer connector, is ensured by splitting the part in half. Whereas traditionally this also used an encapsulation process, it will now be made out of two parts that can be injection moulded. The exploded view shows how the parts work together to create the connector. The two parts are kept together by screws, allowing the part to be reopened. The screws are hidden under the stickers that display lead placement, this is done to ensure a clean product. Besides that, it makes safeguarding the repairing of the product easier, allowing sticker to only be replaced by manufacturers and not hospital staff. The cables will include a stress relief part, closely to the end of

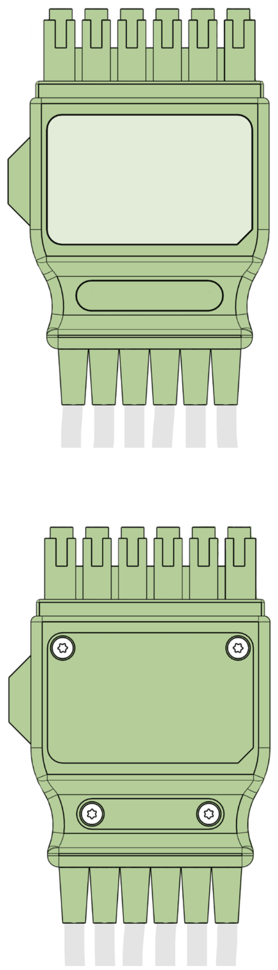
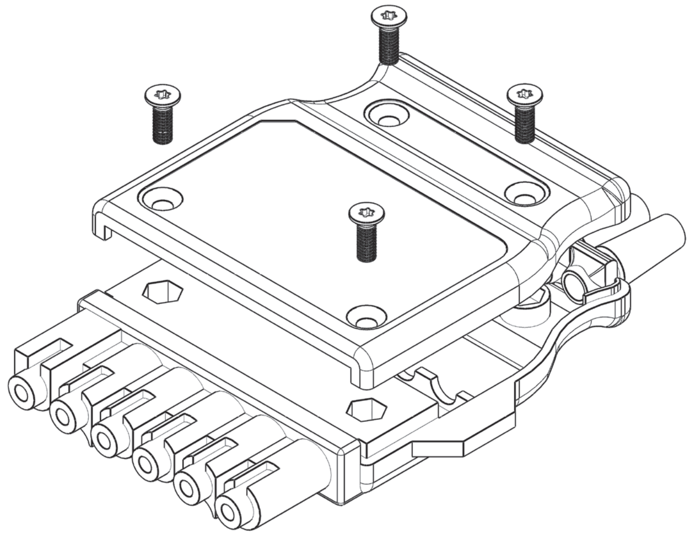
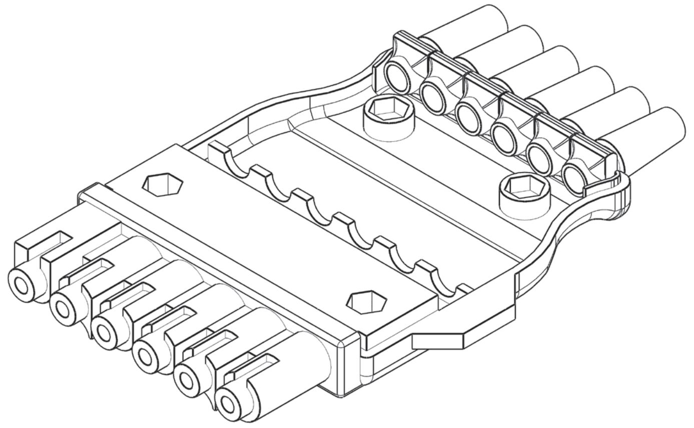


Figure55.Connector with screws exposed after sticker gets removed

the cable. This part fits into the connector, and holds the cable securely in place during the normal use. When a cable is broken, it can be disconnected inside the connector and be swapped out for a new one.





Repair service in detail

The ReLead design envisions that the repairing of the product is managed by the manufacturers. First, the ability of parties, like EMC, to perform product repairs is currently limited by regulatory barriers. Implementing repair is therefore complicated and frequently impracticable due to these regulations, which may include training requirements and accountability issues.

Secondly, given the state of the market, product repairs are still comparatively uncommon. Repair is not standard in regular hospital workflows, and many devices are made to be disposable or single-use. It is difficult to set up decentralized repair networks or train staff because there is no model for this, yet.

These elements combined create the arguments for a centralized repair model where the manufacturer maintains complete authority. In addition to making regulatory compliance easier and guaranteeing constant quality, this supports the larger movement toward circular strategies.

Additionally to addressing sustainability goals, this strategy enables manufacturing companies to gain more value from their products. The model offers potential for integrating revenue streams, even though financing strategies were not the main focus. The system adds value and improves manufacturer accountability by fusing data collection and analysis with product repair. Manufacturers must make investments in service infrastructure and product redesign in order to implement this model. Nonetheless, this shift to a service-oriented business model contributes to the system's long-term sustainability and viability.

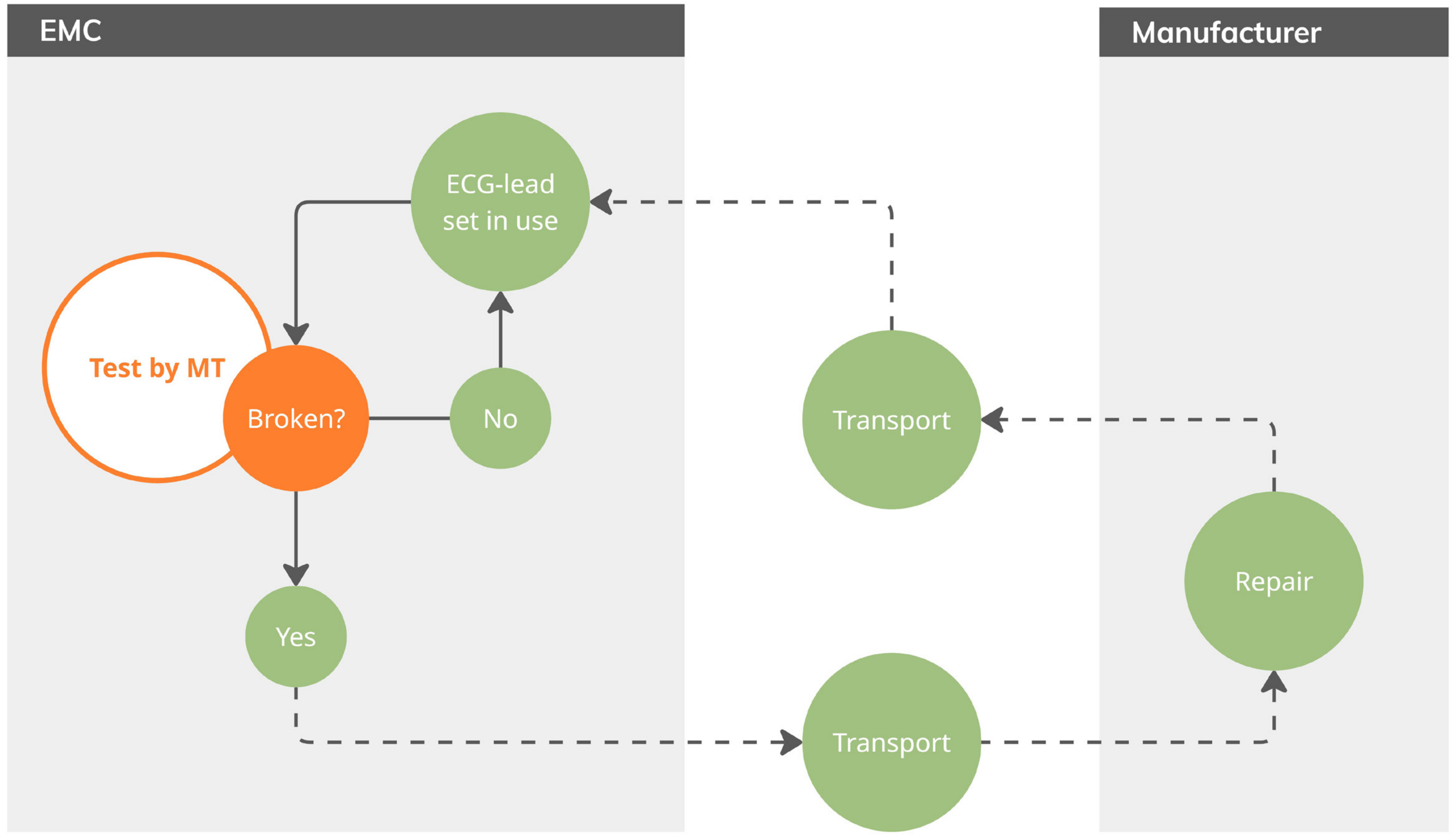


Figure56.The process of repair

Track&Trace

The adapter is the brains of the track and trace system, it houses an RFID reader, battery, and motherboard to make it all work. The adapter is made to fit onto the current Dräger patient computer and be present at all times.

The RFID reader is placed in such as way that it can read out the RFID tag from the ECG-lead set. Using ten-minute cycles, the adapter checks for products in the range, if not the adapter goes into sleep mode to save energy.

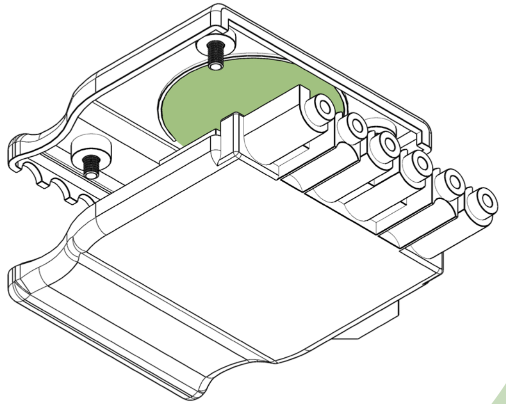
The adapter is highly energy-efficient uses a microcontroller, to regulate RFID communication, Bluetooth Low Energy (BLE) scanning, and data logging. A 13.56 MHz RFID reader is embedded in the adapter to detect the RFID tags.

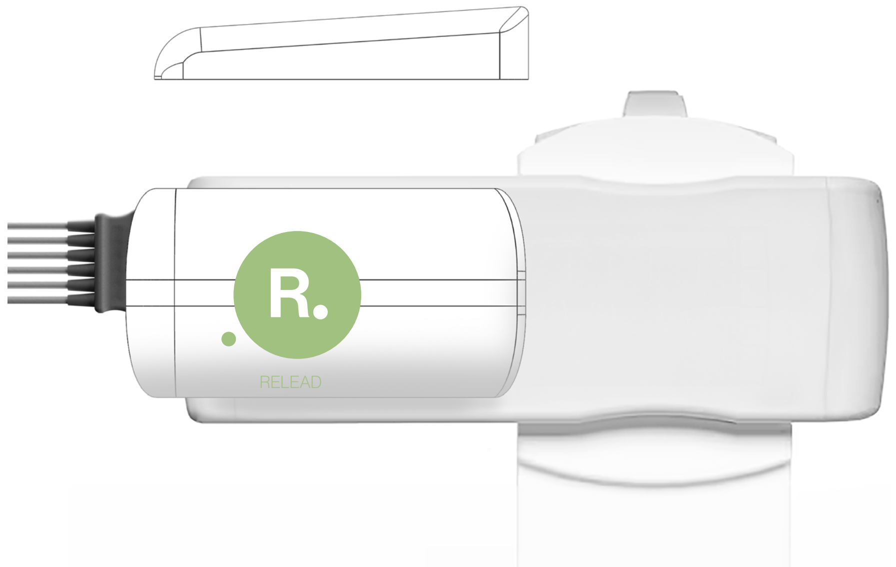
To ensure extremely low power consumption, the adapter uses a digital Hall effect sensor to detect magnetic fields indicating cable insertion or removal. The sensor is positioned near in a similar location as the RFID reader and is triggered when the ECG-lead set (or extension cable) is connected. These sensors consume very low energy in standby mode and serve as a trigger to wake the system.When the system detects that both cables are connected, it wakes briefly to read the RFID tags, scan for nearby BLE beacons to determine its room location, and log a new session with time, cable IDs, and location. Doing this every ten minutes.

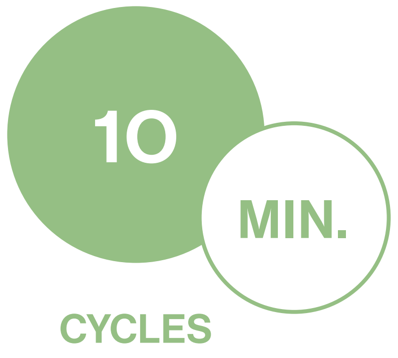
All data is stored in local memory and once per day, the system connects to the hospital Wi-Fi to upload session logs to a central server. This infrequent use of Wi-Fi drastically reduces power usage while still ensuring timely data reporting.

The entire system is powered by a 10,000 mAh rechargeable lithium-ion battery pack, designed to last for at least 9–12 months on a single charge. The intelligent sleep/wake logic, makes the adapter a reliable, low-maintenance solution for clinical use, capable of delivering detailed tracking of cable usage and location without affecting normal hospital workflows or requiring frequent recharging.

Figure57.Connector with embedded RFIF tga







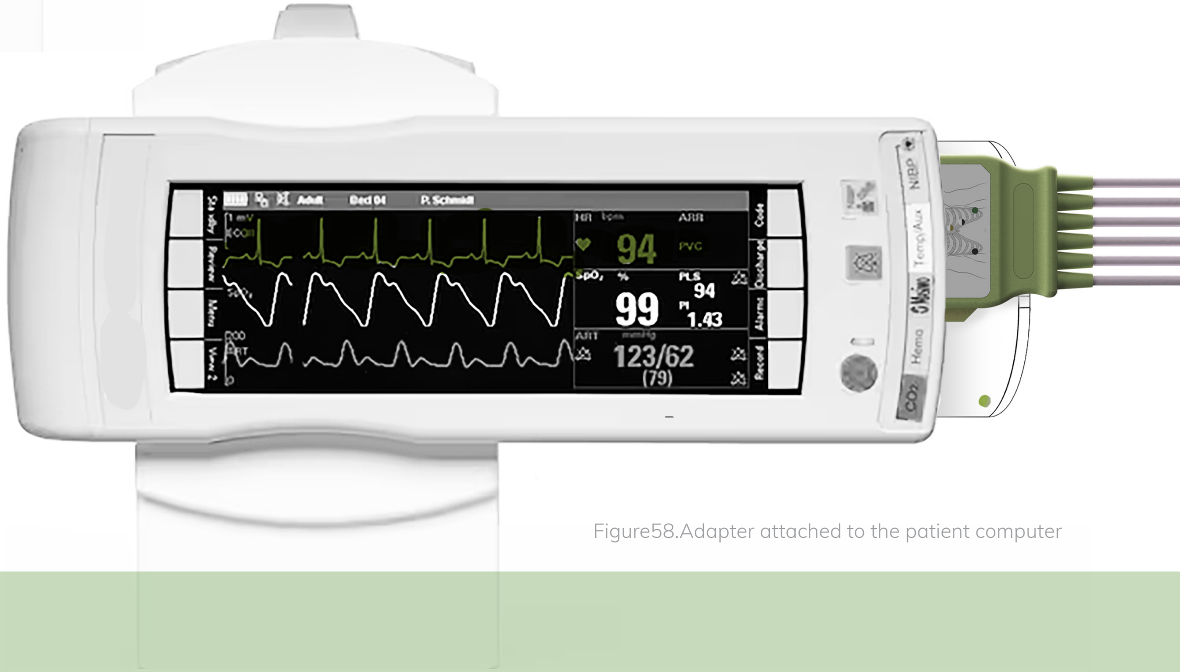


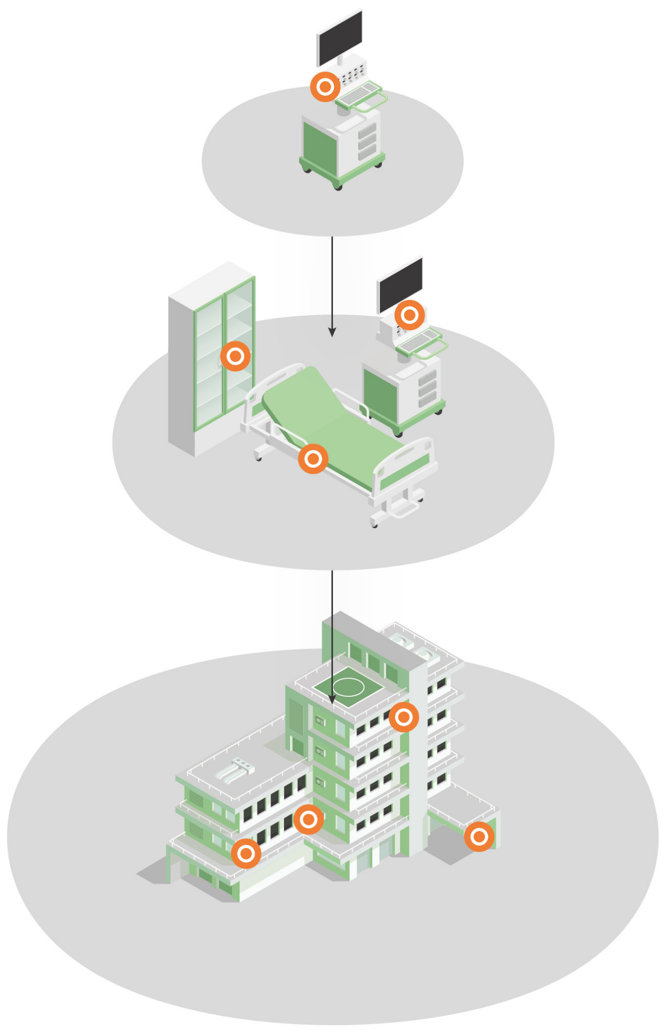
Figure58.Adapter attached to the patient computer

Track & Trace system: explained

The core of the traceability system are the passive RFID tags, and the ReLead Trace adapter. These are the physical aspect of the system, but the infrastructure is just as significant and is what create value for the different stakeholders. Trough data collection, the goal is to account for typical usage patterns and increase efficient use. The current design is intentionally kept simple and robust, to make it a viable first step towards a bigger system.

The system logs key parameters such as asset location, usage status (active or idle), and timestamps. Throughthe idle state introduces some uncertainty about precise usage, this level of accuracy is a realistic and informative compromise for the clinical workflows. The locations are based on room ID's, using Bluetooth beacons the adapter can recognize its location on a room level. By logging just these three parameters, it already has great potential to generate valuable data on which strategic choices can be based.

The future roadmap outlines how this system can evolve into something much bigger. Initial deployment focuses on robust data and "easy" to trace assets like ECG-lead sets. But as the infrastructure grows, the system can expand to room-level tracking by installing additional RFID antennas in select areas. This scalable design supports EMC's long-term vision for smarter, more efficient hospital asset management while allowing incremental investment and technical adaptation.



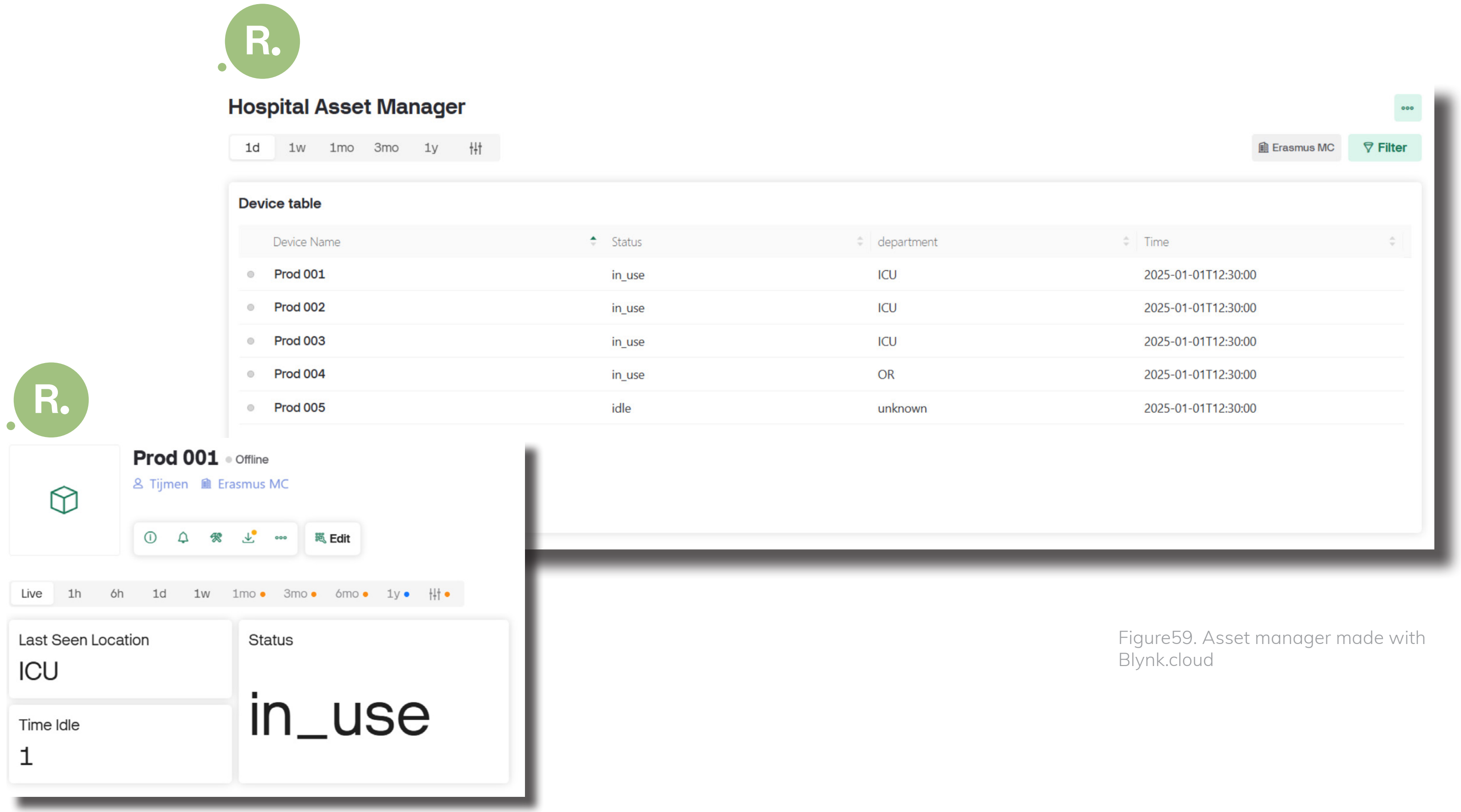
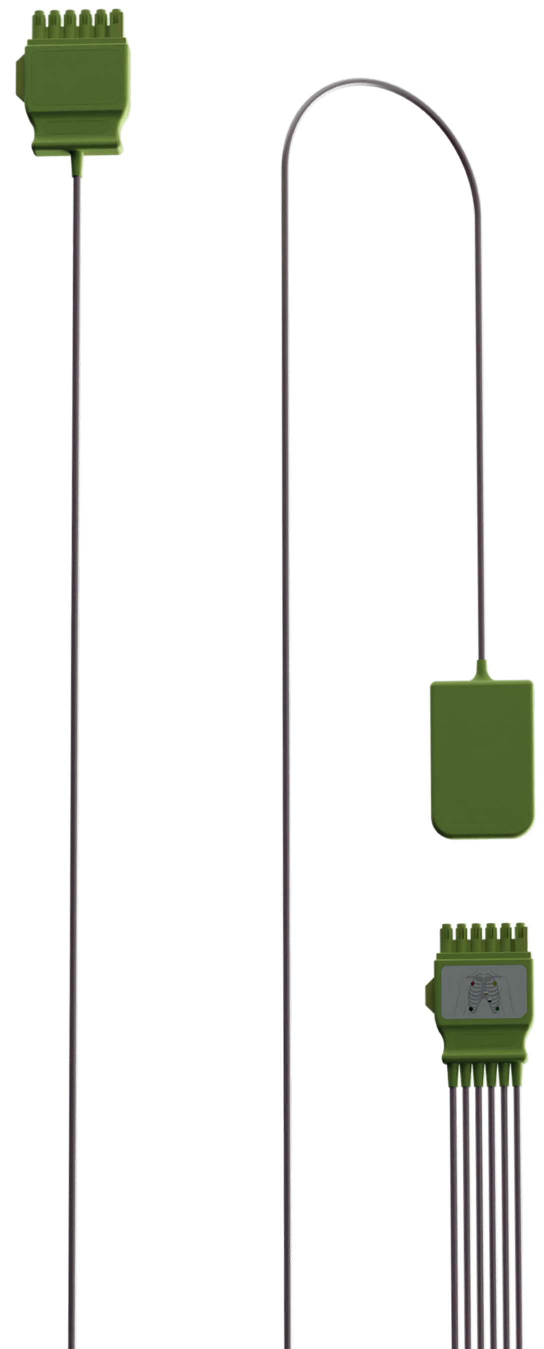


Figure59. Asset manager made with Blynk.cloud

Extension cable

To ensure the track & trace system can work, it is important to have an extension cable that is compatible. To be able to read the product ID of the ECG-lead set, the extension is cable is equipped with an RFID reader. This reader does not use any electricity, but actually physically extends the range of the reader with an antenna (cable).

At the other side, this uses the same computer connector, there is an RFID tag for its own product ID. As well as the other end of the extender, these can both be read by the reader.



RELEAD

Rethinking ECG-lead sets to Reduce environmental impact

7.2 DESIGN EVALUATION

To be able to validate the design on its feasibility and usability, different prototypes were made to test different aspects. Some of these test will be highlighted here, but also different barriers will be discussed. The insights addressed in this section were partly used to improve the final design, other points will be discussed further in the discussion as they were not implemented in the ReLead design proposal.

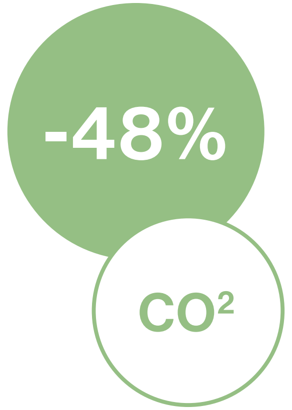
ReLead patch sustainability comparison

The goal ultimately was to reduce the impact on the environment and promote more sustainable product use by proposing this new design. A LCA comparison between the ReLead patch and the original electrode was conducted to determine the sustainability gains (see Appendix B). This is the most accurate and suitable way to measure the environmental impact of the design, since the patch is the biggest improvement, the other design changes are covered separately in the following section.

In addition to removing materials, the final design adds a new plastic holder. To make sure that the design had the greatest possible impact on sustainability, this extra material was deliberately kept to a minimum. By reviewing the plastic holder mass properties in SolidWorks, the total amount of extra material comes to 23 grams of plastic (PP).

Despite this addition, the total weight is decreased by 36%, also due to the removal of the extra sticker film and the plastic cover that was previously used to protect the gel layer.
The eco-intensity has been decreased by 18%, removing the Ag/AgCl material and the gel patch, therefore most/the most valuable materials have been removed. According to this LCA comparison, the total environmental savings come to 48% since CO_2-equivalent impact is determined using both weight and eco-intensity.

A very promising solution with large environmental benefits considering the electrodes, and now patches, get consumed in large volume. Theoretically, it could save 300 kg of metal waste each year in the EMC, keeping valuable materials in the loop.



Dry electrode feasibility evaluation

The proposed dry electrode design is backed up by existing research, which shows that it meets clinical and operational needs very well. Studies show that dry electrodes eliminate the need for resource-intensive gels and adhesive pads used in Ag/AgCl systems, offering a more sustainable and cost-effective alternative (Joutsen et al., 2024). Solid-metal electrodes, such as those made from silver or stainless steel, have been shown to withstand repeated cleaning with alcohol or water-based solutions without performance loss, unlike Ag/AgCl electrodes that degrade with sterilization (Joutsen et al., 2024). Moreover, concerns about signal quality are addressed in recent research, which confirms that well-designed dry electrodes can achieve signal-to-noise ratios and ECG feature detection comparable to or better than gel-based systems in resting and low-motion conditions (Kim et al., 2022; Joutsen et al., 2024). These findings collectively validate the design's clinical suitability, particularly for routine and ambulatory ECG monitoring.

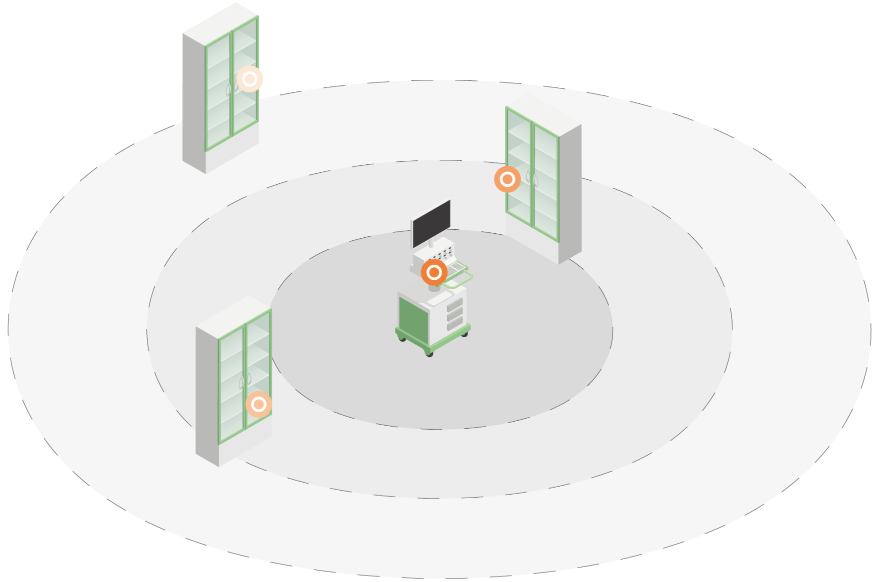
HeartEye's MiniECG device, which records a complete 12-lead ECG using a set of four dry stainless steel electrodes, is a more practical application of the same concept. The feasibility of employing long-lasting, easily cleaned dry metal electrodes for cardiac monitoring is effectively demonstrated by this use in clinical-quality equipment (Product – Hearteye, n.d.). For his graduation project, Lucas Habets worked on this project (Redesign of the HeartEye Portable ECG Device for Home Use, n.d.). He verified that this technology should function, but emphasized that it needs to be tested in this particular use case.

Figure60. Hearteye product using conductive spray

RFID system evaluation

The ReLead Track & Trace system is built on well-established technologies already used across the healthcare sector for asset tracking and management. RFID tracking, passive antenna extension, BLE-based room location, and energy-efficient wireless logging are all validated by large-scale commercial and hospital deployments.

Hospitals and health systems already have implemented RFID-based tracking systems to monitor medical equipment usage and reduce loss and inefficiency. These solutions often use passive 13.56 MHz RFID tags and readers similar to those in the ReLead adapter. For instance, Stanley Healthcare offers comprehensive RFID and RTLS systems used in over 5,000 hospitals globally for asset and patient tracking (Securitas Healthcare, n.d.). Zebra Technologies also provides RFID hardware tailored for healthcare environments and is widely adopted in logistics-heavy hospitals for equipment traceability (Zebra Technologies | Visible. Connected. Optimized. | Zebra, n.d.).



Evaluation of the desirability

To be able to get insight in the desirability of the new design, the design was presented to three different ICU nurses. Based on what the ICU nurses confirmed, the suggested ECG cable design is seen as a good and useful one, especially since it directly addresses well-known and frequent user complaints. Nurses instantly associated the concept of ECG cables with problems such as tangling, challenging cleaning, and breaking, of which some problems are addressed by ReLead. As a result, the prototype felt immediately valuable and based on actual needs. Given that patients may stay in the intensive care unit for extended periods of time, the nurses also valued the attention to comfort. Positive comments were made about the design's ability to enhance hygiene and lessen clutter, and its compatibility with common ICU problems made it an interesting avenue for future research.

That said, the desirability of the design is strongly tied to its feasibility. The nurses highlighted that although the idea is promising, its viability rests on its ability to fit into the ICU workflows. It is believed that features like flexible cable redirection, breath rate monitoring, and the ability to continue using an extension cable are crucial. Of these suggestions, the need for cable redirecting and the use of extension cables, found itself in the ReLead design.
The nurses' readiness to put forward improvements, such as including gel application techniques or employing square electrodes on a single film, showed that they are invested in the design and see its potential. The session helped to validate the desirability, which depended on feasibility mostly. But also was positively influenced by the incorporation of features, like cleanability and ease of use.

Figure61. Feedback session at EMC with ICU nurses

8

CONCLUSION

This project, set off to redesign ECG-lead sets within the hospital context of the EMC. The outcomes of the design work are examined, and barriers and limitations are discussed in detail. Recommendations for future research directions and next steps to evaluate the design are presented, concluding with answers to the research questions and a reflection on the design process.

Project implications

The most valuable aspect of the research phase was the in-depth and context-specific investigation of ECG-lead sets within Erasmus MC. This approach provided the project a strong foundation for the design process. Employee interviews and observations offered clear and practical insights, ensuring the work was grounded in real processes. Sharing these insights within the EMC, and sharing this approach, can benefit future research.

All of this was made possible through direct engagement with the context, which resulted in meaningful interactions, observing, speaking and asking questions. Both quantitative data, like the LCA and product consumption was incorporated, alongside these insights from daily practices. Being part of the context is the key to a grounded project and valuable results.

The environmental benefits, combined with user experience demands, make it a well-supported design. In a context such as the EMC, the design explored circular strategies in a realistic way. By focusing on traceability, repairability, as well as keeping valuable materials to stay in the loop, the project provided insightful concepts that challenge our perceptions of sustainability and products like ECG-lead sets.

Ultimately, the project was successful in finding concepts that can promote healthcare sustainability as well as a clear design opportunity. Beyond this intervention, the research and design methodology can have a larger impact by influencing future projects and, igniting discussions about sustainability across hospital departments. This project reaches beyond just ECG-lead sets and offers an example model for redesigning other disposable medical devices.

8.1 BARRIERS & LIMITATIONS

Several limitation were encountered during the project, affecting both the research and design. This section discusses these limitations and highlights some of the barriers that led to them.

The research would have benefited from a more structured and quantitative approach in some cases. For example, the lack of data within EMC forced the LCA to rely on estimates and assumptions. While this approach was reasonable under the circumstances, it reduced the reliability and robustness of the findings and the conclusions. The environmental impact claims might have been more reliable if they had been done more thoroughly with a more comprehensive materials analysis. Moreover, the inclusion of a survey for nurses from different departments may have revealed more systemic patterns in user behaviour or preferences. This would have provided support for the qualitative claims.

Navigating the complexity of the hospital system presented another difficulty. In order to gain insight into the patient-related issues, all interactions went through the nurses. This indirect approach resulted in a more one-sided perspective. Due to privacy regulations, the project primarily focused on the user experience from a nurse's perspective. The absence of direct patient input limited the ability to create a holistic overview of the system.

As an industrial designer, the research in general was focused on users or user-related aspects. However, this made it more challenging to work on systemic barriers, such as procurement policy and regulatory constraints. While these subjects were mentioned, they weren't discussed in sufficient depth to have a structural impact on the finished design. Given that the designer has no control over more significant systemic decisions (such as single-use policies), it would be more valuable to explore the extent to which product design alone can influence such a regulated system as the hospital.

In the final design, the decision to also focus on the electrode rather than only the cable system was both strategic and limiting. On one hand, the electrode showed the largest potential for environmental impact. However, on the other hand, this choice meant stepping into a technically more complex area. Designing a dry, reusable electrode that works well with current ECG technology, ensures patient comfort, and passes hygiene and safety standards proved to be quite ambitious. While the proposed design direction aimed to address some of these main issues, it remains speculative. Due to constraints of the project time line, only limited validation was possible. Making it hard to reach a go or no-go decision. The lack of electrical tests that were performed means that we cannot reliably say anything. In addition, cleaning procedures for the new design and long periods of testing were only explored in theory.

Furthermore, user testing primarily examined interaction with the prototype rather than actual wear of the product, even though usability concerns like comfort and detachment were recognized. The lack of a full, complete prototype meant that some areas were potentially overlooked. The barrier to creating a test-ready prototype contributed to this limitation. Although the scope and depth of the nurses' testing feedback were limited, it was encouraging. Testing across various patient profiles (such as ICU versus cardiology) and involving infection control experts would be a more direct assessment of cleaning and hygiene risks.

The extent to which circularity strategies were used is another area for debate. While R-strategies like "Reuse," "Rethink," and to a lesser extent "Reduce" were incorporated in the design, other strategies like "Repair" or "Refurbish" were primarily discussed in theory. Assumptions had to be made to design the repair service. But on a systemic level, reprocessing or recycling will offer value for multiple future projects. However, in this project, they were still not explored thoroughly enough to assess the feasibility of the repair service.

Regarding the track & trace system, the potential is clearly visible, but can only be confirmed with testing. Again, assumptions had to be made to design the system, limiting its strength in the supported arguments. Besides, the integration of the system into the hospital is briefly discussed, but requires more extensive research to find a fitting solution. The complexity of integration is overlooked and not discussed as one of its limitations.

Lastly, there was a conflict between trying to challenge the current system and designing for it. The design became more feasible because the project primarily operated within EMC's existing systems and workflows. However, this approach might have lost a chance to challenge the structure more provocatively. Questions like: Are individual stickers for ECG electrodes even necessary? Can't it become a wireless system? These questions were discussed, but eventually rejected in favour of a more modest innovation. This increased the project's viability but also constrained its creative possibilities, and is ultimately the recurring challenge of design projects.

To conclude, the project was successful in finding a logical and significant design opportunity and in defining a concept that supports healthcare sustainability. However, the complexity of the medical system, technical viability, and data uncertainty limit its impact. By working more closely with technical partners, regulatory agencies, and hospital policymakers, future work could build on these areas. By doing this, the design could transform from a viable design proposal to a functional solution.

8.2 CONCLUSION

The ECG system, and in particular the electrodes, contributes significantly to the environmental impact.

RQ. 1 What is the environmental impact of ECG-lead sets and electrodes at EMC, and what are the sustainability challenges?

Because SPU devices generate a lot of waste after each use, ECG-lead sets have a significant environmental impact. Practical barriers like hygiene risks and very specific use cases hinder the wider adoption of MPU alternatives.

Despite their small size, electrodes have the largest and most significant environmental impact due to their volume and material usage. Reducing this waste was successfully identified to reduce the environmental impact of the ECG system as a whole.

ECG-lead sets can be redesigned through circular strategies like reuse, repair, and traceability.

RQ2. What are the main barriers and opportunities for implementing circular strategies in the use of ECG-lead sets?

This project looked into how EMC could use circular strategies to improve ECG-lead sets in order to support sustainability in healthcare. Through the research phase that included context analysis, user interviews, and life cycle assessment, the project was able to determine practical and environmental hotspots associated with the current use of ECG devices.

It demonstrates that it is possible to introduce strategies like traceability, repair, and reuse into the medical practice. Furthermore, a number of challenges, like hygienic risks and cleaning complexity, are examples of practical challenges to implementing more circular strategies. In addition, systemic barriers like complicated regulations and conflicting stakeholder interests are determining the use of more strategies.

Complexity and resistance to change makes sustainable decision-making complex for the healthcare sector.

RQ 3. How do different stakeholders and systemic factors influence sustainable decision-making around ECG products?

The study found several obvious opportunities, including improving procurement's emphasis on sustainability and manually tracking the product lifecycle. These factors could support decision-making, based on actual data. However, it was also found that some stakeholders try to avoid taking accountability for sustainability issues due to practical difficulties with cleaning and infection risks. The project illustrates the challenge of adapting to the complex healthcare system. Stakeholders can uphold their current agendas because new products find it difficult to adapt due to this complexity and resistance to change.

Users priories the practical functions of the ECG-lead sets, and dislike cleaning, tangling and lost sets.

RQ4. What are the user experiences and needs of patients and nurses when interacting with ECG-lead sets?

The project identified practical and environmental hotspots related to the current use of ECG devices through extensive research that included context analysis and user interviews. The most prominent user issues were: difficulty with cleaning, tangling of the lead sets and lost ECG-sets.

The overarching theme is that the medical staff prioritizes the practical functions of the ECG-lead sets. Being able to trust a product, anticipating how it works, is the most important value for them. Employees in the healthcare industry are used to specific workflows, and they do so for a reason, so it's critical to avoid unnecessarily interfering with them.

8.3 PERSONAL REFLECTION

Learning to Involve Others Early
After this project, I have come to learn a lot about doing an individual project for six months, about working in the medical field and about myself. The challenge of managing a project by yourself and going through the process. Incorporating others' input or perspective. One of my main realizations that I had, is that I recognize the value of asking for input and exchanging ideas at the beginning of the process. Asking others for their thoughts or recommendations can lead to more perspectives, more guidance, and better results overall. Looking back, I can see how the process and outcome may have been improved with more frequent participation from others. It was only later in the process that I realised that, although I was in charge of the project, I did not have to do everything by myself and asking for help would help the project to move forward. It showed me how much can be achieved via open cooperation, yet at the time, I was not fully aware of this.

Embracing Ambiguity and Structuring the Process
Throughout the project, I relied heavily on my instincts as a designer, rather than a clear, structured plan, and I adapted to changing context, ideas, and feedback. While this natural approach worked in some moments, it also caused difficulties during more complex stages. It became clear that I need more structure and a coherent storyline to guide my process. Being too close to the work without regularly sharing thoughts with others can make it harder to maintain perspective and assess progress objectively. Looking back, the moments that I did leave my bubble and received feedback helped me structure and prioritize better to move forward.

That said, I've become more aware of where things could have gone better. Managing and leading a project independently is time-intensive and demanding, and I've come to appreciate the importance of taking pride in the work I do. Instead of comparing myself to others, I enjoy the process more, and that realisation is an important part of learning and growth as a designer.

Independent Growth and the Value of Collaboration
To sum up, this project has taught me about working independently while also highlighting the importance of collaborating. I realized the importance of getting others involved, striking a balance between structure and intuition, and taking a step back to think clearly. Above all, it taught me to trust the process and to appreciate the work you put in.

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REWIRING FOR SUSTAINABILITY

A circular approach to the redesign of ECG lead sets to improve sustainability in healthcare

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