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Development of an Integrated Interface for *ex vivo* Organ Perfusion

An Interactive Prototype

Lisa Deckers
S2539136

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Internal supervisor(s):
Dr. Fokie Cnossen (Artificial Intelligence, University of Groningen)

External supervisor:
Dr. Maarten Nijsten (Dpt of Critical Care, Medical Sciences, UMCG)

Abstract

Due to the worldwide organ shortage physicians and researchers have been striving to develop new techniques to increase the number and quality of organs for transplantation. Currently, they are examining *ex vivo* machine perfusion to achieve this. The UMCG is among the leaders in the world who are successfully implementing and developing organ perfusion techniques.

Due to the relative novelty of machine perfusion hospitals do not have a single standard cohesive technological system. Instead machine perfusionists use a collection of devices connected to the organ that control or measure different parameters and display their own output.

The goal of this project was to execute the first iterations of the design cycle to bring these measurements and controls together into one integrated prototype interface. The goal was further to develop a prototype that records and visualizes organ perfusion information to enhance efficiency and performance of machine perfusionists.

To achieve this, initial interviews with stakeholders were held to gather user requirements and needs. This was followed by development of an interactive prototype, which was then evaluated by machine perfusionists. The evaluation brought many valuable improvements and suggestions to light. Nevertheless, the users were enthusiastic about the potential for implementing such an interface for machine perfusion.

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1. Introduction

Worldwide there is a donor shortage as organ transplants are the only treatment for many forms of end-stage organ failure (Manara, Murphy & O'Callaghan, 2012). In part this is the case because not all organs that become available for donation can actually be safely transplanted. In order for organs to be safely transplanted they must display a minimal level of functioning. Depending on the functional assessment, organs may be rejected immediately at the donor or possibly at a later stage before transplantation in the receiving patient. The current preferred method for preserving organs outside of a living body is static cold storage (SCS). SCS has a significant impact on the function of the organs by the time transplantation takes place. SCS is an environment that decreases organ function to a minimum while the organ still remains viable. In SCS organs are kept in conditions where cell metabolism, oxygen requirement and essential nutrient consumption are reduced (Reeb & Cypel, 2016). This reduction in metabolic needs allows for an organ to remain viable outside of the body. However, organs may also suffer from additional cold induced damage in this environment. This cold induced damage may subsequently be aggravated after reperfusion in the recipient (Weissenbacher, Vrakas, Nasralla & Ceresa, 2019). Here we can discriminate between low-risk and high-risk organs, where low-risk organs are more often organs Donated after Brain Death (DBD) and high-risk organs are more often Donated after Circulatory Death (DCD) or from Extended Criteria Donors (ECD). Low-risk organs can generally better tolerate the damage caused by SCS and reperfusion, or so-called ischemia reperfusion injury. High-risk organs are more sensitive to ischemia reperfusion injury, which may lead to loss of the organ after transplantation (Ceresa, Nasralla, Coussios & Friend, 2018). With the dire need for transplantable organs it has become apparent that new methods must be developed to be able to make use of high-risk organs more frequently.

While SCS has its pitfalls regarding preservation of high-risk organs another important disadvantage is that during SCS it is not possible to further assess the organ function (Reeb & Cypel, 2015). Cellular injury can, therefore, occur unidentified which can result in complications after transplantation, such as primary graft dysfunction (i.e. acute injury shortly after transplantation of the organ).

To hopefully increase the number of organs that are suitable for transplantation and obtain more information on organ function before transplantation, researchers are currently working on methods that can keep organs functioning *ex vivo* at a higher metabolic level. This method is known as *ex vivo* organ perfusion or machine perfusion. The aim of this method is to maintain and even improve quality of health of donated organs by keeping the organ in an environment that mimics the physiological environment of the body (Nassar et al., 2015). Since the goal is to have these organs functioning as they normally would, this is also a method that allows for testing graft viability (op den Dries et al., 2013). This means that organs that may have previously been rejected due to uncertainties can now be tested to determine if they satisfy the minimal criteria to be transplanted. The Universitair Medisch Centrum Groningen (UMCG) was the first hospital in the Netherlands and among the first in the world to introduce facilities for machine perfusion as a method for caring for an organ *ex vivo.* The UMCG was one of the first in the world to successfully keep an *ex vivo* liver viable at body temperature (op den Dries et al., 2013). Currently the

UMCG has resources for supporting kidneys, livers, lungs, and hearts in their Organ Preservation and Resuscitation unit (OPR), where the largest steps are being made in liver and lung conditioning.

Several devices are currently used to care for an organ during machine perfusion. These devices all have their own displays and controls, some of which are not ideally located for the operators supervising the machine perfusion. These devices can also be used to adjust certain parameters, such as, increasing oxygen or adjusting the perfusion temperature. However, recording the data provided by these devices has proven to be tedious manual work. In the current perfusion procedure the perfusionists manually record the data on paper every fifteen minutes and take samples every 15 – 30 minutes. Due to these human recording limitations, resulting recordings can only be spoken of in terms of trends due to time intervals between recordings. This setup with a combination of separate devices and manual recording systems would suggest that while the applied principles are cutting edge medical technology, the actual implementation in terms of informatics has been left behind by many other current technologies.

The focus of this thesis was to improve the onscreen technology of these devices by developing a prototype of an interface to present relevant parameters in real time and to allow for controlling these parameters from the interface. The project was based on user-centered and work-centered design approaches. The method for this research was to gather user requirements and work domain constraints to incorporate into one prototype interface where the interfaces of the separate devices are combined into a single user interface. This will be the initial cycles of many in the interaction design lifecycle of user-centered design (Preece, Rogers & Sharp, 2015). The goal was, therefore, to develop a prototype and evaluate said prototype based on layout and information content. Thus, the scope of this project does not go as far as to produce a dynamic product that can be immediately connected to the devices in the OPR.

The goal of the research can be defined by the following research question:

- How can multiple interfaces necessary for *ex vivo* organ perfusion be combined into an integrated interface for improved and more efficient *ex vivo* organ perfusion by optimal presentation and easy adjustment of parameters pertinent to the perfusion process?

This question can be broken down into subquestions that form a framework that supports the main research question:

- What is the current user experience of the separate interfaces in the system?
- What are the user requirements and needs for the new system?
- In what way can cognitive engineering support design choices?

This thesis will begin with a theoretical framework that addresses relevant information on organ perfusion (Chapter 2) and cognitive engineering (Chapter 3) such as situation awareness and previous research on interface design.

The second part of this thesis focuses on the methods (Chapter 4) and design of the prototype (Chapter 6) where we will address the current user experience and determine the user requirements (Chapter 5).

The third part of the thesis focuses on the user evaluation. Here the methods (Chapter 7) and the results (Chapter 8) of the user evaluation are presented and discussed.

In the fourth and final part of the thesis the general results of the project (Chapter 9) are discussed, as well as presenting points of attention for futures cycles (Chapter 11) in the interaction design approach.

Part I. Theoretical Framework

In the following part we will discuss the theoretical background necessary for designing an interface for organ perfusion. First it is important to gain an understanding of organ perfusion, the organ perfusion process and the necessary devices. Secondly, we will examine relevant theoretical background on general interface design. This includes situation awareness, design approaches and information visualization.

2. Organ Perfusion

Because of the aforementioned shortage it has become vital that as many organs as possible that become available for donation can actually be transplanted. While organs can be donated from a living person, this happens mostly only with kidneys and rarely with livers. Otherwise, livers, lungs and hearts can be donated after brain death (DBD) or circulatory death (DCD). Generally, however, the organs that are transplanted are DBD organs (Manara, Murphy & O'Callaghan, 2012). The use of DCD organs is increasing, but there are higher risks of dysfunction after implantation associated with DCD organs (Blok et al., 2016). This is mostly due to ischemia, which can lead to primary graft failure (persistent immediate absence of sufficient function of the donor organ), delayed graft function and other complications such as abnormal narrowing of the bile duct (biliary strictures) in the liver (Manara, Murphy & O'Callaghan, 2012). DCD lungs in particular are also susceptible to hypotension, hypoxemia and aspiration.

Currently the standard method for organ preservation is static cold storage (SCS). The organ is flushed with ice-cold preservation fluid and stored at a temperature between 0ºC and 4ºC. This sharply reduces metabolic demands and helps to maintain the integrity of the organ. Organs do suffer from damage in this cold environment. Damage occurs in organs as they are not oxygenated during SCS this can result in reduced long-term outcomes, such as death of the receiving patient (Hamed et al., 2015). While low-risk organs may tolerate this kind of damage, high-risk organs like DCD organs cannot. Therefore, these high-risk organs may become unsuitable for transplantation (Ceresa, Nasralla, Coussios & Friend, 2018). This makes SCS in principle a suitable method for low-risk organs but much less for high-risk organs.

2.1 Machine Perfusion

To improve preservation machine perfusion (MP), or *ex vivo* organ perfusion, was developed. During perfusion the cellular metabolism of organs is maintained by providing the organ with oxygen and nutrients by pumping a perfusion solution through the organ at a range of temperatures. This perfusion solution essentially substitutes blood. Multiple studies have found that MP is a superior preservation method to SCS for donor organs (Ceresa, Nasralla, Coussios & Friend, 2018; Kaths et al., 2018; Marecki et al., 2017; Reeb & Cypel, 2016). MP helps to reduce ischemia reperfusion injury. Another advantage of MP is that there is a possibility for viability assessment directly before implantation (Sutton et al., 2014). This makes MP not only a valuable preservation method until transplantation but can also help determine if an organ should be transplanted or not.

MP can be applied over a range of temperatures, at 0-12ºC hypothermic machine perfusion (HMP), at 24-34ºC subnormothermic machine perfusion (SNMP), and at 35-38ºC normothermic machine perfusion (NMP). While HMP resembles SCS hypothermic oxygenated perfusion (HOPE) resembles HMP but with an addition of oxygen that has multiple benefits, including lower re-oxygenation injury (Schlegel, Kron & Dutkowski, 2016). NMP maintains cellular metabolism by providing the organ with oxygen and nutrients at 37ºC (Brockmann et al., 2009). This normothermic environment most closely resembles the environment in the body, which allows for full function metabolic activity (Sutton et al., 2014). Therefore, NMP provides the most suitable conditions for viability assessment.

Many devices are used during MP. The UMCG currently has the technology to support kidneys, livers, lungs and hearts and focuses on NMP. The exact set up differs per organ but a number of basic principles are the same. The perfusion liquid is pumped at an specific rate through the organ by pumps, imitating how the heart would pump blood through the organ. A gas exchanger removes carbon dioxide from and adds oxygen to the perfusate and a heat exchanger allows for setting and maintaining different perfusate temperatures. The lungs require an additional device, namely a ventilator.

This thesis will focus on machine perfusion for livers, kidneys, and lungs; however, the main focus will be on livers.

2.2 Organ Assist

Currently the UMCG uses perfusion systems produced by Organ Assist: the Liver Assist, the Kidney Assist, and the Lung Assist (Figure 1).

A combination of HMP followed by NMP is most often used to successfully support livers *ex-vivo* at the UMCG. Rotary pumps are used to provide a pulsatile flow to the hepatic artery and a continuous flow to the portal vein. The Liver Assist pump is a pressure-controlled pump. Oxygenators in the system oxygenate the perfusion solution and a heat exchanger allows for temperatures to be set from hypothermic to normothermic conditions. A detailed depiction of this liver perfusion system can be seen in Figure 2.

Ex vivo kidney perfusion resembles *ex vivo* liver perfusion (EVLP), however there is only one pump for the renal artery and vein (Yong, Hogsgood & Nicholson, 2016). The Kidney Assist is also a pressure controlled pump.

Due to the requirement that a lung must be ventilated, *ex-vivo* lung perfusion (EVLP) differs from the perfusion of other organs. Therefore, the system for lung perfusion includes a ventilator along with in and outflow cannulas, a heat exchanger, a leukocyte filter, a membrane gas exchanger and a pump (Figure 3). In contrast to the Liver and Kidney Assist, the Lung Assist is flow controlled.

Figure 1. The Liver Assist, the Lung Assist and the Kidney Assist (from left to right) as provided by Organ Assist (2019)

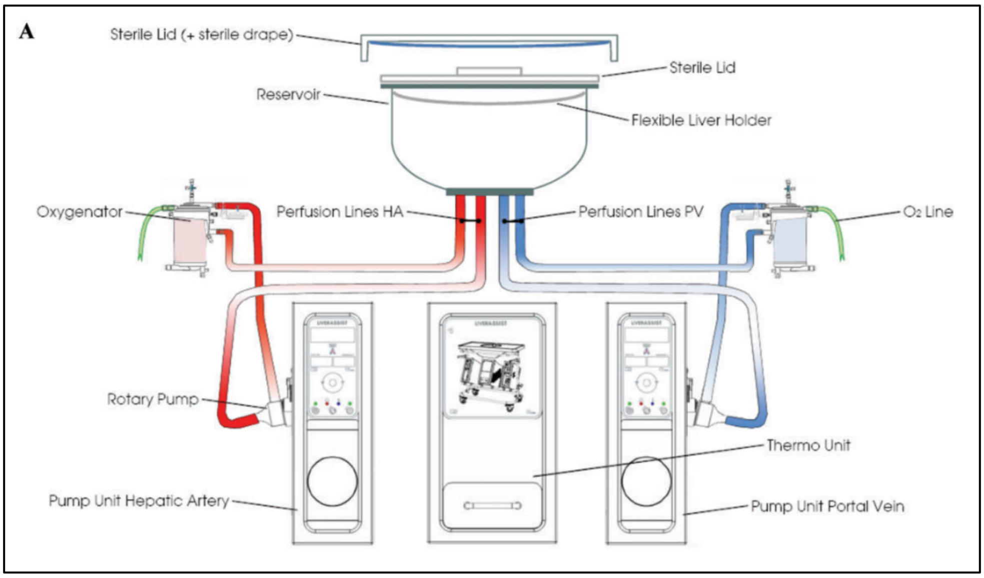

Figure 2. Schematic depiction of liver machine perfusion set up from van Rijn et al. (2017). The system for kidney machine perfusion strongly resembles this system, however there is only a single pump in the system, for the renal artery.

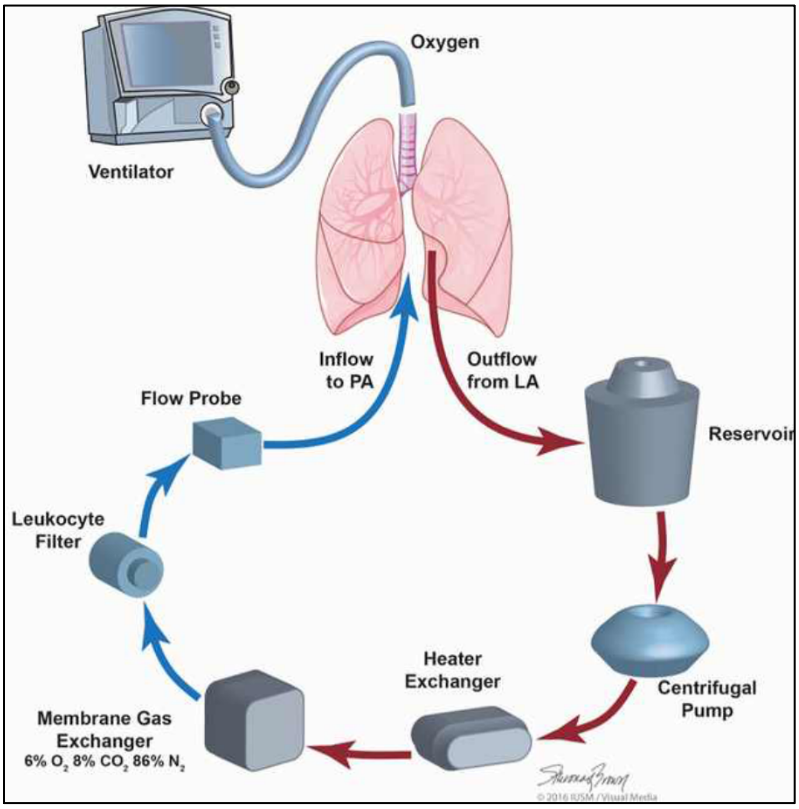

Figure 3. Schematic depiction of the EVLP setup from Makdisi & Wozniak (2017). This system is flow controlled instead of pressure controlled.

2.3 Machine Perfusion Parameters

For this thesis it is important to understand the parameters of machine perfusion. A wide variety of parameters are measured and recorded. Operators are currently interested in investigating multiple parameters. However, no parameters have yet been determined to be reliable parameters for functional assessment (Sutton et al., 2014). This means that all of the parameters should be available for observation.

Parameters are measured in different manners. The Organ Assist pumps have their own sensors that measure and display the following parameters, which we will further refer to as perfusion parameters:

- Flow
- Pressure
- Temperature
- Resistance

These parameters determine if perfusion occurs correctly. If they are not within specific bounds it is a marker that there is something wrong in the system. Either the technology itself is failing or something in the organ is failing. For example if the temperature drops it is a sign that the heater may be malfunctioning. If flow was to decrease there may be something preventing the flow through the organ or the pump may be failing. Operators can manipulate these parameters using controls on the pumps.

An oxygenator can further be controlled to control oxygen flow and percentage of oxygen inspired. This is a device that stands on its own, apart from the pumps. The amount of produced bile and urine for the liver and the kidney, respectively, can also be measured.

Furthermore, samples of the perfusate, bile and urine are manually taken. These samples are analysed in a separate machine to measure metabolic and functional parameters. The results are printed onto a paper receipt by the machine. This machine is a blood gas analyser and measures the following parameters:

- Metabolics:
  - Lactate
  - Glucose
- Electrolytes:
  - Sodium (Na^+)
  - Potassium (K^+)
  - Chlorine (Cl^-)
  - Calcium (Ca^{2+})
- Bloodgases:
  - pH
  - Partial pressure of carbon dioxide (pCO_2)
  - Partial pressure of oxygen (pO_2)
  - Oxygen saturation (sO_2)
  - Bicarbonate (HCO_3^-)
- Oxymetry values:
  - Hemoglobin (Hb)
  - Carboxyhemoglobin (COHb)
  - Methemoglobin (MetHb)
  - Concentration of deoxygenated hemoglobin (HHb)
  - Concentration of oxygenated hemoglobin (O_2Hb)
  - Bilirubin

These parameters help to determine if the organ is functioning properly. If there are no anomalies the organ can be transplanted. If anomalies occur, in many situations operators can attempt to take action and assess if the action improves the situation. If this is not the case the organ may not be functioning well enough to be transplanted. For example, if the glucose levels become too low operators may add potassium gluconate to the perfusate.

For lungs ventilation parameters are also measured and recorded, these include positive end-expiratory pressure (PEEP) and percentage of inspired oxygen (FiO_2), respiratory rate (RR), working pressure above PEEP (deltaP) and tidal volume (TV).

The perfusion parameters that are measured in realtime are displayed on screen on the Organ Assist pumps and manually recorded on paper at regular intervals. These screens do not display changes over time. The pumps record the data as well, but this data is currently inaccessible at the time of perfusion. The oxygen flow and percentage of inspired oxygen are also manually recorded on paper along with the perfusion parameters. The blood gas samples are recorded on printed papers by the blood gas analyser. These are inspected to determine if action needs to be taken to care for the organ.

Ideally, this collection of displays, controls and recordings would be combined into one interface that records and displays the data over time, and allows for the operators to manipulate parameters from the interface itself.

3. Situation Awareness & Interface design

The aim of this project was to design a prototype of an interface. Situation awareness is the foundation for designing systems (Lee, Kirlik & Endsley, 2013). We aimed to base our design on situation awareness theories, user-centered design as well as work-centered design principles; where situation awareness underlies both user-centered design (Lee, Kirlik & Endsley, 2013) and work-centered design (Bennett, Nagy & Flach, 2012). Robust designs include user analysis as well as work domain analysis. Furthermore, good information visualisation methods for the large amount of data output by perfusion devices are critical to both design methods.

3.1 Situation Awareness

Designing interfaces for medical environments is a challenging task. In systems such as nuclear power plant controls (Itoh, Sakuma & Monta, 1995) and aviation systems (Dinadis & Vicente, 1999) operators monitor and control a system that has well-defined conditions that can be determined to be within safe bounds. These systems are essentially designed to be monitored. In the medical world the system is a patient; or in the case of organ perfusion, a single organ. Patients are not designed to be monitored and the interaction between physiological variables is not always well understood. This makes it near impossible to define safe bounds across all patients (Drews & Westenskow, 2006). In the case of an organ the interaction between physiological parameters is even less understood as organs that function outside of the body do not need to support or have the input of the whole body. This makes exact safe bounds unknown. For these medical and nonmedical systems user interfaces are designed to enhance situation awareness to create safer environments (Itoh, Sakuma & Monta, 1995; Dinadis & Vicente, 1999).

Situation awareness is a general understanding of how information, events and ones own actions can have an effect on the on-going and future situation. Adequate situation awareness is of utmost importance in technology-rich work domains, such as an operating theatre (Preece, Rogers & Sharp, 2015). Situation awareness underlies good decision-making (Lee, Kirlik & Endsley, 2013). Endsley (1995) breaks situation awareness into three levels. The levels describe the levels of perception a user undergoes, in this case, when interacting with an interface to act in accordance with the work domain. Level 1 is perception of the environment's elements. Level 2 is comprehension of the current situation. And level 3 is the projection of future events.

Drews and Westenskow (2006) applied situation awareness principles to designing interfaces in the medical domain, with a focus on anaesthesia. The levels when applied to medical situation awareness are as follows: *detection* of a change in the environment, *diagnosis* of the change by integrating pieces of data to understand the meaning and *prediction* of future events to develop a plan of action where the implementation of the plan has been considered.

When a monitored variable changes the operator's attention should be drawn to it. This can be achieved by implementing design principles such as symmetry of geometric objects, emerging features, and patterns (Drews & Westenskow, 2006). Gurushanthaiah, Weinger & Englund (1995) compared detection of changes using numerical, histogram and polygon displays in anaesthesiology. The numerical display simply displayed the numerical values of the parameters. The histogram display showed the numerical values as well as a histogram form, where the normal situation was flat. And the polygon display showed all parameters as a point of a polygon (Figure 4), where a polygon with equal sides showed a normal situation. They found that anaesthesia residents detected changes 20% faster using the histogram and polygon displays compared to the numerical display. Their response latency also improved accordingly.

After a detection of change, the pattern of the changes must support a diagnosis. This can be done through an analytical process or a visual problem-solving process (Drews & Westenskow, 2006). Weber, Böckenholt, Hilton, & Wallace (1993) found that physicians tend to refer to similar cases from memory to help them make a diagnosis. This is what Drews and Westenskow (2006) refer to as pattern matching.

And finally a treatment should be administered that can be accompanied by a prediction of the future situation. An interface that supports these levels must aid in making rapid detection and diagnosis and administering treatment.

We can apply detection, diagnosis, and prediction as the levels of situation awareness as suggested by Drews and Wesrenskow (2006) to organ perfusion. In this case *detection* requires operators to detect that the state of the organ is changing, either positively or negatively. *Diagnosis* requires operators to determine what this change means for the organ, and *prediction* requires operators to determine on the

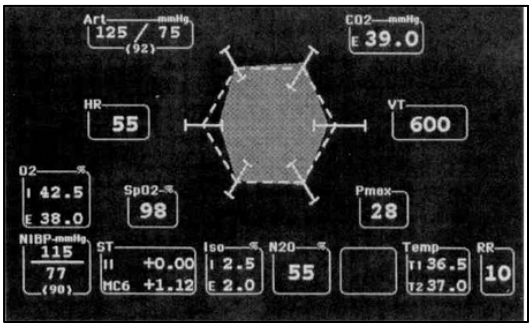

Figure 4. Gurushanthaiah, Weinger, Matthew, and Englund's (1995) anaesthesiology interface.

basis of their diagnosis what actions need to be taken or can be taken to improve the state of the organ for successful transplant at the end of the perfusion.

3.2 User-Centered Design

The idea of user-centered design has risen from technology growing and directly impacting the every day lives of its users. While it was previously seen as a technology-driven process, Eason (1989) proceeded to develop the idea that society is being reshaped by technology while actually very little thought is given to the world that it created. In order to address this, Eason (1989) established a set of tools that can be used along with technical system design techniques, to result in a user-driven technology that serves the users.

Three principles build up an iterative user-centered design (Gould & Lewis, 1985). They are:

1. Early focus on users and tasks
2. Empirical measurement
3. Iterative design

In order to adhere to these principles two contributors are necessary: *experts* and *stakeholders*. The experts have an understanding of the specialist issues while the stakeholders seek to gain from the designed solution. Together these two groups determine a framework that includes the design options and criteria. Design options can come from analyses of users and their tasks together with options that are available on a technical level, i.e. what is possible to program. Here the experts play a significant role in conducting the analyses and determining what appropriate and realistic options are that fit the task. The design criteria are the explicit goals and also the outcomes to avoid. The stakeholders (especially potential users) play a significant role in establishing these criteria. These criteria are known as user needs and requirements and should be gathered at early stages of the design cycle (Gould & Lewis, 1985). The collection of user needs and requirements can be achieved by conducting interviews or issuing questionnaires for example (Preece, Rogers & Sharp, 2015). However, the users should be involved throughout the entire design process and not only in early stages. They should further be involved in the empirical measurement, which is now referred to as user testing or evalution. Potential users interact with prototypes and any problems found during this stage are fixed and further testing is performed, which satisfies the iterative design principle. Preece, Rogers, and Sharp (2015) sum up these principles in a lifecycle model for interaction design (Figure 5).

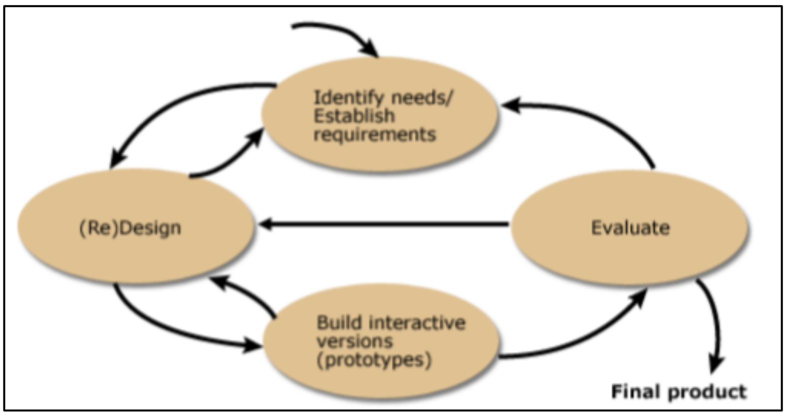

Figure 5. Rogers, Preece, and Sharp's (2015) interaction design life cycle.

3.3 Work-Centered Design

Lee, Kirlik and Burns (2013) argue that solely basing designs on users is insufficient due to the fact that users do not always have a complete understanding of the environment. Therefore, it is important to consider constraints and possibilities that come directly from the working environment.

Subsequently, taking a step further from user-centered design Bennett and Flach (2011) introduce yet another approach. The aim of an interface is to support decision-making and problem solving for the user who is working in a domain. The approach that stems from this idea is the triadic or *meaning processing* (Figure 6) approach to interface design where the success of an interface is dependent on the interaction between all components of a triad. Interfaces should be designed to support specific work demands (domain/ecology) and to leverage on perception-action skills of humans (human/awareness). The available interface technology is to be used to wisely represent data in way that is understandable (interface/representation). Importantly, the components each introduce a set of constraints that need to be taken into consideration when designing. The work domain offers constraints that are pertinent to the nature of the work. The human agent introduces constraints regarding cognitive and behavioural capabilities and limitations, while the design of the interface itself offers constraints concerning necessary cognitive resources for working with the interface.

Furthermore, when designing an interface, Bennett, Nagy, and Flach (2012) suggest three problems that should be taken into consideration: the *correspondence problem*, the *coherence problem*, and the *mapping problem*. The *correspondence* problem is a semantic problem regarding the information that should be presented to represent the work domain. This is the link between the interface and the work domain: does the interface accurately represent the work domain? The *coherence* problem is a syntax problem regarding how elements within a representation compete for attentional and cognitive resources. This is the link between the user and the interface: how does the user perceive the elements presented in the interface? The third problem is the *mapping* problem. This problem is reliant on correspondence and coherence. This is the mapping from the work domain to the representation to human perception, with the focus on the visual properties in the representation. Does the user perceive the elements in the interface in such a way that they correctly perceive the

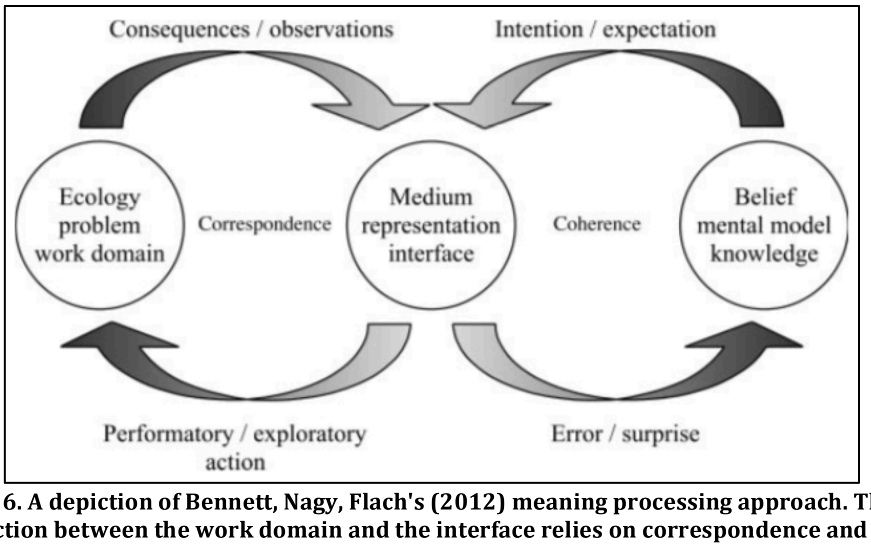

Figure 6. A depiction of Bennett, Nagy, Flach's (2012) meaning processing approach. The interaction between the work domain and the interface relies on correspondence and the interaction between the interface and the mental model (i.e. the user) relies on coherence.

work domain? In the end an interface must be a representation of the domain where the domain, not the interface, drives the user's tasks. This means that the interface must map the work domain in such a way that the user can act in accordance with the domain.

The interaction between components in the triad can, furthermore, be discovered and evaluated using a *Cognitive Work Analysis* (CWA) (Rasmussen, 1986), which aims to uncover requirements, constraints and affordances for cognitive work in a domain (Lee, Kirlik, Roth & Bisantz, 2013). On a more simple scale a *Hierarchical Task Analysis* (HTA) (Annett, 2003) can also be used. This task analysis identifies the most relevant user tasks and breaks them down into subtasks, operations and actions. This results in fine detail of a task, even down to simply pressing a button.

3.4 Information Visualisation

Bringing both user-centered and work-centered design concepts together we wanted to create an interface that maps the medical domain onto a visual representation that allows the user to accomplish the task of monitoring and caring for an organ. Understanding the work domain is of importance in addressing the mapping problem (Bennett, Nagy, and Flach. 2012).

Organ perfusion can be considered to be a law-driven work domain, where undertaking action during organ perfusion has a law-driven result. For example, changing the temperature results in a different manner of organ function due to the way temperature affects an organ's metabolic needs. For addressing the aforementioned problems, this means that abstract forms need to be developed to reflect the real constraints of the domain. In other words, visual representations must be accurate reflections of abstract domain constraints to allow for perception of the presented information that is inline with the current situation. Representative information visualisation is necessary to achieve this. Poorly designed visualization can lead to incorrect interpretation and insight (Card, Mackinlay & Shneiderman, 1999). Proper insight can be gained through the interaction between the user and the visualisation as suggested by embodied interaction (Wilson, 2002) and distributed cognition (Liu, Neressian & Stasko, 2008). Therefore, the mapping problem as presented by Bennett, Nagy, and Flach (2012), is an important aspect that needs to be kept in mind when designing a visualisation.

The most challenging aspects of information visualisation are the complexity of various types of information and the scalability of large quantities of data (North, 2012). Instead of simply presenting the user with visual representations good information visualisation also allows the user to interact with the data. North (2012) suggests that an iterative requirements analysis, design and evaluation process is the design process for data visualisation, which very much resembles Preece, Rogers and Sharp's (2015) interaction lifecycle approach. In such an iterative design both user-centered and work-centered design come together, where user tasks and domain knowledge are analysed. The requirements analysis phase requires determining what the characteristics of the information that should be visualized are and the types of insights that should properly arise from the visualization.

The process of converting data into a comprehensive interactive visual form is known as the visualisation pipeline (Card, Mackinlay & Shneiderman, 1999). The pipeline can be seen in Figure 7. Transforming raw data into a dataset is the step of receiving data input and converting it into something that can be visualized. This can

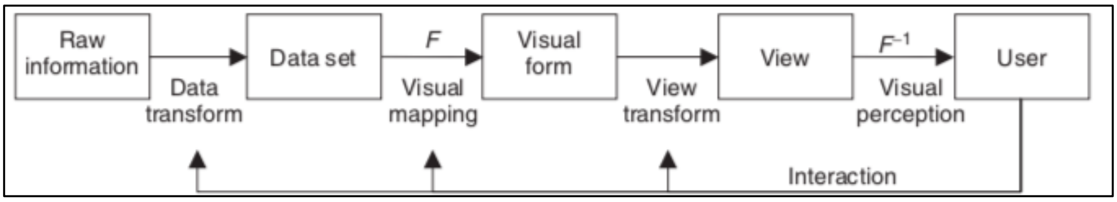

Figure 7. The visualization pipeline as North (2012) adapted from Card, Mackinlay and Shneiderman (1999).

be seen as part of the database construction of an interface. In further steps of the pipeline the dataset is mapped to a visual form and shown to a user who interprets the visual form according to their visual perception. The main focus of visualisation lies in the visual mapping step (North, 2012). Card, Mackinlay & Shneiderman(1999) suggest that visual mapping can be split into two substeps. The first step consists of mapping data entities to visual glyphs, such as points, lines and icons. In the second step values of the data are mapped onto visual properties of their glyph. Examples of visual properties are spatial position, size, colour, and shape. Different visual properties have proven to be more effective than others (North, 2012). It is, therefore, necessary to prioritize data based on determined requirements. Data with a higher priority can be assigned more effective visual properties to be more salient. The commonly accepted order of effectiveness from most to least effective for quantitative data is position, size, colour, orientation and shape (Cleveland & McGill, 1984; Nowell, Schulman & Hix, 2002). However, for categorical data colour and shape are more effective (North, 2012).

Furthermore, as data becomes more complex different strategies can be applied to improve visual mapping. Understanding the structure of the information comes first. Then, Shneiderman and Plaisant (2004) suggest the following steps that should be followed when the quantity of information to be visualized increases: ***overview, zoom and filter and then details on demand***. North (2012) translates these steps into three types of strategies: *overview*, *navigation*, and *interaction*. These strategies as well as information structure will be discussed in the following sections.

3.3.1 Information Structures

It is important to find the underlying information structures in the dataset. The structure provides high-level organization and guidance (North, 2012). These structures usually have a high priority when it comes to perceiving and understanding the presented information; therefore, information structure is usually mapped in a spatial manner, which is the most effective visual property. North (2012) argues that there are four classes of structures that are not necessarily mutually exclusive. The structures are *tabular*, *spatial and temporal*, *tree and network*, and *text and document collection*. We will only discuss the first three of these structures.

Data entities and attributes make up the rows and columns, respectively, that are found in *tabular structures*. Databases and spreadsheets are examples of tabular structures. Scalability is a problem in these structures as there are only so many unique visual properties one can choose from.

Spatial and temporal structures generally require navigation strategies due to their one- two- or three-dimensional components. Examples of structures with one-, two-, and three-dimensional components are timelines, roadmaps and magnetic resonance imaging (MRI), respectively. Spatial displays are the most suited for these kinds of structures.

Tree and network structures have links and connections between data entities. The entities are vertices and the connections are edges in graph theory terms. Examples include hyperlinks, menu systems and file directories. In the case of the latter two of the examples, they are tree structures. Here the connections are between parent and child nodes, where each child should only have one parent. Large networks and trees also generally require the application of navigation strategies

3.3.2 Overview Strategies

When dealing with large amounts of data it becomes impossible to visualize it all at once in a manner that is comprehensive to a user. In this case, users can only visually perceive a part of the data, for example only several rows in a table when the table has thousands. This is known as the *keyhole problem*, as it is like looking into a large room through a keyhole (North, 2012). To address this problem we can start by giving users an overview of the data. However, Hornbaek, Bederson and Plaisant (2002) found that an overview did not improve performance. Although interestingly, users preferred interfaces that did make use of overviews. This would suggest that overviews may not always be necessary to perform tasks but rather that they are a feature that makes users more comfortable while interacting with an information visualisation. There are two strategies for creating an overview, *reducing data quantity* in the dataset or simply *reducing physical size* of the visual glyphs.

One method to reduce data quantity is *aggregation*. For aggregation, data entities must be grouped and each group becomes its own data entity, which is often achieved by using the mean, minimum, maximum or count.

Filtering is another method that can be used to reduce data quantity. Here a representative subset of data entities is chosen to represent the whole dataset. The choice can be made on the basis of data density or importance.

3.3.3 Navigation strategies

Once an overview has been established it becomes of importance to determine how users can navigate towards finer details of the data. This is also the third step of the visualization pipeline (Figure 7): *view transform*. North (2012) determines three navigation strategies: *overview + detail*, *zoom + pan*, and *focus + context*.

The *overview + detail* strategy presents an always-present overview. Here multiple views are combined to be able to view the detail and the overview simultaneously as depicted in Figure 8. The idea is that an always-present overview prevents the user from becoming lost in the information. It is important that the detailed view not overlap the overview, although, this is an ideal situation and not always possible in practice. Multiple detail views can be displayed simultaneously as well, to allow for a comparison between data entities. For complete orientation an indicator in the overview indicates where the detailed view is within the overview. This is commonly found in image editing software (Plaisant, Carr & Shneiderman, 1995). It is also particularly useful for maintaining awareness of dynamic events in the overview, such as war gaming where it is important to maintain an overview of how the war as a whole is going as well as the current battle in front of the player.

Zoom + pan navigation allows users to zoom in from the overview into more detail. It also allows users to pan through finer details without have to zoom back out to the overview. Zooming can be either continuous, like zooming in on a map, or in discrete steps. The disadvantage is that users may become lost due to the lack of an overview once zoomed in. However, Hornbaek, Bederson and Plaisant's (2002) experiment showed that while users preferred to have an overview for this very reason, users without an overview actually performed their task faster. They believe that users performed the tasks faster due to the use of navigation cues in the form of semantic zooming. This would suggest that refined zoom navigation might nullify becoming lost in the data if an *overview + detail* strategy is not applied.

The *focus + context* strategy is much like sliding a magnifying glass around directly on the overview. However, the part of the overview that is not magnified must be distorted, otherwise part of the overview will be lost. This is referred to as

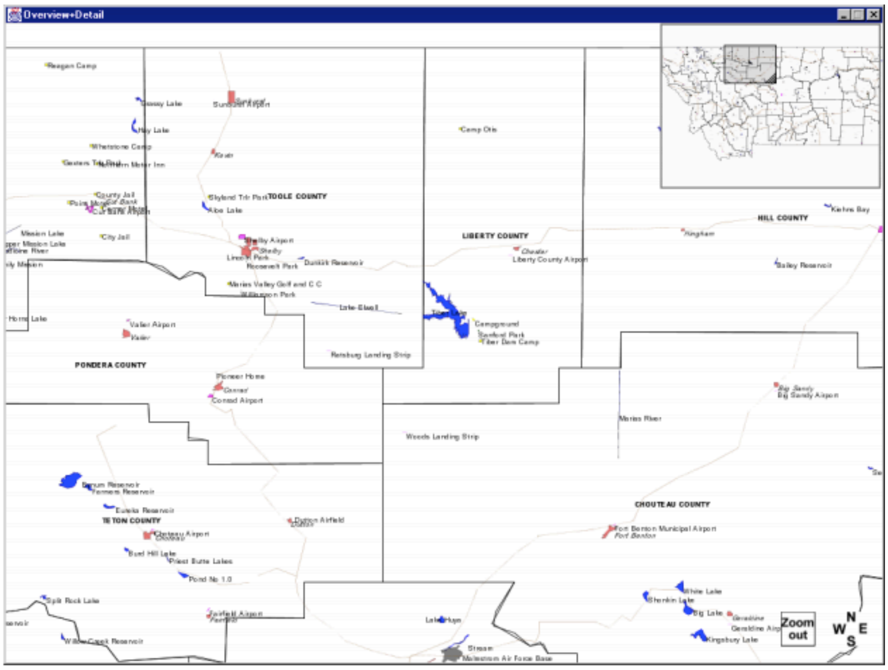

Figure 8. An example of the overview + detail navigation strategy from Hornbaek, Bederson, and Plaisant (2001). A detailed view of a map is depicted and in the top right there is an overview of the entire map

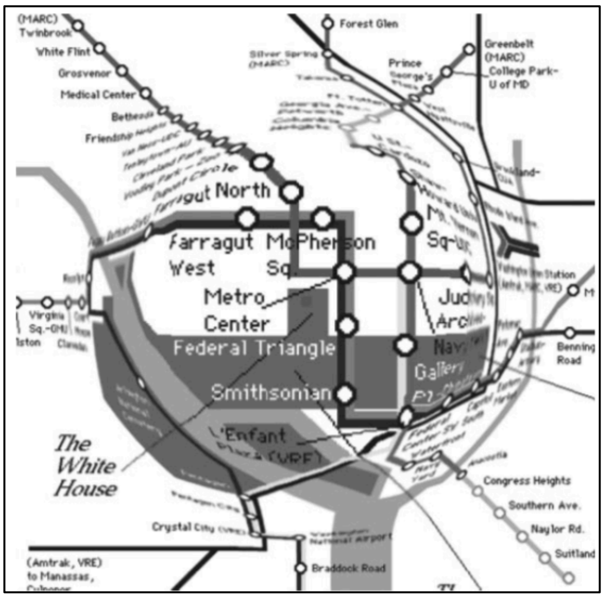

Figure 9. A visualization of the focus + context navigation strategy from Keahey and Robertson (1996).

fisheye (Furnas, 1986) or distortion-oriented (Leung &Apperley, 1994) as seen in Figure 9. This allows for nearby entities to still remain visible, as these are generally the entities that are of the most importance to the magnified area. Due to the necessary distortion it should only be applied to nonspatial information structures.

3.3.4 Interaction strategies

Interaction occurs at all steps of the visualization pipeline (Figure 7), this makes interaction strategies an important factor to consider when designing. Interaction strategies allow users to manipulate visualisations and further explore the data in more detail. Yi, Kang and Stasko (2007) highlight seven interaction strategies. Of these seven North (2012) argues that *selecting, linking, filtering* and *rearranging* are the major strategies.

The first of these strategies includes *selecting, grouping* and *extracting* individual data entities. Here the user can get details on demand by selecting data that is of interest to them. There are two selection strategies, *direct* and *indirect*. An example of a direct strategy is having a user point at a glyph and receiving information about it. An indirect strategy involves selection criteria, for example the user could ask to see all entities within a range of values, or searching for a word and being shown all entities that contain that word.

The *linking* strategy can be used to show the link between information in different views. This is useful as data can be mapped to different views to allow for different insights while still making it obvious to the user that the data is linked to each other. Becker and Cleveland's (1987) brushing and linking strategy is the most commonly applied linking strategy, where selections of entities in one view automatically highlight corresponding entities in the other views. This strategy is particularly useful when different information structures are in use. In Figure 10 we see an example of brushing and linking where the highlighted points on the map are also highlighted in the bar chart.

The *filtering* strategy is much like the indirect selection strategy, but slightly broader. The focus here lies on data attributes instead of single entities. Users query the system to show them a selection of data attributes that matches their query.

Finally the *rearranging* or *remapping* strategy gives users the freedom to customize the mapping. The most effective approach to remapping for new insights is changing the spatial layout, as this is the most salient visual property.

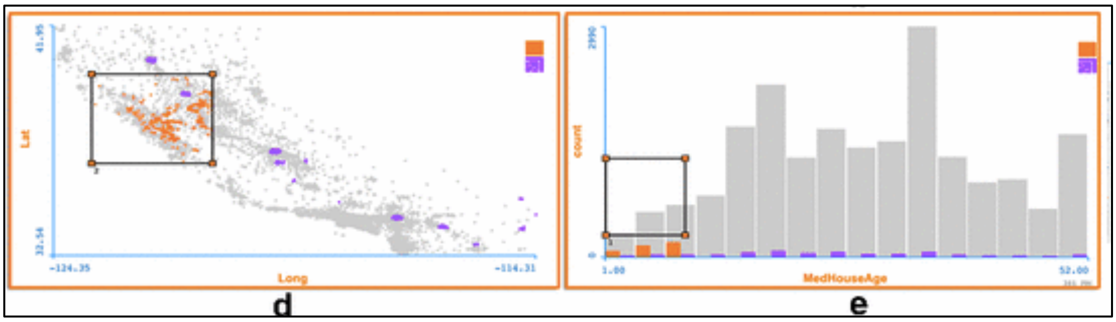

Figure 10. A visualisation from Splechtna et al. (2018) of brushing and linking. The information highlighted in orange and in purple in d is also highlighted in e.

In this part we discussed the theoretical framework that is necessary to understand for this project. The basics of machine perfusion were discussed. Furthermore, we discussed situation awareness and how this can be applied to medical interfaces. Finally, we looked at user-centered and work-centered design and information visualisation principles. This framework will be used to drive design and implementation of the prototype interface.

Part II. Design

This part covers the steps towards building an interactive prototype for user evaluation. The steps in this part follow the steps in Rogers, Preece, and Sharp's (2015) interaction design lifecycle (Figure 5) namely: identifying needs and requirements, (re)design and building interactive prototypes. To identify needs and requirements user interviews and observation in the organ preservation and resuscitation unit (OPR) were conducted. The results from these requirements and needs collection methods are presented here. This is followed by the process of designing the interface, from a mock up to an interactive prototype for user evaluation.

4. Methods Towards Designing an Interactive Prototype

The goal of this project was to develop an interface for use in the OPR to support the operators in their task. In order to achieve this, the project consisted of several phases. The initial phase included gaining a general understanding of organ perfusion up to a level that interviewing stakeholders would be possible and understandable. This was followed by the second phase of gathering user needs and requirements by interviewing users and observing several perfusions in the OPR. This is inline with the step of gathering requirements and establishing needs in Rogers, Preece, and Sharp's (2015) interaction design lifecycle. A total of 9 interviews were conducted, of which 8 were with perfusion stakeholders and one was with a stakeholder involved with the Electronic Patient Dossier (EPD) at the UMCG. All interviews were conducted in the UMCG.

A total of three perfusions were observed, over two sessions. During the first session both a liver and a kidney perfusion were observed and in the second session a lung perfusion was observed. Once this had been done the third phase was started, making a simple mock up for evaluation, or the design step of the interaction design lifecycle. After evaluation an interactive prototype with limited functionality was programmed, inline with the step of building interactive prototypes in the interaction design lifecycle. The third phase drew from the steps of the visual pipeline (Figure 7), where raw data was transformed into a visual representation for the users. We also drew from situation awareness levels in the third phase. In the fourth and final phase user evaluations were conducted. The third and fourth phases were repeated. These design phases are inline with interaction design (Preece, Rogers, Sharp 2012) and iterative design (North, 2012). In the initial iteration of the third and fourth phases, the supervisors of the project and the coordinator of the OPR were consulted for their feedback. Their feedback was applied to the interface, followed by a final user evaluation for this prototype, which can be found in Part III.

Many more iterations of the design and evaluation phases will be necessary following for example database design and actual data input from the devices used in the OPR before producing a final product.

5. Identifying Needs and Establishing Requirements

In the following chapter we will discuss the methods that were used to identify and establish user needs and requirements, namely interviews and observation. The results from the interviews and observation are presented here as well. The corresponding user requirements are presented along with the results.

5.1 Methods

In order to identify needs and establish requirements semi-structured interviews were conducted and several perfusions were observed in the OPR. The aim was to interview different types of stakeholders that are associated with the OPR as the perfusion process has many different levels. Here it is important to note that the perfusion process is still being developed and researched, therefore, different stakeholders value different elements at differing levels. It is important to gain an understanding of these elements for the levels of situation awareness. From the interviews we must be able to address how operators *detect* important changes during perfusion, and then support understanding of what this change means by providing the correct information for *diagnosis.* Finally, the operators should be able administer the appropriate *treatment*. These interviews therefore aimed to gain an understanding of what is of utmost importance to the different stakeholders at and to determine the amount of flexibility the system needs to satisfy potentially differing user needs.

On top of this, the goal of the interviews was to gain an understanding of the perfusion process as well as of the work domain i.e. the OPR. Observation in the OPR was used to support data gathered during the interviews as well as gain relevant insights that stakeholders may have missed or not deemed to be relevant. From the observation and the interviews a hierarchical task analysis (HTA) (Annett, 2003) was also constructed. In this way we combined user-centered and work-centered design to gain a complete understanding of the elements of the work environment of the OPR.

5.1.1 Participants

Semi-structured interviews were conducted with four different types of stakeholders: perfusionists, surgeons, transplant coordinators and researchers. A total of 9 stakeholders were interviewed of which four were perfusionists, two were surgeons, one researcher, and one transplant coordinator.

5.1.2 Procedure

The interviews were initially approached in broad terms. We asked stakeholders to participate in an interview about the OPR and the technology that was used there, but did not notify them immediately that the end goal was to build an interface to use during perfusion. The purpose of this was to gain a complete picture of the activities in the OPR and the state of the OPR without interviewees already focussing in on just the interface. Interviews were conducted at the UMCG. Interviews started with the collection of demographic data followed by questions about the OPR in general. Then the end goal of the project was explained and further questions were asked about topics relevant to the design of the new interface.

The whole interview protocol can be found in Appendix A. The questions were not applicable to all stakeholders involved in organ perfusion. We will discuss the results from the interview and how these have been translated into user requirements and needs in the following section.

5.2 Results and Resulting User Requirements

We started by collecting demographic data. We further inquired over the general steps of organ perfusion, the stakeholder's current opinions about the perfusion process (what works well and what needs improvement) and specifically their thoughts on the material in the OPR. This was followed by questions about designing a new interface. The following themes were identified: *time*, *crowdedness*, *process in development*, *data recording*, and *visualisation of parameters*. We will discuss these themes and present the corresponding user requirements in the following sections.

5.2.1 The Task of Organ Perfusion

We inquired about the global steps of organ perfusion in the OPR. These global steps have been incorporated in an HTA (Annett, 2003) along with the steps as observed in the OPR. Observation proved to be a valuable tool in evaluating the work domain. While interviewees struggled to express how they made final decisions on transplanting the organs, in the OPR they knew exactly how to make these decisions. The HTA has been simplified into a version that excludes detailed medical processes. This simplified version can be seen in Figure 11.

Operators spend a significant amount of time in the OPR with one organ, ranging from anywhere between two and 10 hours, with hope that in the future an organ can stay on the pump for 24 hours. Most of these hours are made during the night due to logistical reasons. Several interviewees mentioned that for this reason blue should be a primary colour in the interface.

5.2.2 Process in Development

A reoccurring theme throughout the interviews was that organ perfusion is a relatively new process that is still very much in an exploratory phase. This is a point of importance that should be kept in mind throughout this thesis. Operators are still learning to recognize and find safe ranges of markers that are an indication of the organs health while functioning outside of the human body. This is due to the fact that an organ that function outside of a body does not have to work on sustaining a whole body but only itself. Markers that are known to give a very clear picture of the organs health can currently not yet be measured in this setting, such as cytokines. Therefore, the current goal of such an interface is to support the operators by providing them with all the information about the organ in a manner that supports exploration of the data and learn from the data (this is why comparison with previous organs is important). To support the developing process the following user requirement was established:

> *UR1. An interface that helps the operators to explore the data and support learning and development of the process.*

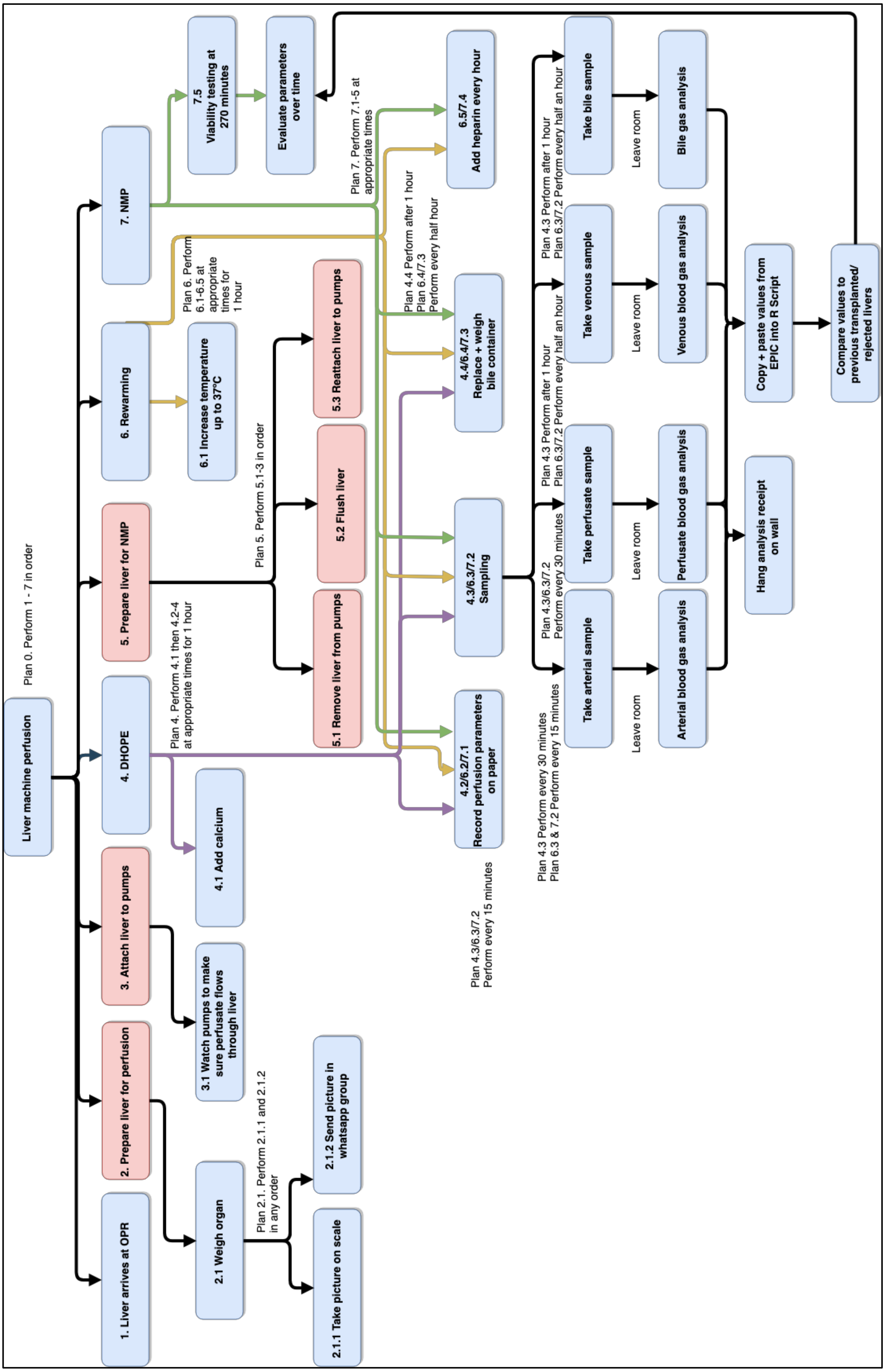

Figure 11. Simplified hierarchical task analysis for liver perfusion as performed in the OPR at the UMCG. The red boxes represent steps that the surgeons must perform. The blue boxes represent tasks for the perfusionists. The purple lines represent DHOPE, the yellow line represents rewarming and the green line represents NMP tasks.

In general interviewees found it difficult to say if the process was going well, also simply because the process is still in development. This was also the reason that many noted that there were a lot of uncertainties in the process. Ideally, a golden standard value would be able to show if the organ can be transplanted or not. This golden value, however, does not (yet) exist, but with further research they hope find something of significance. Since this was a reoccurring theme across many of the questions this was translated into the following user requirement:

> *UR2. The system should be flexible, for example: customizable warnings and alarms and the ability to determine which parameters should be prominently displayed.*

5.2.3 Crowdedness

Many interviewees were also able to name points of improvement. The most reoccurring point was the OPR is quite small and that the number of people in the room at the same time can be quite high. Observation in the OPR confirmed that this environment can be very busy and people very easily get in the way of each other. Eliminating the need for operators to always stay with the organ could help to reduce the crowdedness. And could potentially reduce the stress of working at night by allowing operators to rest and be alerted if action is necessary. However, interviewees noted that they would have to gain a significant amount of trust in the system before the organ could be left completely unattended. This leads to the following user requirement:

> *UR3. A trusted interface with alarms that alert the users when action is necessary, which could eventually allow for operators to leave the organ unattended.*

Expanding on this point of crowdedness, for the liver an R script has been developed. This script produces graphs of parameters presented over time, however these are displayed on a monitor in the corner of the room. Here upwards of five people gather around when making the crucial decision to transplant the organ or not. Many interviewees noted that while the script is incredibly valuable the current manner of displaying it is not optimal. Because so many people gather around the screen at a time, a second row occurs, where people are not quite as involved in the acquisition and evaluation of the information. In order to address this issue the following two user requirements were established, where both could potentially be the solution to this issue:

> *UR4. The interface should be displayed on a large screen prominently in the room.*
>
> *UR5. Allow for the interface to be viewable outside of the room as well.*

This would also keep people aside from the operators, such as the surgeons, outside of the room while still allowing for them to check in on the organ. Interestingly, surgeons and operators are also interested in the visual appearance of the organ, which is also one of the reasons surgeons come into the OPR. Including a camera output in the interface would allow for surgeons to visually monitor the organ without entering the OPR, which once again reduces the amount of people in the OPR at a given moment. But it would also help to address elimination of the need for operators to always remain in the room. Currently pictures of the organ are sent in a

WhatsApp group to keep stakeholders at different levels in the loop. To eliminate this, the following user requirement was determined:

UR6. Include a camera output.

5.2.4 Data recording

A common comment was that the perfusion process was quite dynamic and prone to human error, in that not much of the process is automated but it relies heavily on many actions that must be performed by operators and surgeons. Data recording is included in these actions where the operators use pen and paper for recording. This can occasionally lead to incorrect records, especially during the night after being present in the OPR for many hours already.

While data recording does occur automatically for the parameters recorded at the pumps (flow, pressure, temperature, and resistance) they are not recorded in a way that is easily accessible to the operators in realtime. Currently operators log several parameters with pen and paper. And blood gases have to be manually sampled and inserted into a blood gas analyser that reports the values on a printed piece of paper. This analyser is located in the room next to the OPR. These papers are then hung on the wall at different heights as an attempt to show the trends over time. All interviewees noted that the changes over time are currently the hardest information to obtain in the current perfusion process. The blood gas analyser also sends the results to EPIC (the UMCG's electronic patient dossier software) after analysis, however, this still needs to be copied to the liver R script by hand. For this reason the following user requirement was established:

UR7. Establish a link with EPIC to automatically obtain the blood gases.

This may also be helpful in addressing the overcrowded room by eliminating manual recording. Observing and interviewing a lung-heart machine perfusionist also revealed that there are sensors that automatically sample blood gases without having to manually take a sample from the blood or other perfusion solution. However, these sensors are unfortunately not available to the OPR and they are not as accurate as the results from the blood gas analyser. Therefore, a development of an upgraded sensor would be necessary to completely eliminate manually taking samples.
The following user requirement arises from these results:

UR8. An interface that automatically records and displays parameters in realtime and shows changes over time.

Observation in the OPR also demonstrated how the operator in charge of recording the data is also responsible for notifying the rest of the team when certain actions have to be taken, such as taking a sample or administering heparin according to a schedule. To address this the following user requirement was determined:

UR9. Include reminders.

5.2.5 Parameters and Visualisation

Interviewees also commented on the parameters, and how parameters are manipulated and displayed. Below is a list of the most important parameters, as noted by the interviewees:

• Flow (mL/min)	• Pressure (mmHg)
• Temperature (ºC)	• Resistance (mmHg*min/L)
• CO_2 (kPa)	• pO2
• Lactate (mmol/L)	• Glucose (mmol/L)
• pH	• Bicarbonate (HCO_3) (mmol/L)
• Bile pH (liver)	• Urine (kidney) (mL)
• Pressure volume curve	• PEEP (lungs)
• Liquid in the lung (mL)	• Compliance (lungs)

The parameters are not listed according to importance. The importance of each parameter is currently still subject to opinion. However, flow, pressure and temperature (further referred to as perfusion parameters) are constantly monitored, as these must remain at the right levels to be able to perform perfusion. This lead to the following user requirement:

UR10. Prominently display the perfusion parameters.

Also of importance to the flow is the homogenous flow of the perfusion solution through the organ. This can be seen using a thermal camera.

UR11. Include space for presenting a thermal camera output.

Interviewees also noted which parameters they would wish to see (in realtime) in an ideal world. Many of the parameters they mentioned cannot currently be measured or the UMCG does not have this kind of technology readily available. A complete list of these parameters can be found in Appendix B.

Interviewees noted that they would like to see a differentiation between parameters that were within safe bounds and especially values that were deviating away from safe bounds. Several interviewees suggested that this differentiation could be achieved by comparing to previously perfused organs. The previous organs could be split into transplanted and rejected organs. The averaged transplanted and rejected values could then be display alongside the current organ. The following user requirements were identified for deviating values:

UR12. Differentiate between good and bad values.
UR13. Compare the current organ to previous organs.

The following user requirements were identified in respect to general visualisation of the parameters:

UR14. Line graphs to visualize parameters.
UR15. Make different pages by splitting up the parameters by group (e.g. perfusion parameters, metabolism parameters, function parameters)
UR16. Include an overview page.
UR17. Users should be able to choose what to see.
UR18. Perfusion parameters should always be visible.
UR19. Graphs should be legible on a mobile phone.

5.2.6 Miscellaneous User Requirements
The following miscellaneous user requirements arose throughout the interviews:

UR20. There should be instruction on how to use the final interface before it is implemented in the OPR.
UR21. Users need to be able choose for which organ the interface is going to be used for.
UR22. There must be a backup.
UR23. Sterility of the OPR must be kept in mind.

To summarize the user requirements, the interface should be an interface that can be trusted by operators, supports learning and development of the process, and helps decision-making. Parameters should be automatically registered and displayed in realtime and allow for comparison with previously perfused organs. Together this should eventually allow operators to leave the organ unattended.

6. Designing the Interactive Prototype

Following from the previous chapter the next step in the interaction lifecycle was made: designing a prototype interface. The corresponding user requirements are noted with corresponding design choices.

A mock-up of the interface was designed. This mock-up was then implemented as a web application as this addresses the user requirement of being able to monitor the organ while outside of the OPR (*UR3/UR5*). It also fulfils the ability to view the interface on multiple screens at the same time, which would be necessary if the interface is always displayed on a screen near the organ and users outside of the OPR also want to view the state of the organ (*UR4/UR5*).

The prototype is based on a liver. The liver was chosen because there is a relative amount of data available to simulate a plausible situation. The simulation is simply a snapshot of a moment in the perfusion. This was achieved by using data from previously perfused livers. Development of a database will be necessary before a dynamic implementation and simulation of a realtime stream for the interface can be made, which is not within the scope of this project.

6.1 Mock-up

In the mock-up we made global design decisions involving the overview and navigation strategies for the interface. Here we also determined which features should be incorporated in the system. The finer details of these features as well as most of the interaction strategy choices were made during building of the interactive prototype. There are no interactive elements in the mock-up making it unsuitable for user evaluation but suitable as a guideline for building an interactive prototype.

The mock-up was made using *moqups.com* (S.C Evercoder Software S.R.L., 2018). The initial step was to determine what the *structure* of the data is. The data that is output by the machines in the system is stored in a spreadsheet, making it a tabular structure. However, because the data is measured at time points, which are of importance to the task, the data also has a one-dimensional temporal structure. As the operators are interested in the changes in parameters over time (*UR8*) we chose to adhere to the temporal structure as the main view of the data to allow for a visualisation that is most easy to perceive. This is inline with the user requirement of

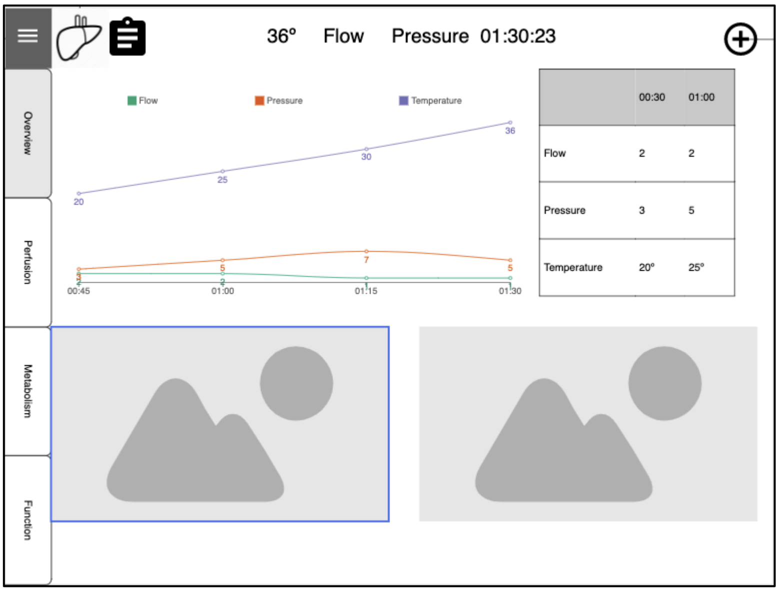

Figure 12. Mockup of the overview, made using *moqups.com* (S.C Evercoder Software S.R.L., 2018)

wanting to view the parameters in a line graph (*UR14*). This has already been applied to the liver using the aforementioned R script, to produce basic line graphs per measured and calculated parameter. Currently a total of 52 parameters are consulted during the perfusion process. Clearly, it is not possible to display all of these at the same time. To address this keyhole problem we adhered to Shneiderman and Plaisant's (2004) design steps, "*overview first, zoom and filter, then details on demand*". We, therefore, designed the interface to start with an overview that leads to several pages where more information is available. The users also determined that this would be the desired format of the interface (*UR15/UR16*).

The mock-up of the overview can be seen in Figure 12. Mock-ups of the other pages and features can be found in Appendix C. On the overview page there is a graph and table that show the most important parameters. The output of a normal camera and a thermal camera will also be found on the overview page (*UR6/UR11*).

Users can navigate to the other parameters using the tabs on the side of the page; these tabs are visible on all pages. The tab that is currently opened is highlighted. As suggested in the interviews we initially chose to split the graphs by perfusion parameters, metabolism parameters and function parameters. On these pages users can choose to toggle between graph and table views of the data, where the graph visualisations are default. Also visible on all pages is the toolbar at the top of the page. A combination of the *zoom + pan* and *overview + detail* navigation strategies were applied. Users navigate away from the complete overview page in discrete steps by opening a new tab. However, the toolbar remains visible allowing for an overview of the most pertinent parameters and the highlighted tab shows the user where they are (*UR10/UR18*). This should help users *detect* crucial changes in the perfusion parameters quickly, inline with level 1 situation awareness. Buttons to view static parameters, such as arrival time at the OPR, and control parameters, such as to increase the temperature or add medicine, are also found in the toolbar. This allows for easy access to these tools from any page for quick action based on level 3 situation awareness: prediction of future events for *treatment*. The addition button opens a control popup. This prevents users from having to leave the page where they found information that they wish to act upon. In the top left of the interface is a menu button. From the menu users can set alarms, logout, or end the perfusion.

6.1.1 Evaluation of the Mock-up

The supervisors of the project performed initial evaluation of the mock-ups to determine that all main elements were accounted for. They were satisfied with the general layout and division of the pages. Furthermore, they requested the addition of a scheduling tool that would allow operators to set the system to perform certain steps automatically, such as increasing the temperature and pressure according to the rewarming protocol. The comments from the evaluation were taken into consideration towards programming the interactive prototype.

6.2 Interactive Prototype Design

This is the final step of the interaction design lifecycle before user evaluation: building the interactive prototype. The final prototype was implemented as a static simulation, using data from previously perfused livers. The interface was programmed using React (Walke, 2013), a JavaScript front-end framework. React was chosen because the reactive programming paradigm is well suited for realtime applications (*UR8*). A predesigned React template, namely the Shards Dashboard Lite template, was used as the basis of the interface (Design Revision, 2019). The graphs were made using the package Chart.js (Timberg et al., 2014).

The design was implemented in two iterations. In the first iteration the mock-up was used as the basis for designing the prototype. This version of the prototype was subjected to evaluation by the medical supervisor of the project and the coordinator of the OPR. The results from this evaluation were implemented in the second iteration. The interface produced after the second iteration was the prototype used for the user evaluation study. Larger and more detailed images of the prototype can be found in Appendix D.

6.2.1 First Iteration Prototype

Comments from the evaluation of the mock-up and the mock-up were used to direct programming of the prototype. The Shards Dashboard Lite was used as the basis of the interface (Design Revision, 2019). The template provided basic components like buttons but also the basis for routing between pages.

Originally, the overview page adhered to the same layout as in the mock-up, it can be seen in Figure 13. The images at the bottom of the page are placeholders for input from a normal and thermal camera (*UR6/UR11*). The graph displays one parameter, but using the dropdown menu the user can select which graph should be on display (*UR17*). This is in line with the selecting interaction (North, 2012). The table displays three measured values from the past half an hour.

The page division we initially chose was overview, perfusion parameters, metabolism parameters and function parameters. Similar to the mock-up these pages can be chosen from the sidebar. Instead of tabs they are more traditional buttons, to allow for horizontal text. A settings button replaced the menu button in the mock-up. Within the settings are links to set warnings and alarms (*UR2/UR3*), set an automatic planner, set reminders (*UR9*), and end the perfusion or log out.

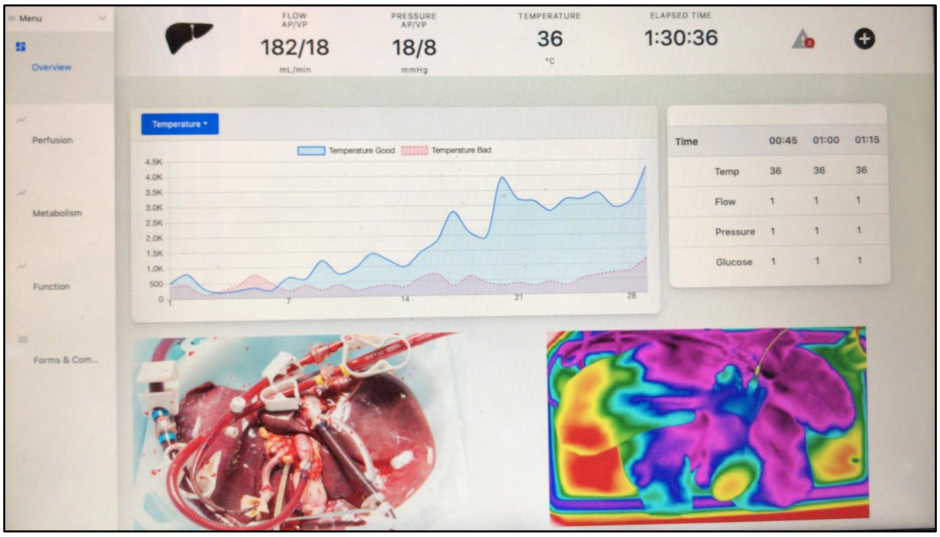

Figure 13. Depiction of the overview after the first iteration. The content and layout were changed in the second iteration. And colours were added to the tool bar to differentiate between hepatic arterial and portal venous parameters.

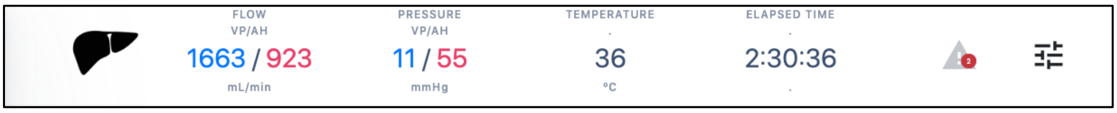

Figure 14. The interface's toolbar after application of the colours to discriminate between hepatic arterial and portal venous parameters.

Toolbar

The order of the toolbar was designed to build up from static to dynamic aspects of organ perfusion, as seen in Figure 14. The toolbar was chosen to give users access to the most important functions from all pages in the interface. It was also chosen to show users the most important parameters at all times (*UR10/UR18*). Starting with the static parameters of the liver that can be found under the liver button. Then the dynamic perfusion parameters are displayed. These parameters were chosen to be displayed in the toolbar to satisfy the user requirement of always having the perfusion parameters visible due to their importance (*UR18*). This is inline with filtering data based on importance of the entities (North, 2012). These parameters also provide a general overview about how the perfusion is going. If any of these parameters go into abnormal bounds something in the system could be failing and immediate action could be necessary. Therefore, presenting them in the toolbar helps with easy *detection* of changes in the perfusion parameters (situation awareness level 1) possibly requiring immediate action. These parameters are then followed by a dropdown of warnings (Figure 15left) that arise because of the perfusion parameters and any other warnings that have been set. This also aids with *detection* of changes (situation awareness level 1). And finally the control button is found in the top left, this slider icon replaced the addition button in the mock-up as it better represents general controls. This opens a control panel popup. In the control panel parameters can be manipulated and medicine can be added. Automatically adding medicine is a function that relies on external technology being made available, currently this technology is not available to the OPR. Instead to bridge the time between the currently available technology and new technology a function was added to also be able to set reminders to add medicine (*UR9*). For example, heparin is added every hour, so the operator can set a reminder to do this. Additionally, users can also log this addition in the system, which creates a corresponding marker in the graphs.

Static parameters

The static parameters are important information that is connected to the individual organ. These parameters include weight of the organ but are mostly times when events occurred in the OPR, such as arrival of the organ, start of perfusion, start of flush etc. The times are indications to the operators as to when certain actions have to be taken, such as when the liver has to be flushed, but also how long the flush lasted. They are presented in a dropdown, accessible by clicking on the liver icon. Users can enter these times by typing. Weight falls under static parameters, at least currently as the organ is only weighed before and after perfusion. Ideally though the organ would be weighed constantly.

The final part of the static parameters is a note function. This function allows users to enter any notes that are of importance to the perfusion that cannot be entered anywhere else in the interface.

Warnings

Warnings can be found in the dropdown under the warning icon, as seen in Figure 15left. The warnings are alarms or alerts, as requested per the user requirements (*UR2/UR3*). These warnings aid situation awareness at level 1: *detection* of changes. The warnings can draw extra attention to changes that have a high priority, like the temperature dropping, or the pressure becoming too high.

The number of unacknowledged warnings is given as a badge above the button icon. These badges will disappear if the dropdown is open or the original warning is clicked. In order to prevent users from becoming irritated by warnings that continuously go off when they deem them to be unnecessary warnings the users can set the bounds of the warnings or if they even want a warning for that specific parameter. These settings can be found under the settings in the top left and open as a popup as seen in Figure 15right. For complete flexibility users can turn off warnings or set the bounds to prevent irrelevant alarms and warnings from occurring (*UR2*).

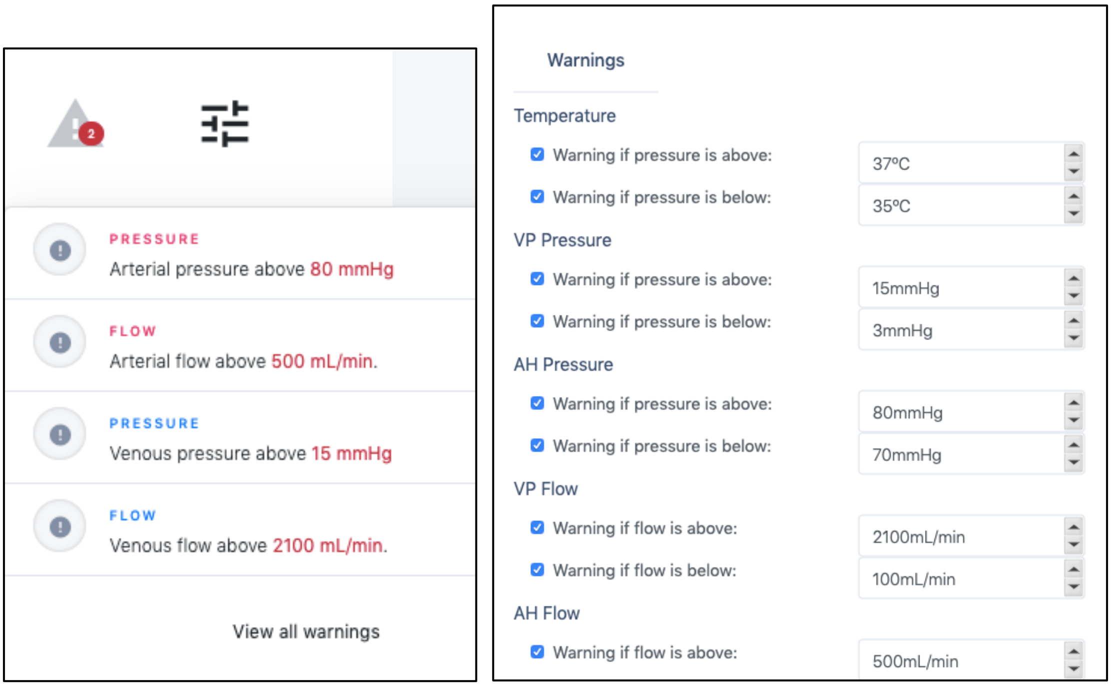

Figure 15. Left: warnings displayed in the warning dropdown. Right: warnings popup to select which warnings are active and select warning bounds

Control panel
The control panel opens as a popup (Figure 16). When the popup is open the toolbar is still visible, allowing users to consult the parameters in the toolbar while using the control panel. All of the parameters that can be directly manipulated are found in the control panel. Medicine can be added from here, a popup allows users to enter how much they would like to administer (Figure 16 bottom left). A corresponding marker is added to the graphs accordingly when medicine is administered. The "log manual addition" is to allow for users to enter that a medicine as manually been added (Figure 16 bottom right). Here they are given full freedom to type whatever the medicine is and do not have to select one from a menu. Entering a time of administration will cause a marker to be added to the graphs accordingly. Adding markers to the graph can potentially aid *diagnosis* (situation awareness level 2) by providing extra evidence as to why a parameter may be changing. Both popups are protected by a final notification asking users if they are sure they would either like to cancel or to add x, known as "safe" popups (Preece, Rogers & Sharp, 2015).

Under the additions controls are the perfusion parameters controls. Changing these will result in direct feedback to they pumps, this is why the control panel is closed with a cross in the top right instead of with accept/cancel buttons. The system is pressure driven so there are no controls to directly influence the flow; changing the pressure does this. Oxygen flow and saturation are sliders in the control panel. The sliders mimic how operators control these values using the medical equipment.

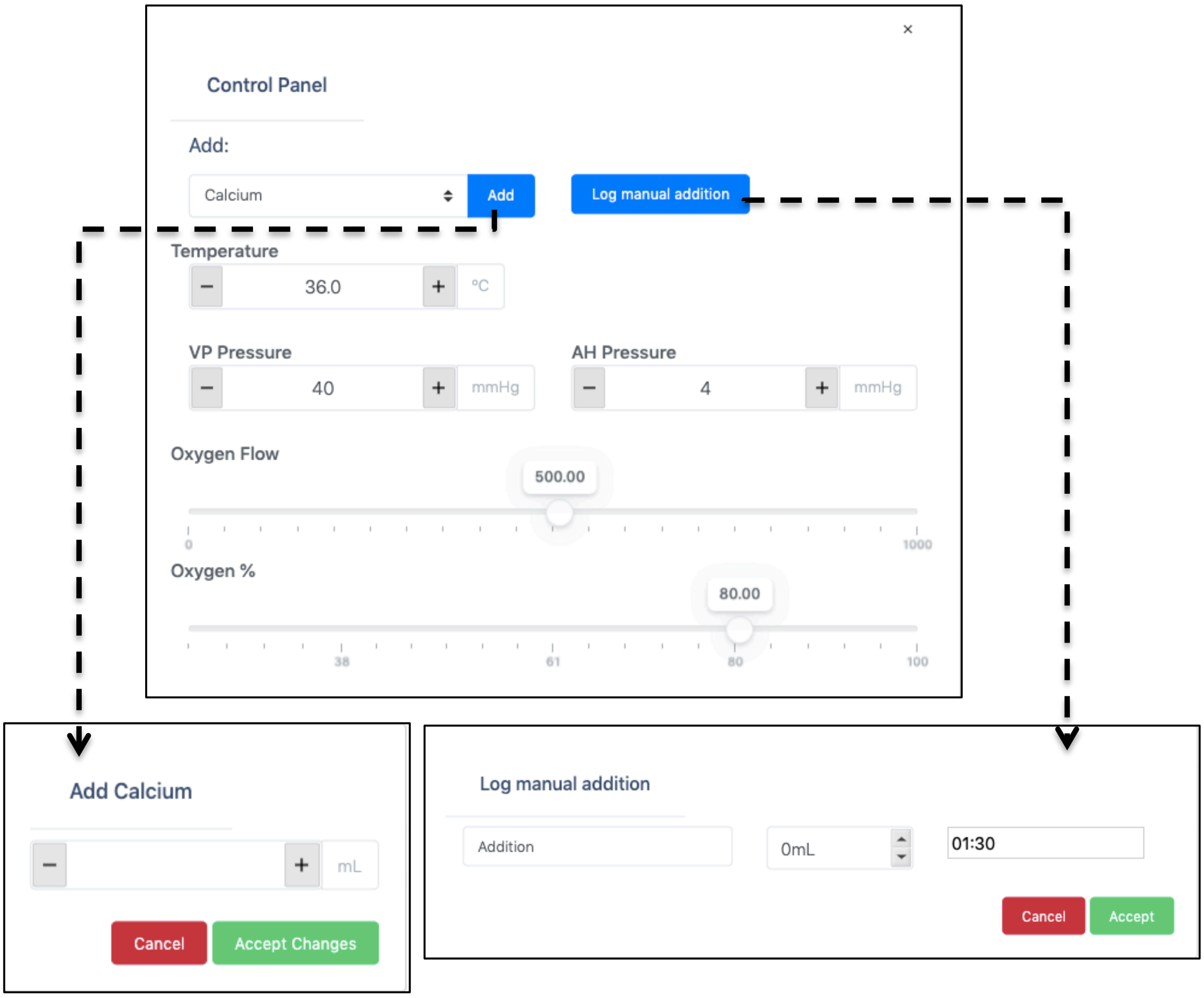

Figure 16. Control panel popup, the addition popup, and the manual addition popup that open through buttons in the control panel.

Automatic planner
The automatic planner allows users to program the pumps to automatically control temperature, pressure and heparin addition without intervention of the operator. This feature can allow for operators to leave the organ unattended while the system maintains a safe environment for the organ (*UR3*). It opens from the settings as a popup and can be seen in Figure 17. Any changes to the settings must be accepted. Upon choosing to accept or cancel the user is asked to confirm they would like to take that action. Users are in of choosing which parameters they would like the system to control itself and which parameters they would like to manually control themselves. On top of that they are given complete flexibility by choosing what the exact values should be, should they choose to let the system control any parameters (*UR2*).

The temperature settings follow the different protocols used for liver perfusion. DHOPE maintains a cold temperature. Rewarming follows a protocol that would be preprogrammed in the system to increase temperature and pressure at specific time intervals. This is necessary to shift from cold to warm perfusion for viability testing. Having the system automatically apply the rewarming protocol would eliminate the need to have a perfusionist monitor the temperature and pressure and increase them every 15 minutes. This could help to address the theme of crowdedness found during the interviews and evaluation. And finally NMP would maintain a warm temperature.

As the system is a pressure-controlled system the users are given the choice to set the system to simply maintain a certain pressure setting or to adjust the pressure to maintain a certain flow. Since the liver has two blood vessels these options are available for both these vessels, namely the hepatic arterial and portal venous.

Finally, the user can also choose to have heparin automatically administered at a predetermined time interval. Currently the protocol dictates an addition of heparin every hour after the start of rewarming. However, if the operators wish to do this manually they can opt to set a reminder to add heparin instead. This is currently the only automatic addition that can be programmed in the system.

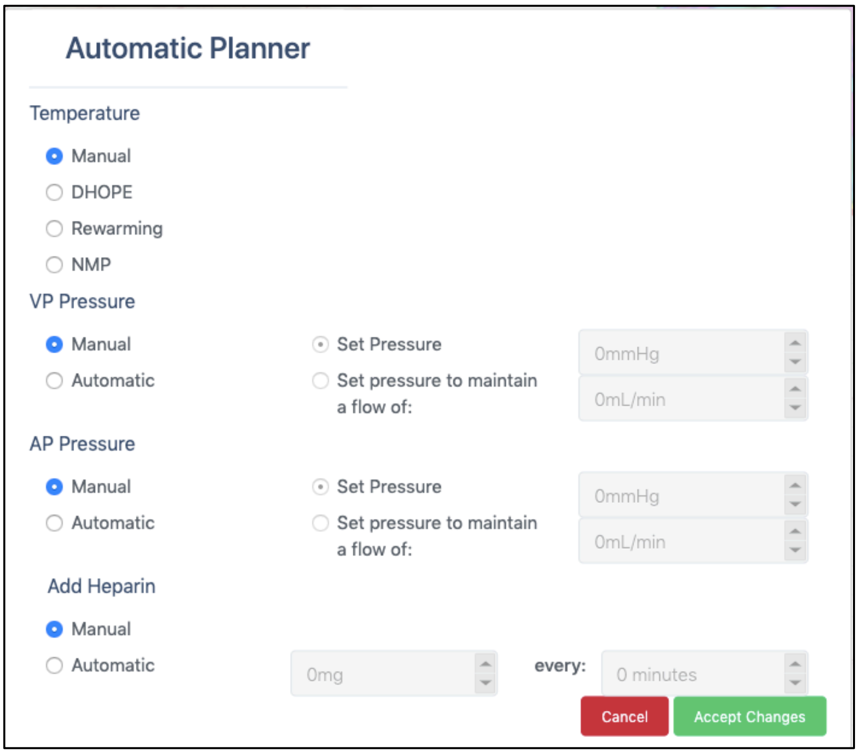

Figure 17. The automatic planner popup.

If the user were to manually change any of the parameters set to automatic these parameters should change back to manual control.

Reminders
As previously mentioned the users can also make use of a function to set reminders (*UR9*). The reminder also opens as a popup from the settings and changes must be accepted. The popup can also only be closed after confirming the choice to cancel or to accept changes. Operators can choose to activate these reminders or have them turned off, which gives the operators flexibility (*UR2*). Due to technology limitations at this point operators in the OPR must take samples of the perfusate at different locations in the system (and for the liver the bile as well) for analysis by the blood gas analyser. Protocol dictates that this has to happen at regular intervals. Hepatic arterial samples are taken every 15 minutes starting from the rewarming period; portal venous samples are taken every half an hour, as are perfusate and bile samples.

Here the user can also set a reminder to add heparin every hour, as previously mentioned.

Graphs
The graphs were designed using the Chart.js package (Timberg et al., 2014). Each graph is displayed on its own card, which keeps the graph space distinctly its own. All of the graphs are line graphs (*UR14*). There are three types of livers plotted in each graph, except for the perfusion parameters graphs where only the current organ is shown. The blue line shows the liver that is currently being perfused. The green and red lines show the average for transplanted and rejected livers, respectively (*UR13*). The colour difference between groups should be effective as this is categorical data (North, 2012). The x-axis for all graphs is the elapsed time in minutes. This adheres to familiarity with the graphs that are currently available in the OPR. The x-axis is the length of the pervious perfusions, to show users the trend in which the parameter should be changing. This leverages on aiding operators with *pattern matching* (Drews & Westenskow, 2006). Furthermore, this helps to support *prediction* of future events by showing operators what could be expected if the organ continues to follow the same trend (situation awareness level 3).

For the perfusion parameters the x-axis is up until the current moment, and therefore continuously increases. The y-axis is for the parameter. Markers on the graph indicate events during perfusion, such as the start of rewarming and an addition such as heparin. The graphs are another implementation of the *overview + detail*

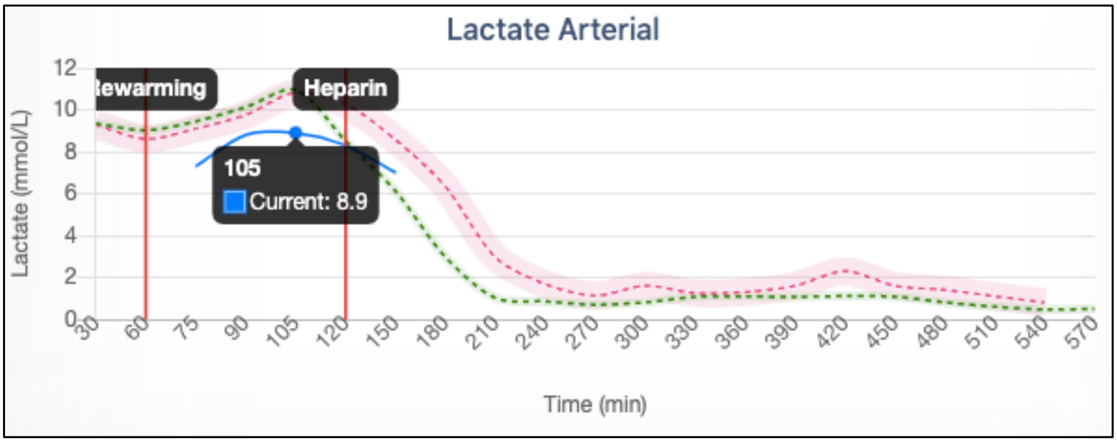

Figure 18. Example of a graph and tooltip after addition of confidence intervals from the second iteration.

Figure 19. Depiction of the dropdown menu for filtering graphs.

overview strategy, where the overview is the whole graph and the visualized data points are the details. Users can find more detail on demand while still viewing the overview. North (2012) determines that tooltips are reasonable applications for a small amount of details. Therefore, a tooltip was applied that allows users to point at a line and see the respective value at that moment. The tooltip shows the minutes and which type of liver is selected. In Figure 18 we see the graph for hepatic arterial lactate where the tool tip shows that there was 8.9mmol/L in the sample at the 105th minute of perfusion.

The graphs were distributed between the metabolism parameters and function parameters pages. Because of the amount of graphs per page a filtering interaction strategy was applied to the graphs (*UR17*). This strategy allows for reduction of quantity of information based on data attributes (North, 2012). These filters are direct queries where selecting them has a direct effect on the visualisation by hiding information that does not match the filter (Ahlberg & Wistrand, 1995). There are two filter options: the users can filter based on parameter or on location (hepatic artery, portal vein, and bile). These are two dropdown menus located at the top of the pages, as seen in Figure 19. For example, a user can choose to see all of the graphs that contain lactate values or all of the graphs for the hepatic artery. Users can also choose to see all of the lactate graphs for the hepatic artery, by filtering using both filters.

Tables

The table view (Figure 20) of the page was designed to give the users a numerical view of the data, which comes closer to their mental models of the results produced by the blood gas analyser. Because of the long list, a search function was implemented at the top of the table. The search function matches text, so the user can search for any variable. All variables that do not match the text are hidden.

6.2.2 Initial Evaluation of the Interactive Prototype

Before conducting a user evaluation an evaluation was conducted with the medical supervisor of the project and the coordinator of the OPR. Both were satisfied with the perfusion parameters being displayed in the toolbar and they did not find that any critical parameters were missing from the graph pages. They were also positive about the functionality of the automatic planner and the flexibility of setting warnings.

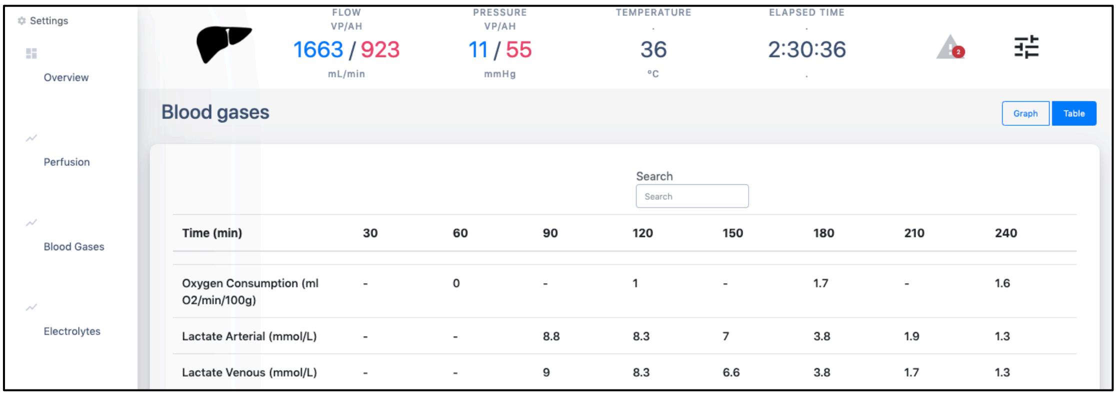

Figure 20. Depiction of the table view and search bar for the table after reorganization of the graph division from the second design iteration

There were several points to improve on before presenting a prototype for user evaluation. Firstly, the content of the overview was not satisfactory. The parameters most important for viability testing were determined to be more appropriate information for the overview page. Secondly, it was unclear as to what the difference between function and metabolic parameters was for the division of the graphs. It was noted that parameters could be both. Thirdly, there was also a consensus that confidence intervals should be added in the graphs. The addition of confidence intervals allows for determining if the current organ is in a "good" or "bad" zone (*UR12*). And fourthly, it was suggested to make use of familiar colours in medical visualisation.

6.2.3 Second iteration prototype

From the comments from the initial evaluation several changes were made to the prototype.

The camera outputs remained on the overview page, however, the approach to designing the rest of the overview was changed after the initial evaluation. The final overview page can be seen in Figure 21. The filtering strategy was applied with a focus on the most important entities (North, 2012). Since the perfusion parameters are already visible in the tool bar arterial lactate, the ratio between bile and arterial glucose, bile minus arterial HCO_3 and bile minus arterial pH were chosen. These parameters and their changes over time are often the indicators that the operators and surgeons look for to determine the viability of the organ.

Secondly, the division of graphs between pages was changed. The distribution between metabolism and functional parameters was not clear, as multiple parameters can arguably be both. The division that was chosen was between blood gases and electrolytes. This is a division that can also be found on the results receipt from the blood gas analyser. Although, the electrolytes are arguably also part of the blood gases.

Thirdly, confidence intervals were added to the transplanted and rejected data. This was applied to make it even clearer if the current liver is in a "good" zone or a "bad" zone instead of solely relying on pattern matching (*UR12*). This can help operators understand if the changes that are occurring are improving the state of the organ or decreasing the state of the organ (situation awareness level 2). This technique can be seen as relying more on spatial cues as the operator can rely on the location of the line of the current liver to determine if the liver is doing well.

Unfortunately, Chart.js does not support confidence intervals and the graphing packages that do, require a database that is specifically designed for the package. We strongly recommend that the D3 charts (Bostock, Ogievetsky, & Heer, 2011) or Google Charts (Google LLC, 2008) package should be consulted and implemented. In order to simulate the look of confidence intervals, the “accepted” and “rejected” lines were drawn again but translucent and with a larger thickness.

Finally, it was suggested that we leverage on the colour use for medical visualisation when making a distinction between portal venous and hepatic arterial parameters. The portal vein is often represented by the colour blue and the hepatic artery by the colour red. This colour scheme was applied to the variables in the toolbar as well as to some of the text in the warnings. This allows for operators to see the distinction between the categories in a glance and therefore, for fast *detection* of changes (situation awareness level 1).

After the application of these changes the interactive prototype was in the state that was used for evaluation.

In this part we addressed the steps of identifying and establishing user requirements, (re)designing and building an interactive prototype of the interaction design lifecycle (Figure 5). We discussed the methods that were used to establish user requirements and the resulting user requirements. We applied these user requirements and principles previously discussed in the theoretical framework to the design of the prototype. After two design iterations we completed the interactive prototype for the user evaluation. We will discuss the evaluation in the next part.

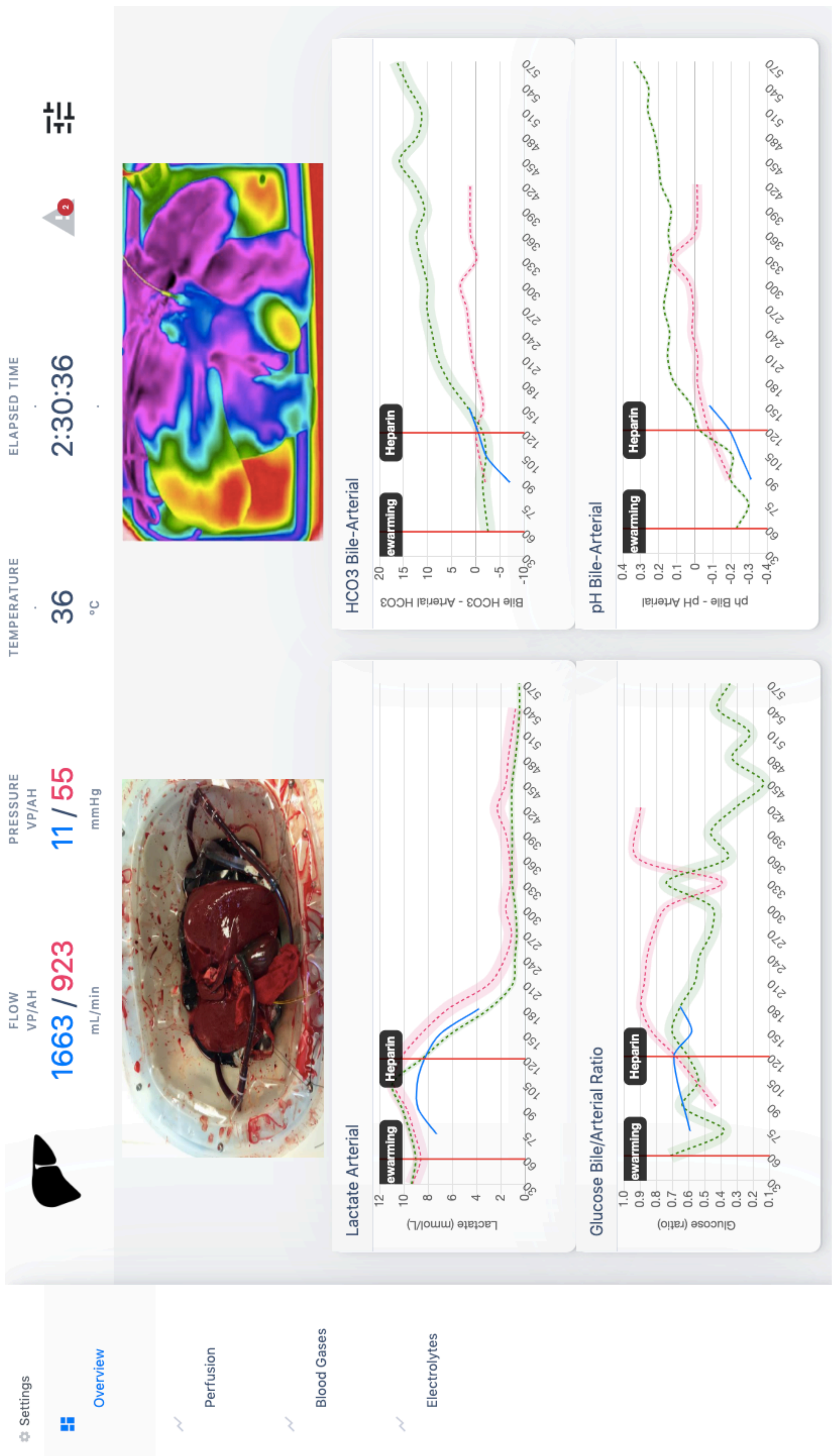

Figure 21. Depiction of the overview page after the second design iteration.

Part III. User Evaluation Study

In the previous chapter design and implementation of the interactive prototype for machine perfusion was discussed. In this chapter we will discuss the extensive user evaluation that was conducted. The new interface should allow operators in the OPR to explore the perfusion information as well as aid in making decisions, from administering extra medicine to transplanting the organ or not. The operators should also become comfortable with the idea of leaving the organ unattended with the interface fully implemented. The goal at the end of the study was not to have a fully functional interface. The goal was to gather information to put towards redesign and building an interactive prototype for future cycles of the interface design life cycle.

In the following sections we will discuss the methods for the user evaluation study as well as the results and resulting suggestions for improvement.

7. Methods

7.1 Participants

The user evaluation study was conducted in the UMCG with four liver perfusionists and one former liver perfusionist, all from the UMCG. We will further refer to the participants of the study as the users. This may seem like a relatively small group, however, in total there are only five liver perfusionists at the UMCG. Additionally Nielsen (1992) determined that approximately 75% of all usability problems can be found by 3 – 5 experts. Therefore, a total of five users was deemed to be sufficient for this study.

7.2 Materials

The prototype was run on a Apple MacBook Air, 1.4 GHz Intel Core i5, 8 GB DDR3 RAM, 13.3-inch LED display (1440x900 pixels). Google Chrome was used as the application to display the prototype.

7.3 Design

The evaluation consisted of four parts: general prototype exploration, scenario-based evaluation, semi-structured interview, and questionnaires.

Users started by exploring the prototype using a thinking aloud method (Erikson & Simon, 1984). This was followed by a scenario-based evaluation consisting of 6 tasks. The scenarios were chosen to represent a wide range of tasks that occur frequently in the OPR. The scenarios also make use of a wide range of the most important functions. This allowed us to examine if users were capable of correctly interpreting and using these functions. The time to complete a task was recorded as the moment the task was started until the user vocally concluded that they had completed the task. Completion of the 6 tasks was followed by a semi-structured interview, the interview protocol can be found in Appendix F. Finally users filled in two questionnaires, a ranking of their top 5 most important parameters and the System Usability Scale (SUS) questionnaire (Brooke, 1996) two questions were added to the SUS questionnaire namely:

- It was easy to find the information I was looking for.
- I would trust this information.

The first additional question was added to get an idea that users were satisfied with the information included in the system. The second question was added as users had indicated in the initial interviews that gaining trust in a new system could be an issue. These extra questions were excluded from the calculation of the system usability score.

A with-in subject design was used: all users participated in all four parts of the evaluation with the same interactive prototype. The order of the four parts was always the same as was the order that the scenarios were presented in.

This was the users first encounter with the prototype interface. The evaluation lasted 30 – 45 minutes.

7.4 Data Collection and Analysis

Throughout the evaluation user's comments were logged. The time it took users to complete the tasks in the scenario-based evaluation was recorded. The semi-structured interviews were logged using pen and paper. Users filled out both questionnaires on paper.

A usability score was calculated from the SUS questionnaire. This was done by subtracting 1 from the given answer for odd numbered questions and subtracting the given answer from 5 for even numbered questions. This resulted in answers between 0 and 4. Then the given answers were summed and multiplied by 2.5. The mean score per question was also calculated as was the count of each answer per question.

7.5 Procedure

At the beginning of the session the users were told that the end interface was meant to monitor and control a liver that was hooked up to the pump. It was also explained that this prototype was essentially a snapshot of a moment of time during the perfusion, but that the goal was to have a dynamic interface where parameters were automatically updated without needing manual input from the operators. It was also explained that the idea was that this would be remotely accessible and therefore there would be an initial login. Controls would only be accessible through the OPR login and initial login would allow users to select which organ is ready for perfusion.

Further explanation was given that the photos at the top of the overview page were placeholders for camera output.

7.5.1 Prototype Exploration

Users were given around 10 minutes to explore the prototype. They were told they could click on anything they wanted. They were asked to vocalize what they were thinking inline with the thinking aloud method (Erikson & Simon, 1984). They were specifically asked to vocalize if they were searching for any information, what they were looking at, and what their expectations were when they clicked on something. During this time they were also allowed to ask for clarification on any features. Before an answer was given the user was first asked what they thought the intention was.

7.5.2 Scenario-Based Evaluation

In the second part, the users were given six tasks to complete using the interface. The tasks were (translated from Dutch):

1. Add heparin
2. You added something manually, log this: what you added, how many mL and at what time
3. Set the interface so that it maintains a flow of 520 mL/min and so that 2 mL of heparin is added every hour
4. You are irritated by a warning about temperature that keeps going off, change this alarm so that it is triggered at a different value
5. Look at all of the pH graphs for AH, VP and bile.

After completion of these first five tasks the users were asked to look around the system and determine if there was anything wrong with the organ and if there was if they would do anything about it. One participant was excluded from this task as they had helped to determine this scenario. The goal was to have them assess that the pH was too low and potentially to add HCO_3 to try to restore it.

7.5.3 Semi-Structured Interview

The third part of the study was a semi-structured interview. The complete interview protocol can be found in Appendix F. The focus was on specific design elements and the users opinions about them and if they thought anything was missing. Here the information we were looking for was more directed and covered areas that did not come up during thinking aloud or the situation-based evaluation. Although during the thinking aloud part users already had many comments that fell under questions in the interview. In this case they were either asked to elaborate on the comments or they were asked if they had any additional comments on the topic.

7.5.4 Questionnaires

In the fourth and final part users were asked to fill in two questionnaires, both can be found in Appendix F. The first questionnaire was a list of all of the relevant parameters, they were asked to pick the top five parameters that they deemed to be the most important and rank them as well. The second questionnaire was the SUS questionnaire (Brooke, 1996). Users were asked to give an answer using a 5 point Likert scale, where 1 was strongly disagree and 5 was strongly agree.

8. Results and Discussion

The results from the user study can be split into the corresponding four parts of the study: p*rototype exploration*, *scenario-based evaluation*, *interviews* and *questionnaires*. We will include suggestions and possible fixes to any problems that were found by the users in this section. The first impressions and suggestions from the prototype exploration are discussed here. The completion time for the scenarios and the scenarios that users had difficulty with are discussed here as well. This is followed by specific comments and suggestions derived from the interviews. And finally the results from the questionnaires are presented and discussed.

Small straightforward remarks, improvements and suggestions that do not need any explanation can be found in Appendix E. The rest of the results we will discuss and elaborate on in this section.

8.1 Prototype Exploration: First Impressions

The results discussed in this section cover first impressions about the prototype, as well as specific thoughts that were mentioned while thinking aloud.

The general reception of the interface was positive. All of the users thought that the interface looked "nice" and "smooth". Many users mentioned that they were happy to adopt this system over current system for visualizing graphs (i.e. an R script). They mentioned that this was due to the fact that they were not quite confident with using R and when an error occurs in R there are very few of them that could fix this. This system would not require them to enter data to produce graphs but instead this will happen automatically. They were also all pleasantly surprised with the implementation of functions such as the automatic planner and reminders. Users were content that they could still have complete control and that there were no pre-set functions that couldn't be changed to better suit the current situations, like the ability to change the bounds for warnings.

Users also noted that the interface would be very valuable to the surgeons. This interface would allow surgeons to view the status of the organ themselves whenever they would want to, instead of calling the OPR and asking for a report or coming in to the OPR themselves. Furthermore, users noted that they could see the potential for this system to allow them to not have to always be present in the OPR.

Users were also asked to mention what they expected when they clicked on something on the interface or if what they saw was where they expected it to be. Most expectations matched the actual reality. There were two notable mismatches. The first one was in regards to the *warnings*. Three users clicked on the warnings in the dropdown menu, which in reality does not do anything. These users were expecting to go the parameter in question. For example, if there were to be a warning about the pressure they would expect to go to the pressure graph if they clicked on the warning. Furthermore, users expected these warnings as a popup or banner instead of badges on the warning symbol. There were, however, different opinions about warnings, as one user mentioned that popups would simply be clicked away if they occurred too often and found that popups would become annoying if they were trying to acutely solve a different problem. For this reason the implementation of banners may be the solution, this would allow operators to continue solving other issues without blocking the whole system.

The second mismatched expectation was about the *administration of medicines*. Firstly, one user noted that they would not expect to find this in the control panel but rather under its own button in the toolbar. Secondly, a user expected the actual name of the medicine to be in the list of available medicines, including the concentration. Even one step further, this user expected to see what the projected result of adding an amount of medicine was. This is important because the results of the blood gases are in mmol/L. Operators can notice that this value is too low and then have to calculate how many millilitres need to be added based on the concentration of the medicine to reach the reference value. This is a task that operators can struggle with, especially at night. For example, we want to add 5mL of glucose, how much would the mmol/L increase? This would help support situation awareness at level 3: *prediction* of future events for *treatment*. The system should be able to calculate the projected increase in mmol/L. Take this even one step further, if the system notices that a value has diverged too far away from a reference value or a set warning, the system could also suggest a course of action and if the operator wants to apply said suggested action.

Users had many thoughts and suggestions regarding the presentation of the data in the graphs.

Many users questioned how the bounds of the axes were chosen. Instead of having the maximum of the data presented in the graph as the maximum of the data visualized in that graph, they suggested that the maximum should be the same among all of the graphs (arterial, venous, and bile) for that given parameter. This would allow for better comparison between the measured places. Furthermore, the y-axis for the electrolytes does not have to be 0. Here the aforementioned maximum rule can also be applied to the minimum of the y-axis for electrolytes. Electrolytes will never have a value of 0. Because the axis is set to 0, it is not possible to see the changes over time because they are relatively small on this scale. These changes, however, are there and are also important to monitor.

All users mentioned that flow and pressure are very closely linked in this system. The pressure controls the flow. In order to allow for better visualization users commented that they would like to the see the pressure and flow graphs more integrated with each other. Several suggestions were rearranging the perfusion graphs so that the hepatic arterial pressure graph would be followed by the hepatic arterial flow graph, followed by the same construction for the portal vein. Or further integration could be achieved by including them in the same graph, where one y-axis could be used for flow and the other for pressure.

Finally, all users noted that at the UMCG they can use two kinds of perfusate, hemopure or blood (RBC). They both have different effects on certain parameters in the perfusion. In the original graphs produced using the R script the previously perfused organs and the type of perfusate that was used are split and both shown in the graphs. They missed this distinction in the prototype. However, they did note that comparing the current organ to previous organs that were perfused with a different perfusate is not completely relevant. If this is the case then simply allowing users to choose the perfusate at the beginning of the perfusion could be sufficient. Another option would be to allow users to toggle between the perfusates in the graphs.

All users noted that they like the graph view better than the table view. However, one user noted a function to the table view regarding deviant values. We will further discuss this in Chapter 9.3.

A complete list of suggestions and improvements can be found in Appendix E. After the users were satisfied with their exploration we moved onto the task portion of the evaluation.

8.2 Scenario-Based Evaluation Results

The tasks were used to assess if users were able to find all of the functions, without any initial technical support or instruction. However, implementation of new interfaces at the UMCG is usually preceded by instruction sessions.

It was evident that users that had spent more time exploring the interface also performed the tasks faster; they knew exactly where to click. The first task of adding heparin did not cause any problems for any of the users. This is supported by an average short task completion time of 20.2 seconds. The fifth task that required users to filter the graphs was also accomplished without any notable problems. The average task completion time was 8.8 seconds.

Task 2: Log a manual addition

The second task turned out to be more confusing. The average task completion time was 28 seconds, while this would seem to be fast the majority of the users incorrectly completed the task. In this tasks users had to open the control panel and press on the “log manual addition” button (see Figure. 16) to log a medicine that they had manually administered. Several users simply used the dropdown and “Add” button, which would have resulted in the system also adding said medicine. Adding the same medicine twice could have detrimental consequences for the organ. Therefore, it is important that the distinction be made clearer between having the system add a medicine and simply logging that the operator added a medicine manually. Additionally, for the users that found the manual logging function it was unclear what the time was that they had to enter. Is this time the time on the clock or the elapsed time? Everyone indicated that the time on the clock would be more useful. One user suggested that this could simply be a button for “now” and additionally add “+” and “-“ buttons to add and subtract minutes from now.

Task 3: Set maintenance of flow and addition of heparin to automatic

All users had some difficulty with the third task, the average task completion time was 84 seconds. Here they were required to open the automatic planner from the settings tab (see Figure 17) and change the flow the system should maintain and have the system add heparin every hour. Users had trouble finding where they could set these parameters. They started either by opening the control panel or going to the perfusion parameters tab. Perhaps it would in fact make sense to include a link to these settings on the perfusion parameters page. Furthermore, users noticed that when they changed a parameter in the automatic planner popup and then changed another one, the first parameter they changed would jump back to 0. Furthermore, one user noted that the option to have the system maintain a certain flow should be removed. This setting can be quite dangerous as flow controlled perfusion can result in damaging the organ. This is because a kink can easily occur in the entry paths to the organ. If the system has to maintain a certain flow and a kink occurs, it will increase the pressure but nothing will pass, this can result in the organ ripping and consequently having to be rejected.

Task 4: Change the bounds of a warning

Users had no problems in finding the warning settings for the fourth task, as reflected in the average task completion time of 16.4 seconds. The slight difficulty was with applying the warnings. The content of the warning popup is longer than the physical on screen size of the popup, which forces users to scroll down to accept or cancel changes. This caused some confusion for the users, as they did not initially notice that they could and had to scroll down the popup.

Task 6: Evaluate the scenario

Finally, the users conducted evaluation of the current liver at the simulated time point. The average time before users came up with a final evaluation of the scenario was 75 seconds. The users came up with multiple points for attention, which were all valid points. In the most extreme cases users final evaluation was determining that the liver would probably be rejected. Several users did note that the pH was too low and after some inspection said that adding HCO_3 was an option but not one they were keen on doing. Most users found this to be a difficult task because they had not actually being sitting with the liver for the 2.5 hours that the interface was simulated to be at.

8.3 Semi-Structured Interviews: Opinions on Specific Elements

The interviews were used to gather any other important information that was not found during the exploration session and the tasks. The complete list of questions can be found in the evaluation protocol in Appendix F. The questions aimed to gather opinions about specific elements in the design namely: the *overview page*, the *colour* usage, the *toolbar*, *reminders*, the *control panel*, and features of the *graphs*.

In general users were very positive about the interface. They found everything to be generally clear. They were satisfied with the flexibility that was provided to them. They acknowledged that while it is great that the system could do tasks for them, they liked that it was also possible to leave the actions in their own hands; for example, the ability to turn off warnings. However, one user mentioned that they were missing alarm bells for warnings, where ideally all of the different warnings would have different sounds. And the flexibility to turn off the sound attached to the warning while still receiving a warning would also be necessary.

Users were positive about the content of the *overview page*. All users acknowledged that the four chosen graphs were in fact the most important graphs to see. It also made sense to all users that they were chosen for the overview page.

Users were also positive about the use of *colours*. They stated that it helped to discern between hepatic arterial values and venous portal values. They could also imagine that the colours would be good in the OPR during the middle of the night.

The users were also satisfied with the parameters in the *toolbar*. However, several extra labels should be added for clarification, such as where the temperature is measured and the elapsed time in minutes under the elapsed time clock.

In addition, several users noted that they would like to see how much time was left before the *reminders* are triggered. These timers could also be a part of the overview page, where operators can see how long until the next sample needs to be taken. This would help to be prepared with all of the correct materials to take the samples.

Almost all of the users noted that they would like easier access to the *control panel*. Controls could be directly added around the parameters in the toolbar. Additionally, if the interface were to be displayed on a much larger screen in the OPR, the control panel could always be displayed on the overview page.

Users would also like to see some kind of *end report* at the end of the perfusion, something like a summary. They would also like the ability to save said report. This could be as simple as a PDF of the graphs at the end of the perfusion.

While there is no *login* or startup design, several users had ideas about information and steps that should be included there. First the user should be asked for which organ perfusion should be started, this should be followed by a perfusate selection, followed by the temperature settings and corresponding alarms. This is of importance as the safe bounds for different parameters changes depending on the temperature settings. Pressure is for example, lower for hypothermic perfusion. Finally, the weight of the organ should also be noted at login. This would allow the system to calculate the goal flow for normothermic perfusion, which is about 110% of the weight.

Most of the users were satisfied with the *division of the graphs* between blood gases and electrolytes. However, one user would have liked to see the calculated parameters, such as the glucose ratio between bile and the hepatic artery, on a separate page. Other users would have liked to see three graphs in a row to view the three locations a parameter is measured at in a row. The 13" sized screen that was used for the evaluation was not large enough to display three graphs in a row without losing too much detail. If the display for the OPR is larger, then this could be changed. Users would like to either see the three locations of samples for a parameter in one row or the two graphs of the parameters that are used to calculate a calculated parameter.

Furthermore, users were very fond of the *filter* feature for the graphs. However, they would also like to be able to view two sample locations simultaneously, especially hepatic arterial and bile, and not all or one. To facilitate this users should be able to select more than one option in the drop down, or alternatively eliminate the dropdown and work with buttons. There are only four options in the dropdown for measurement location. These could all be displayed as their own buttons instead, where selecting a button displays that location and more buttons can be selected simultaneously. A more flexible filtering function could also be extended to the parameters dropdown, as it is also interesting to see certain parameters together; for example, HCO_3 and pH.

Finally, one user mentioned that they would like to see more evidence of *deviant values*. Currently, to their experience values are called out in the OPR but without any acknowledgment if the value is within a safe range. To our previous knowledge there were no previously determined reference values to use to create safe bounds per parameter, however, for the liver these values have recently been, at least in part, determined. Because these values are available it will be possible to create more prominence in graphs and features when the values deviate outside of the safe bounds. This could be achieved in several ways. Since spatial features have been found to be the most effective (Cleveland & McGill, 1984; Nowell, Schulman & Hix, 2002) graphs that contain parameters that have deviant values could be shuffled up to the top of the page. Furthermore, the cards the graphs are displayed could also have coloured borders, where red could indicate that the values are deviating. These methods could support *detection* of changes in the organ (situation awareness level 1). Further inspiration can be taken from EPIC, where arrows are shown next to parameters to indicate if they are above or below safe bounds. This feature could be implemented next to graph titles or next to parameters in the table view. The addition this arrow may be useful in *diagnosis* and understanding of the situation (situation awareness level 2). In EPIC the reference value is also displayed with the parameters, therefore, it may be useful to include these here as well to keep operators mental models of different systems as cohesive as possible.

8.4 Questionnaire Results

The users filled in two questionnaires. In the first questionnaire users were asked to rank their top five most important parameters. The results showed that all users thought that the parameters that were chosen for the overview were in fact the most important organs. Several users also marked pCO_2 to also be important.

The second questionnaire was the SUS questionnaire. From this questionnaire a usability score was calculated. In order to compare the results to industry standard, questions 11 and 12 were excluded from calculating the usability score. The usability score was calculated for each user. A score above 68 is above the industry average score. All users had a score above 68, where the user average was 89. Scores above 80.3, which all of our results are, mean that users appreciate the system and would recommend it to others.

Furthermore, we calculated the average score per question and the count of a given answer per question. The results can be seen in Table 1. The count for the given answer per question was also calculated and can be found in Figure 22. In general we can see that the users on average at least agreed with all of the questions where agreeing was the positive outcome and at least disagreed with the questions where disagreeing was the desired outcome. We see that users are particularly positive about using the interface frequently. All users strongly agreed that they would like to use the system frequently. They also found that the interface was easy to use, where four users strongly agreed and one user agreed. Users concluded that it would not be necessary to receive excessive technical support or to learn a lot of extra things before being able to use the system. Also of importance is that users thought that they could trust the system, three users strongly agreed and two users agreed.

Table 1. Average answer per question in the SUS questionnaire with the addition of questions 11 and 12.

Question	Mean score
1. I think that I would like to use this system frequently.	5.0
2. I found the system unnecessarily complex.	1.4
3. I thought the system was easy to use.	4.8
4. I think that I would need the support of a technical person to be able to use this system.	1.2
5. I found the various functions in this system were well integrated.	4.4
6. I thought there was too much inconsistency in this system.	2.0
7. I would imagine that most people would learn to use this system very quickly.	4.8
8. I found the system very cumbersome to use.	1.6
9. I felt very confident using the system.	4.2
10. I needed to learn a lot of things before I could get going with this system.	1.4
11. It was easy to find the information I was looking for.	4.0
12. I would trust this information.	4.6

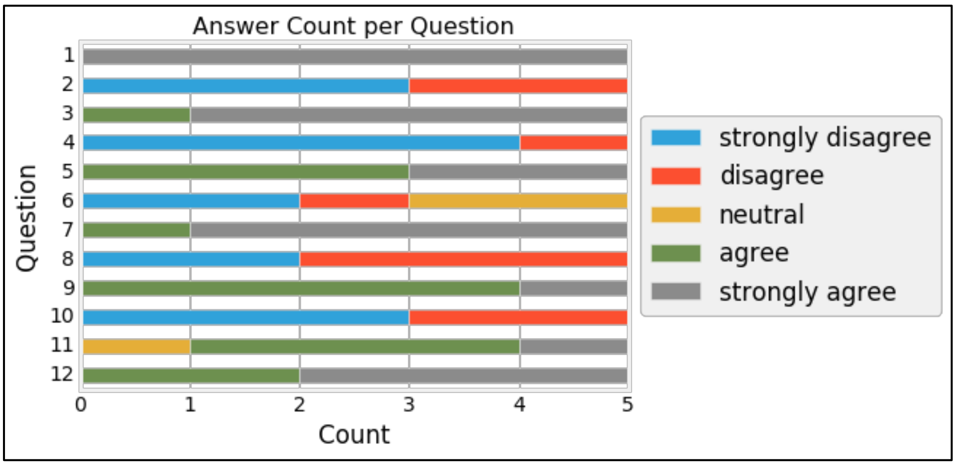

Figure 22. Count the amount of times a given answer was given to each question.

Part IV. Discussion

In this final part we will discuss the general results of the project. We will further discuss how the prototype can be extended for use with other organs. Finally we will present our suggestions on the future work that is necessary before the final stage of the interaction design lifecycle: implementation of a final product in the Organ Preservation and Resuscitation unit (OPR).

9. Discussion of the Main Results

The goal of this project was to set the first steps towards developing an interface for use in the OPR for *ex-vivo* organ perfusion. This was achieved by implementing Rogers, Preece, and Sharp's (2015) interaction design life cycle. By interviewing stakeholders involved in the organ transplantation process and observing work in the OPR we addressed the first sub research question. Here we observed and evaluated the current experience of working with the separate interfaces, or lack there of for data registration. This led to the identification of needs and the establishment of user requirements for the interactive prototype that we implemented, addressing the second subresearch question. The basis of the theoretical framework we presented in Part I discussed how design principles should be implemented while keeping users in mind. This together with construction of the HTA and addressing the previous two questions built the framework as to how cognitive engineering can support design choices. This addresses the third and final sub research question. Through combining the framework resulting from addressing the subquestions the prototype interface was implemented to produce the answer to the research question. Finally, the success of said implementation was evaluated which provided insights into future work for the interface. In the previous section the results of this evaluation were presented and possible design fixes were suggested to address any found issues. In this section we will discuss the conclusions that can be made from the evaluation, generalisation to other organs and further future direction for the interface.

The general impression from the interviews was very positive. All of the users expressed their enthusiasm to have such an interface implemented in the OPR. They did, however, note many points to be improved on. These points were arguably points that could have been gathered during the interviews to gather user requirements. However, during these interviews it was noticeable that the interviewees struggled to get a grasp on what they could exactly ask for. Putting an interface in front of them seemed to give them a better idea of the scope. Since we approached the interviews more vaguely, without giving away what the exact project was until half way through the interview, this may have been the first moment that they thought about and imagined such an interface for the OPR. Approaching the interviews more head on instead of the tactic that we applied could have possibly avoided this. By trying to get a general picture of how the OPR works before the interviewees could filter out what they themselves deemed to be unimportant we may have missed the opportunity to allow them to think about what they would want in an interface before coming to the interview. Arguably, we may not have gotten the more general picture of the work domain had we immediately told them what we were working on. And in this sense we got the general picture in the initial interviews and more detailed ideas during the evaluation.

While the users had many suggestions for improvements the results from the questionnaire showed that they were very positive about the system. This would suggest that they were looking beyond the improvements that need to be made and focused more on the potential of the interface. Results from the questionnaire also showed that users were prepared to trust the information presented in the interface. Many noted they were very excited to have this work in the OPR, as it would improve their working experience there. They were especially positive about the potential to be able to leave the organ physically unattended. This would suggest that the choice to implement the interface as a web application was the right choice. They were very adamant about proper security and backups of the system. These are important aspects that need to be taken into consideration in future implementation of the interface.

10. Generalisation to Other Organs

To make the interface applicable to the other organs that the OPR can support, organ-specific changes need to be implemented, but the basis of the interface can be kept. The largest discrepancy between organs lies in the initial stages and the different parameters.

In broad terms, perfusion of the kidney is similar to perfusion of the liver. To implement the interface for a kidney bile could be swapped out for urine and the use of two pumps would need to be reduced to one. For the lungs this is not quite as straight forward. *Ex vivo* Lung Perfusion (EVLP) has a somewhat increased complexity due to the addition of a ventilator. This ventilator would also have to be controlled through the interface if we want to combine all aspects into one integrated interface. Therefore, these controls and corresponding parameters would need to be added to the interface. Furthermore, the standard protocols for each organ has to be considered. This is of importance for the implementation of automation. Where the liver has a standard protocol for rewarming, which can be selected in the interface, the lungs have a different protocol to reach 37ºC, where different parameters need to be adjusted accordingly. For EVLP this standard protocol is applied to the first hour of perfusion. An additional feature that can be added to the lungs is automation of calculations for the optimal ventilation per lung, which the operators currently have to calculate by hand. This could be calculated at login and selection of the lungs as the organ for perfusion, much like the suggestion to calculate the goal flow based on the weight of the liver at login.

Before moving on to implementing the interface for the other organs it would be wise to reach a satisfactory implementation of the general interface for the liver. This will allow for all of the general features to be properly devised. These features can then be applied across the interfaces, keeping the general design consistent. This is of importance as the machine perfusionists are not necessarily exclusively perfusionists to one single organ. Maintaining consistency across interfaces should help to prevent any errors due to inconsistencies across interfaces.

11. Future Work

There are still many steps necessary before the implementation of the interface in the OPR. Issues that were found in this project and the solutions that we have suggested need to be applied to the prototype and generalization to other organs must be researched.

In the grand scheme of the project the design and implementation of a database must also be achieved. The database can be as simple as a plain text file or a comma separated (CSV) file. Additionally, a hardware project must be realized that tackles getting output from the current machines involved in the perfusion process, as well as sending input back the machines that can allow them to change parameters accordingly. An Arduino system or a Raspberry Pi could be embedded in the system to achieve this hardware project. Additionally, a link with EPIC may need to be established to access the results of the blood gases. Included in this hardware project should be the final monitor that will be used in the OPR. From our results we would suggest that a large touch screen would be the most optimal, which is inline with suggestions from users during the evaluation.

Furthermore, security features and a login implementation must be designed. Since the goal is to implement the interface in such a way that users can access it outside of the OPR it would be wise to determine rights to control parameters. At this point a login for the main operator should be the only account that should be able to access the controls. Alternatively, the control panel could be device locked. Otherwise, other users outside of the OPR may try to change parameters while other users are tackling a different problem without proper communication, causing confusion.

Finally, further steps for the interface may be to include more automation. In an ideal world at some point the system would be able to support the organ on its own without any input from the operators. However, this may not be attainable on short term. Instead implementing more suggestive features in the interface may be desirable. The current design implementation had a larger focus on level 1 situation awareness: *detection* of changes. Future work on adding suggestive features may be advantageous in supporting level 3 situation awareness: *prediction* of future events for *treatment.* During one evaluation a dialogue about such features was carried. Based on reference values of the parameters the system would know what safe bounds are per parameter. Should these parameters deviate outside of the safe bounds the system could make suggestions on what actions to take, which we previously touched upon. For example, if the glucose became too low the system could suggest adding 2mL of potassium gluconate. The operator could then choose to accept this action, change the quantity or take no further action. Not only should the system give suggestions but the system should also give prospective results should the operator want to take action, much like the suggestion with the addition of medicines mention in Chapter 8.1. Such an implementation could be a valuable addition to the interface. Endsley (1999) had subjects perform tasks with varying levels of automation. She found that situation awareness was increased and the workload was lower when the system selects options and the user makes the final choice for action. These results support the implementation of a suggestive system where operators have the final say over the actions in the system.

In following iterations of the interface it may be useful to work more closely with a medical expert. This will allow for a better understanding of physiological bounds for the interface as well as aid in the implementing suggestive functions.

Stemming from both the initial user requirements interviews and the user evaluation it is evident that medical technology is still a limiting factor. It is currently not possible to display blood gases in realtime due to the lack of a realtime measuring sensor in the OPR, for example. Other parameters that would be solid indicators of organ health cannot currently be measured in this setting. And the OPR does not have cameras or a scale that the organs can always be weighted by. These are limitations that would need to be addressed for the interface to be able to function at full potential.

12. Conclusion

This project consisted of the initial iterations of an interaction design lifecycle to produce an integrated interface for use in the OPR. The initial step was to gather user requirements, which were applied to a design concept and implementation of a first interactive prototype. The final step of this project was to evaluate this prototype with future users to provide insights for future implementations before reaching a final product. From the results it is evident that many iterations will still be necessary before a final product can be implemented in the OPR. However, users see the potential of such an interface and they are enthusiastic about the implementation of a final product for the OPR. In the future technological limitations in the OPR must be addressed and it would be wise to work closely with a medical expert in the following iterations.

Hopefully, this interface can become a valuable tool in gaining a better understanding in the underlying functions of *ex vivo* organ perfusion and will be useful towards transplantation of more organs.

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Appendix A. Interview Protocol

Verhaal voor begin interview:
Wij zijn dus geïnteresseerd in de gebruiksvriendelijkheid van de apparatuur dat aangesloten wordt op een orgaan tijdens ex-vivo orgaanperfusie, dit willen wij gebruiken als ondersteuning tot een nieuw ontwerp. Wat we precies willen maken zal ik zo verder vertellen maar ik zou graag eerst wat algemene vragen over orgaanperfusie willen stellen.

Algemeen

- Wat is uw functie?
- Wat is uw rol binnen het perfusieproces?
  - Hoe lang bent u actief bezig met deze rol?
- [voor OPR/lab operators] Zou u kunnen omschrijven hoe het proces in zijn werk gaat? i.e. wat zijn de **globale** stappen?
- Hoe vindt u dat het perfusieproces nu gaat?
  - Wat werkt heel prettig?
  - Zou daar iets in veranderd/verbeterd moeten worden? Zo, ja wat?
  - Wat vindt u van de materialen?

Apparatuur

- Met welke apparaten werkt u? Per apparaat:
  - Hoe werk je daarmee?
  - Wat kan worden ingesteld?
  - Wat voor output komt eruit? Waarom is dit belangrijk?
  - Wat kan er mis gaan?

Verhaal over de interface:
Het doel uiteindelijk is om een interactief prototype interface te ontwerpen voor machine perfusie. Hierbij is het doel dat we alle apparaten die aan een orgaan worden aangesloten vanuit een punt kunnen bedienen en ook dat alle informatie over het orgaan daar verzameld wordt. Dus dat er onder andere grafieken beschikbaar zijn die in realtime worden geüpdate. Bijvoorbeeld als er meer zuurstof wordt toegediend dan is de bedoeling dat het ook op dat moment grafisch zichtbaar wordt.

Dus naar aanleiding van dit verhaal heb ik nog wat specifieker vragen over het gebruik van beeldschermen/monitoren waar uw gebruik van maakt

Interface

- Wat zijn de belangrijkste items waar u naar kijkt?
  - Waar gaat u echt naar op zoek? Wat is nu moeilijk te vinden?
  - Hoe kunnen dit het beste gevisualiseerd worden volgens u?/ Hoe zou dit het makkelijkste zijn om te lezen?
- Wat vindt uw specifiek prettig aan de schermen die nu in het systeem zitten?
  - Zou daar iets aan verbeterd kunnen worden? Zo ja, wat?
- Moet alles op een pagina zichtbaar zijn? Of kunnen meerdere pagina's ook?
- Waar zou u het liefste ten opzichte van het scherm zitten?
  - Altijd bij de hand of eentje bij het orgaan?
- Wat zou u nog meer willen zien in realtime? In een ideale wereld wat zou je allemaal op je scherm willen hebben? Welke parameters? (zelfs wat qua hardware op dit moment niet mogelijk is?

- Kijk je ook achteraf terug naar de data? Zoja, wat is dan interessant om te bekijken (dus niet in realtime)

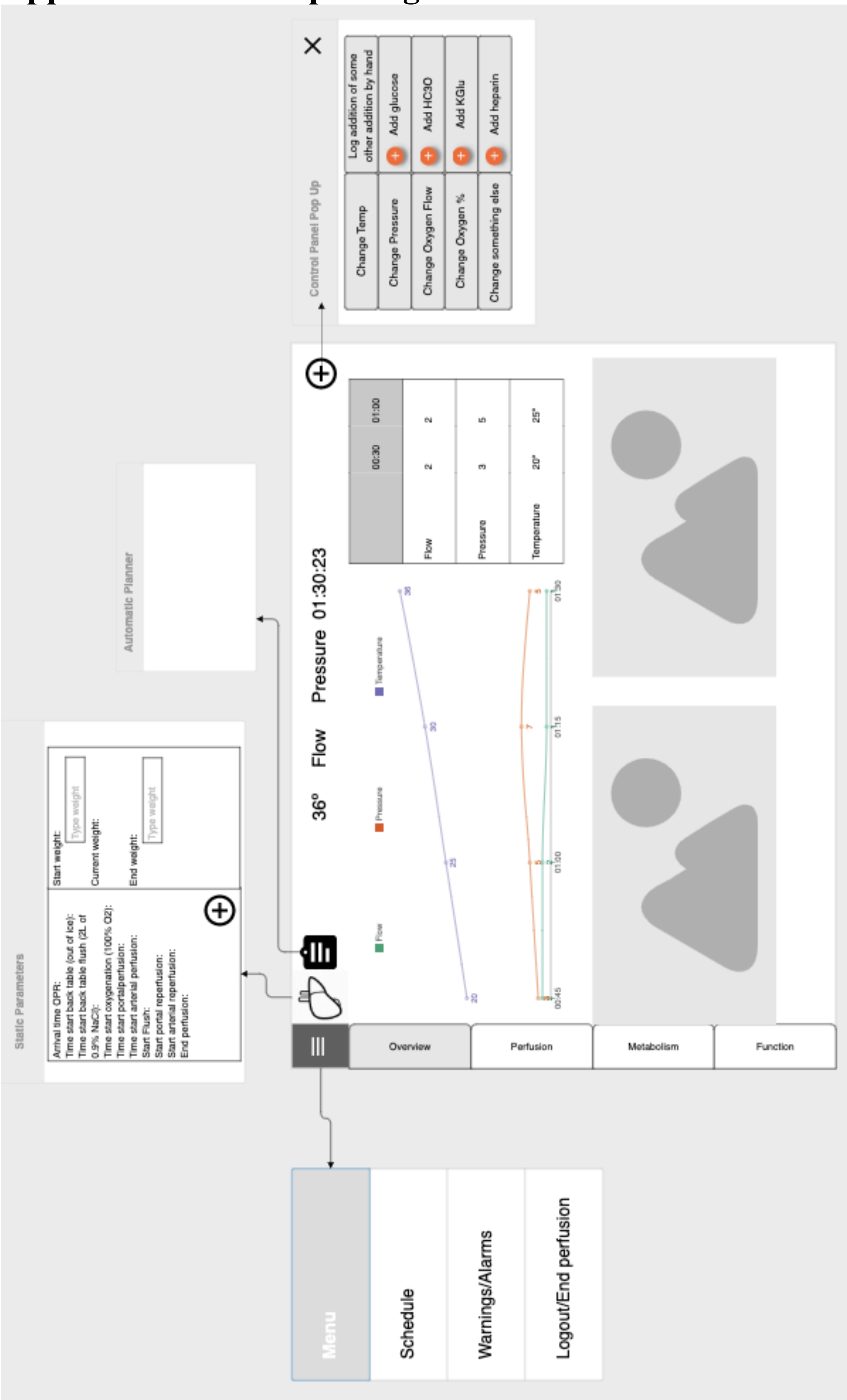
- Wat mag volgens u echt niet ontbreken bij een nieuwe ontwerp?

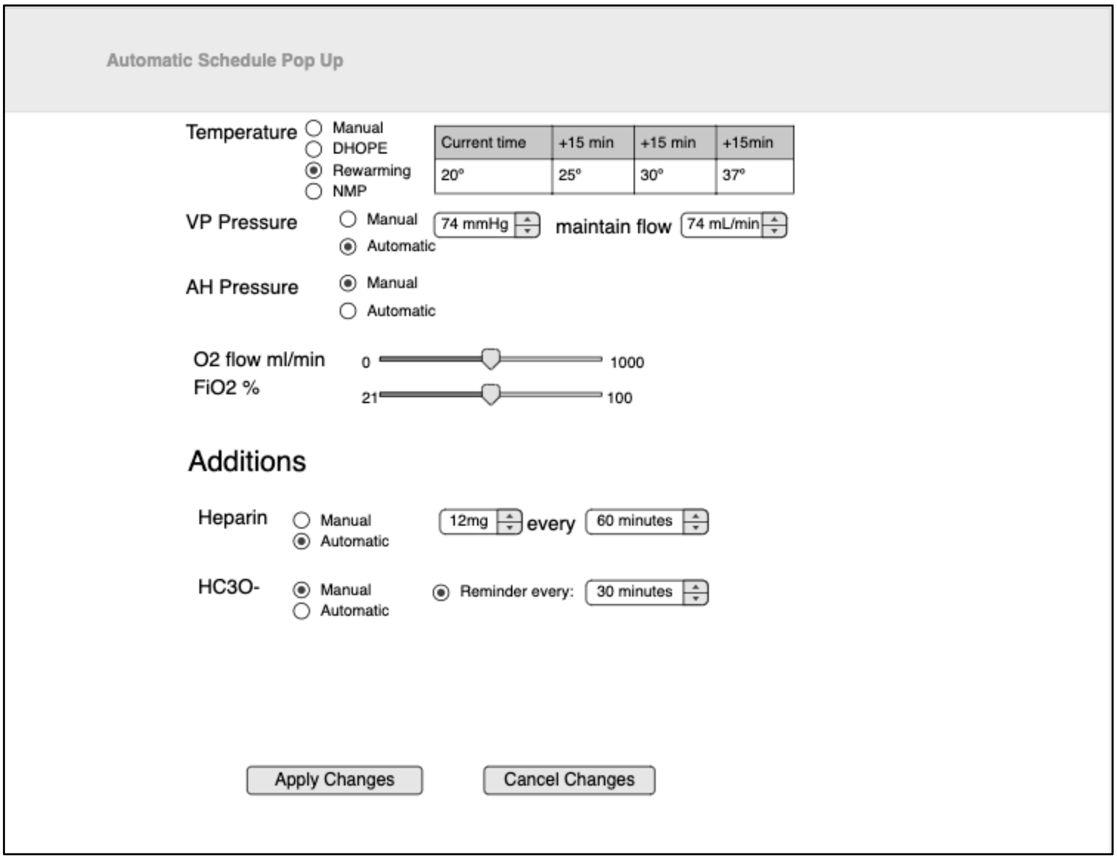
Appendix B. Realtime Parameters in an Ideal World

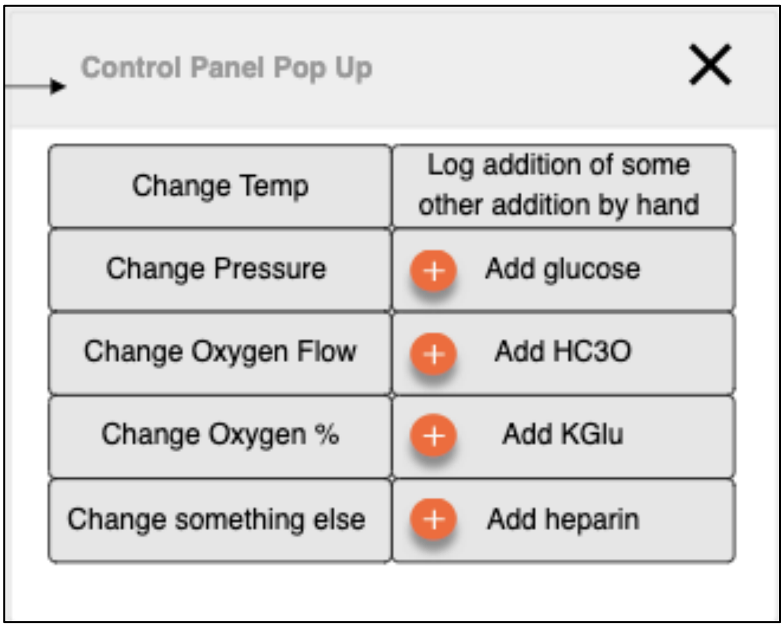
A list of parameters that stakeholders would like to see in realtime in an ideal world. Not all of these parameters are currently measurable.

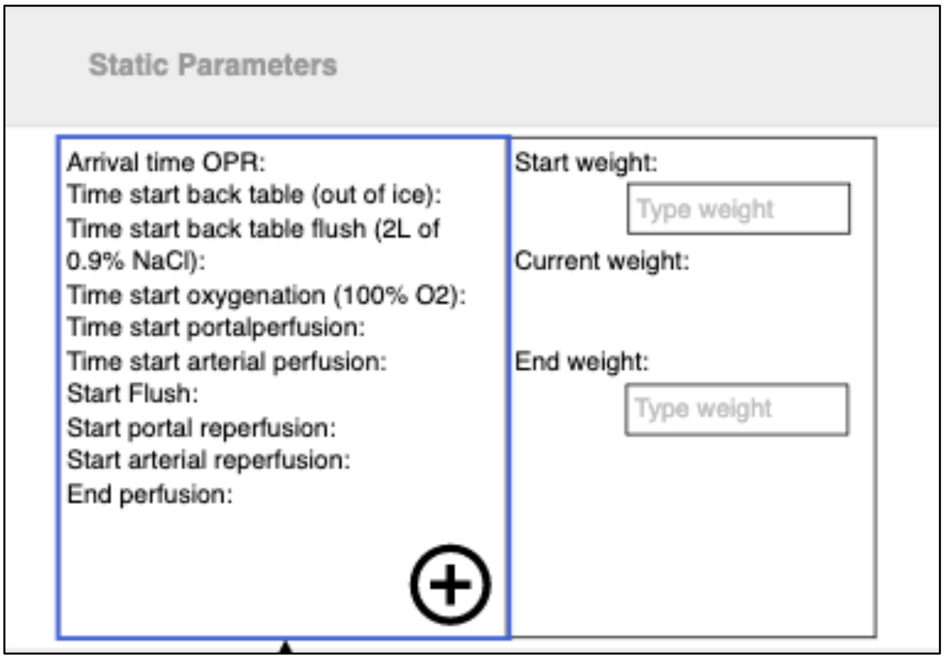
- Perfusion parameters
- CO_2
- Oxygen in and out
- Distribution of perfusion
- Pressure Doppler
- Respiration parameters (lungs)
- Weight
- Cell viability
- Blood flow at a microperfusion level
- Endothelium activation
- PAP (lungs)
- LAP (lungs)
- BO_2
- Lactate
- ATP
- Creatine
- Cytokines
- Urine measurement (kidney)
- Coagulation proteins

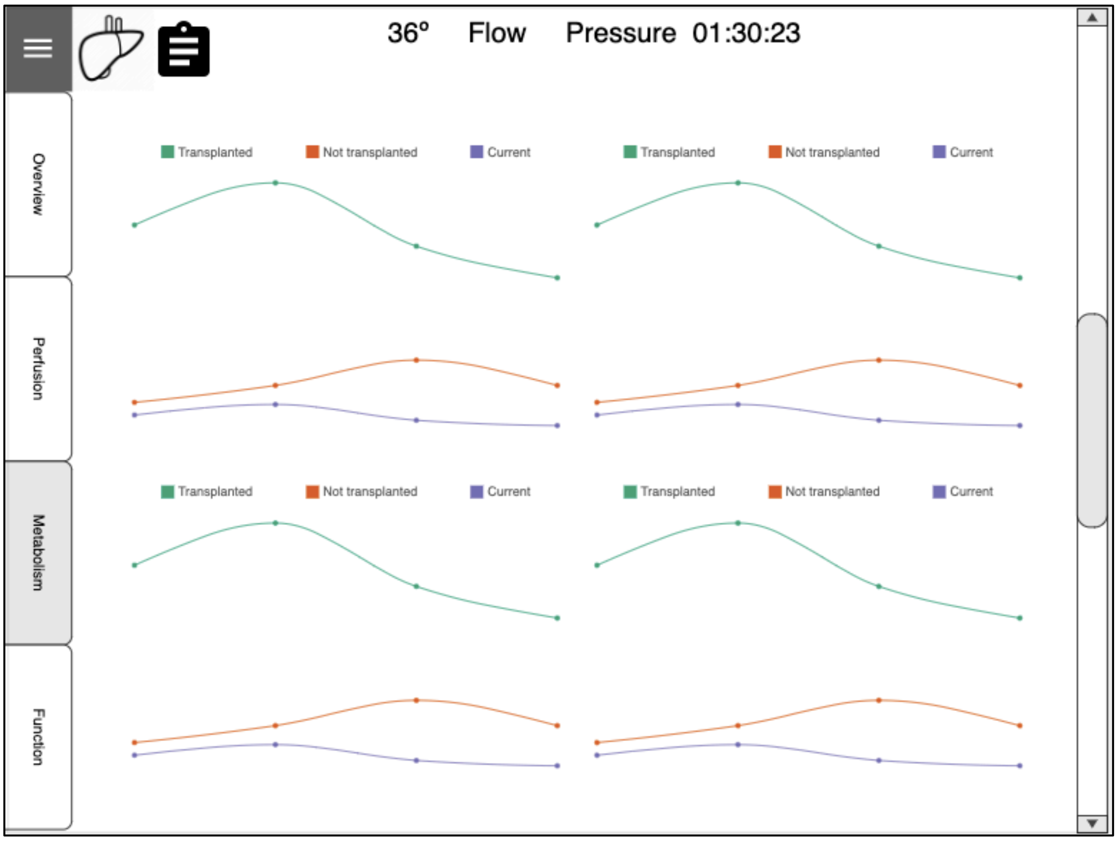
Appendix C. Mockup Design



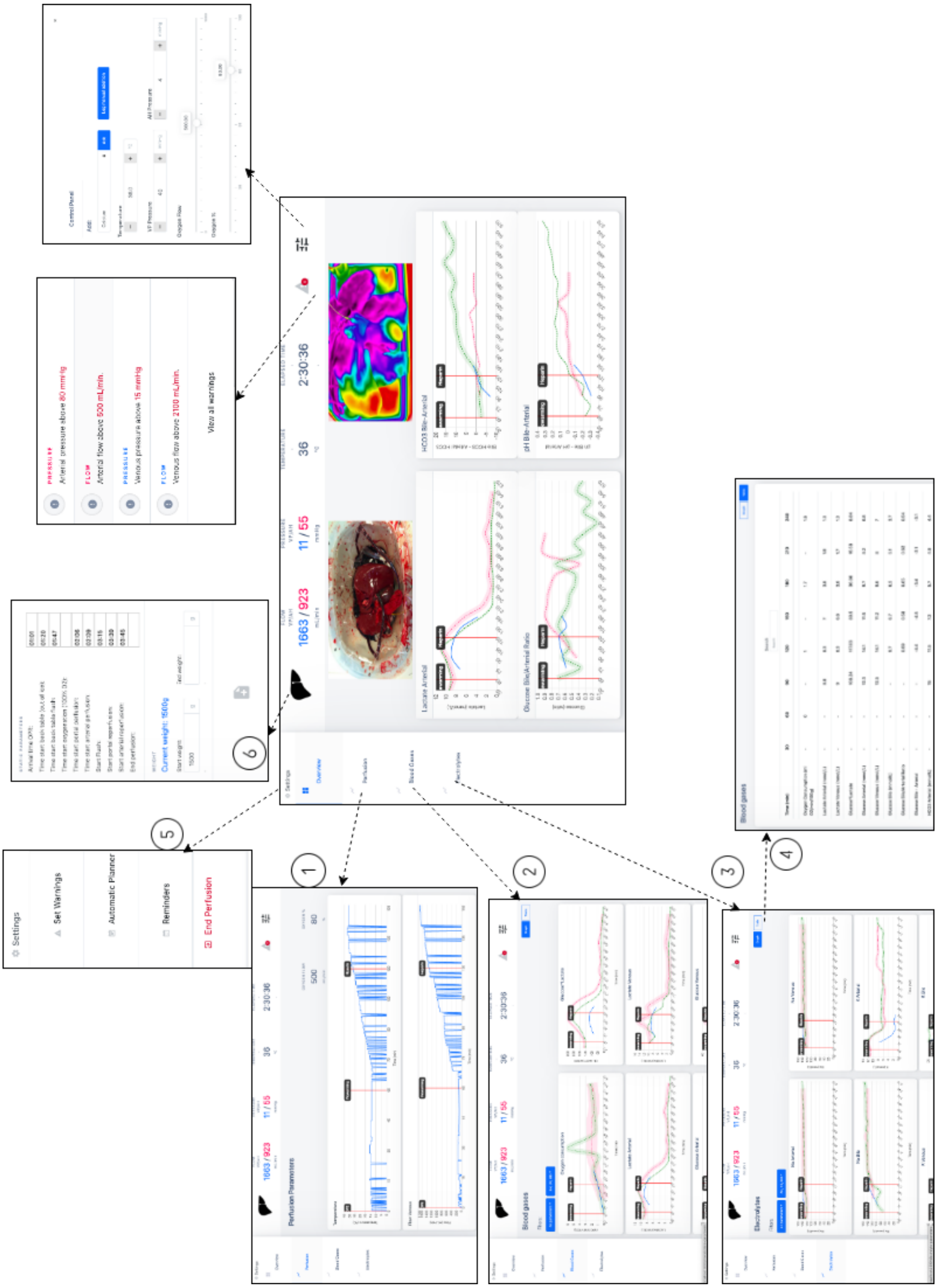

Automatic Schedule Pop Up
Temperature
Manual
DHOPE
Rewarming
NMP
Current time
+15 min
+15 min
+15min
20°
25°
30°
37°
VP Pressure
Manual
Automatic
74 mmHg
maintain flow
74 mL/min
AH Pressure
Manual
Automatic
O2 flow ml/min
0
1000
FiO2 %
21
100
Additions
Heparin
Manual
Automatic
12mg
every
60 minutes
HC3O-
Manual
Automatic
Reminder every:
30 minutes
Apply Changes
Cancel Changes


Control Panel Pop Up
Change Temp
Log addition of some other addition by hand
Change Pressure
Add glucose
Change Oxygen Flow
Add HC3O
Change Oxygen %
Add KGlu
Change something else
Add heparin

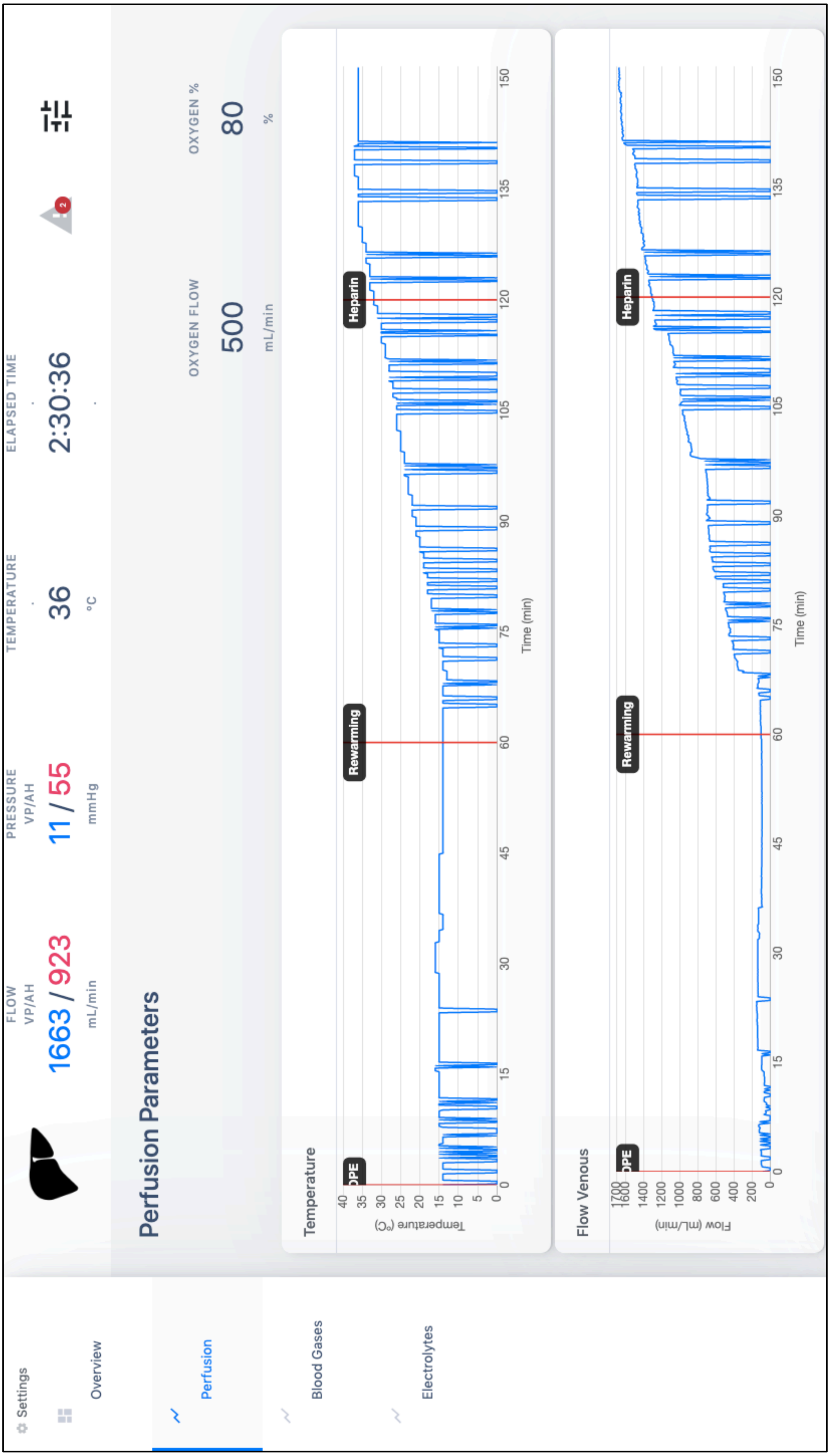

Static Parameters
Arrival time OPR:
Time start back table (out of ice):
Time start back table flush (2L of 0.9% NaCl):
Time start oxygenation (100% O2):
Time start portalperfusion:
Time start arterial perfusion:
Start Flush:
Start portal reperfusion:
Start arterial reperfusion:
End perfusion:
Start weight:
Type weight
Current weight:
End weight:
Type weight


36°
Flow
Pressure
01:30:23
Overview
Perfusion
Metabolism
Function
Transplanted
Not transplanted
Current

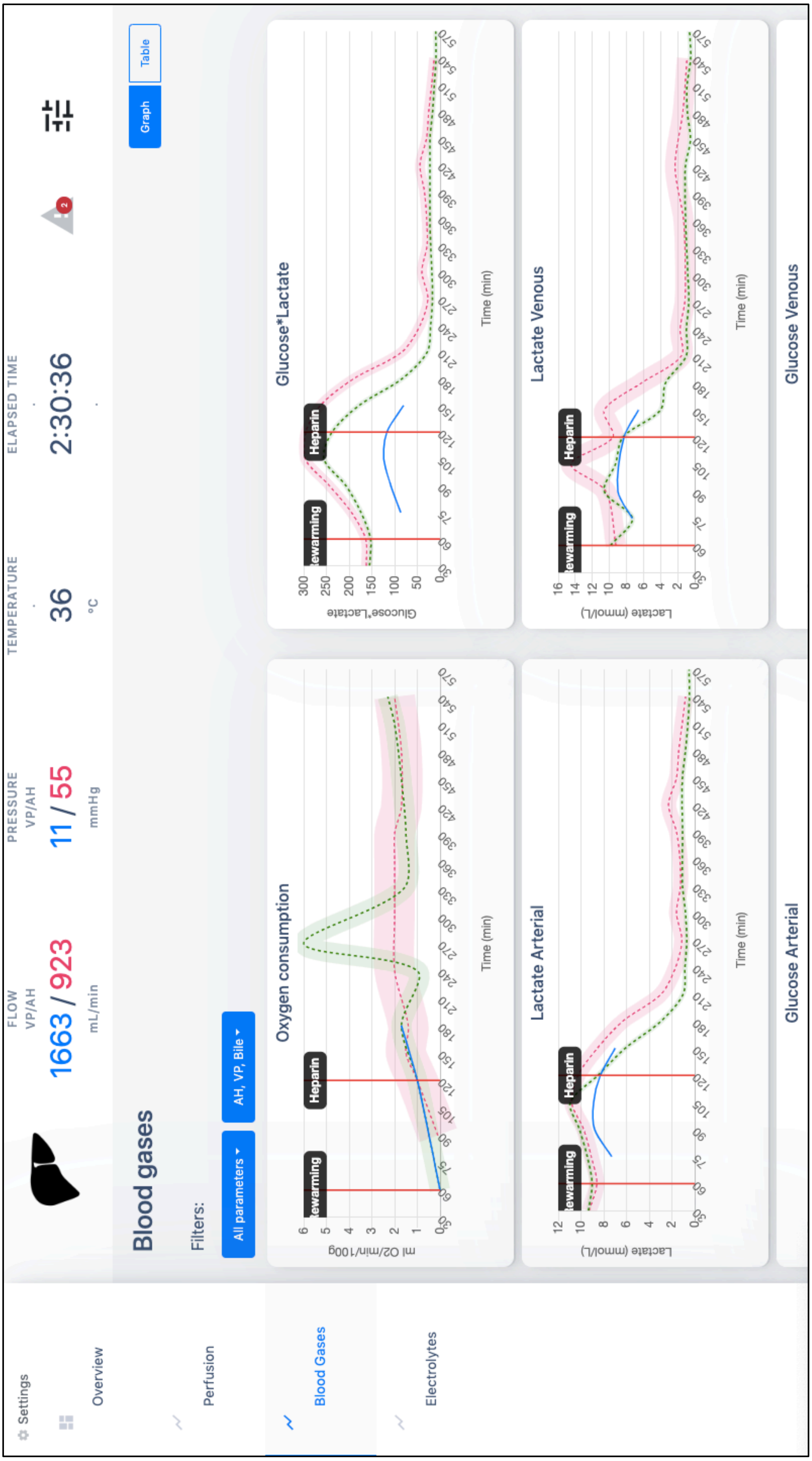
Appendix D. Prototype Interface Design



1

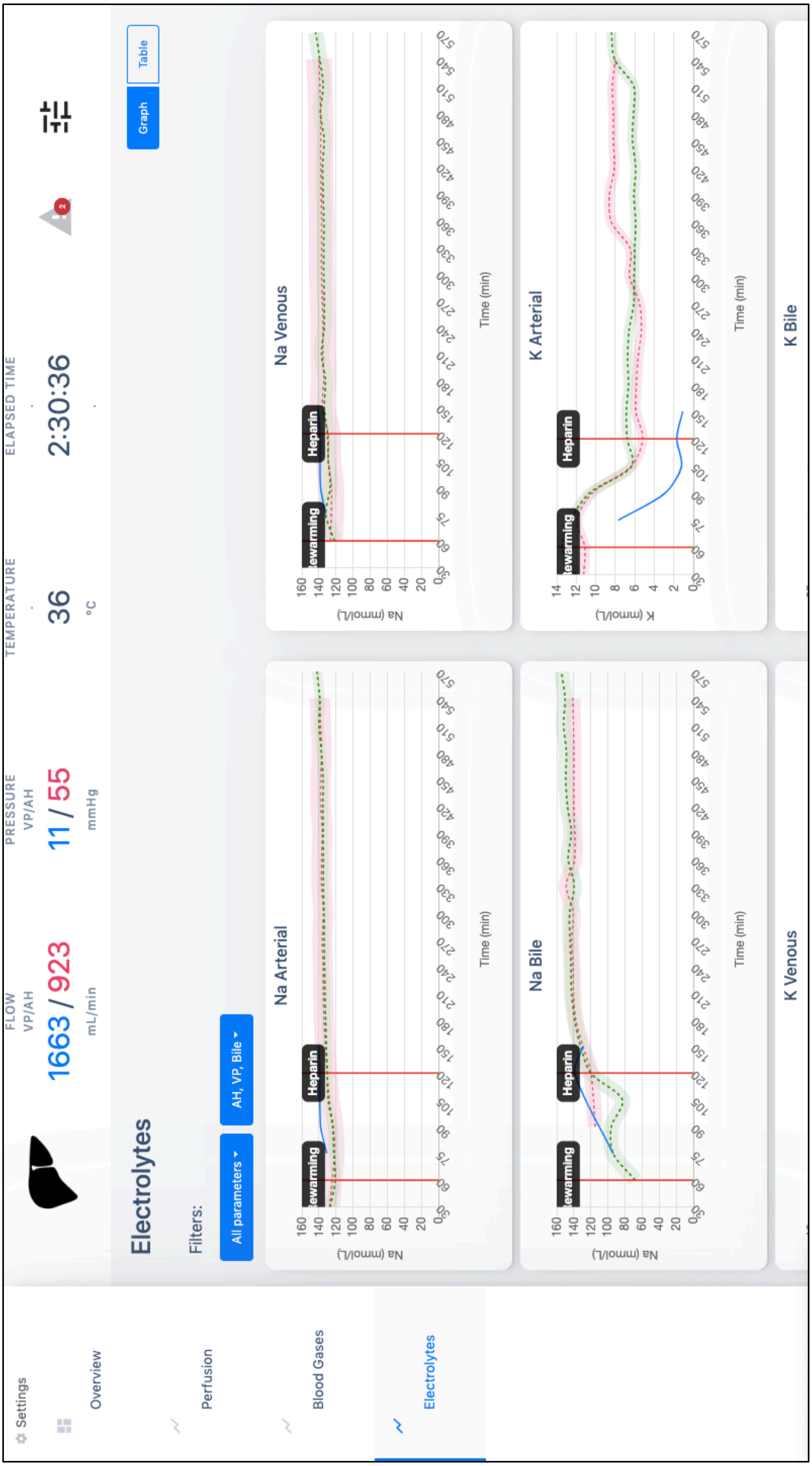

Settings
Overview
Perfusion
Blood Gases
Electrolytes
FLOW
VP/AH
1663 / 923
mL/min
PRESSURE
VP/AH
11 / 55
mmHg
TEMPERATURE
36
°C
ELAPSED TIME
2:30:36
Perfusion Parameters
OXYGEN FLOW
500
mL/min
OXYGEN %
80
%
Temperature
Temperature (°C)
Time (min)
Flow Venous
Flow (mL/min)
Rewarming
Heparin

2



Settings
Overview
Perfusion
Blood Gases
Electrolytes
FLOW
VP/AH
1663 / 923
mL/min
PRESSURE
VP/AH
11 / 55
mmHg
TEMPERATURE
36
°C
ELAPSED TIME
2:30:36
Graph
Table
Blood gases
Filters:
All parameters
AH, VP, Bile
Oxygen consumption
ml O2/min/100g
Heparin
Time (min)
Glucose*Lactate
Lactate Arterial
Lactate (mmol/L)
Lactate Venous
Glucose Arterial
Glucose Venous

3



Settings
Overview
Perfusion
Blood Gases
Electrolytes
FLOW
VP/AH
1663 / 923
mL/min
PRESSURE
VP/AH
11 / 55
mmHg
TEMPERATURE
36
°C
ELAPSED TIME
2:30:36
Graph
Table
Electrolytes
Filters:
All parameters
AH, VP, Bile
Na Arterial
Na Venous
Na Bile
K Arterial
K Venous
K Bile
Heparin
Na (mmol/L)
K (mmol/L)
Time (min)

4

Settings

Overview

Perfusion

Blood Gases

Electrolytes

FLOW VP/AH 1663 / 923 mL/min

PRESSURE VP/AH 11 / 55 mmHg

TEMPERATURE 36 °C

ELAPSED TIME 2:30:36

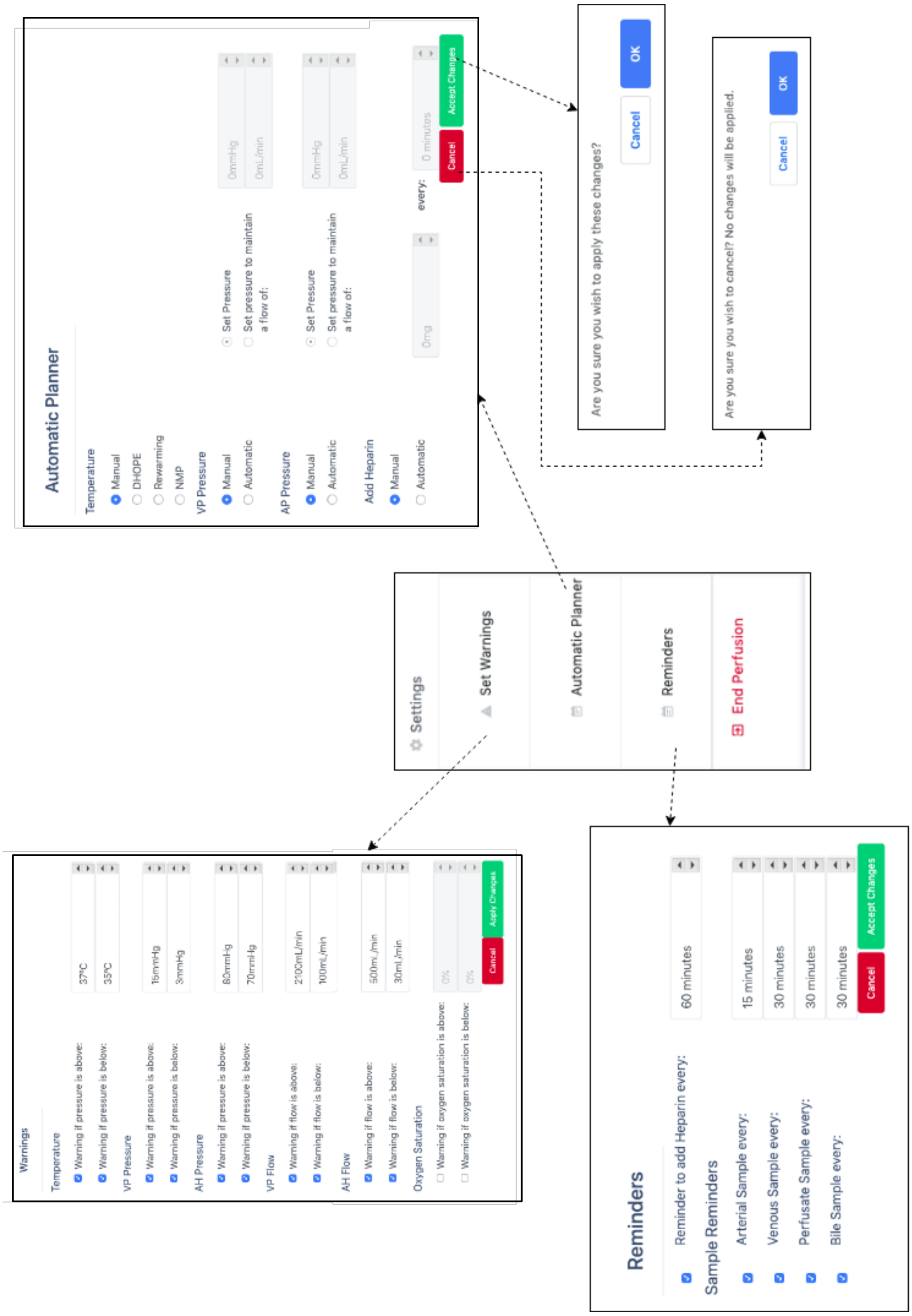
Blood gases

Graph Table

Search

Time (min)	30	60	90	120	150	180	210	240
Oxygen Consumption (ml O2/min/100g)	-	0	-	1	-	1.7	-	1.6
Lactate Arterial (mmol/L)	-	-	8.8	8.3	7	3.8	1.9	1.3
Lactate Venous (mmol/L)	-	-	9	8.3	6.6	3.8	1.7	1.3
Glucose*Lactate	-	-	108.24	117.03	80.5	36.86	15.58	8.84
Glucose Arterial (mmol/L)	-	-	12.3	14.1	11.5	9.7	8.2	6.8
Glucose Venous (mmol/L)	-	-	12.5	14.1	11.2	9.6	8	7
Glucose Bile (mmol/L)	-	-	-	9.7	6.7	6.3	5.1	3.7
Glucose Bile/Arterial Ratio	-	-	-	0.69	0.58	0.65	0.62	0.54
Glucose Bile - Arterial	-	-	-	-4.4	-4.8	-3.4	-3.1	-3.1

5


Automatic Planner
Temperature
Manual
DHOPE
Rewarming
NMP
VP Pressure
Manual
Automatic
Set Pressure
Set pressure to maintain a flow of:
0mmHg
0mL/min
AP Pressure
Manual
Automatic
Set Pressure
Set pressure to maintain a flow of:
0mmHg
0mL/min
Add Heparin
Manual
Automatic
0mg
every:
0 minutes
Cancel
Accept Changes
Are you sure you wish to apply these changes?
Cancel
OK
Are you sure you wish to cancel? No changes will be applied.
Cancel
OK
Settings
Set Warnings
Automatic Planner
Reminders
End Perfusion
Warnings
Temperature
Warning if pressure is above:
37°C
Warning if pressure is below:
35°C
VP Pressure
Warning if pressure is above:
15mmHg
Warning if pressure is below:
3mmHg
AH Pressure
Warning if pressure is above:
80mmHg
Warning if pressure is below:
70mmHg
VP Flow
Warning if flow is above:
2100mL/min
Warning if flow is below:
100mL/min
AH Flow
Warning if flow is above:
500mL/min
Warning if flow is below:
30mL/min
Oxygen Saturation
Warning if oxygen saturation is above:
0%
Warning if oxygen saturation is below:
0%
Cancel
Apply Changes
Reminders
Reminder to add Heparin every:
60 minutes
Sample Reminders
Arterial Sample every:
15 minutes
Venous Sample every:
30 minutes
Perfusate Sample every:
30 minutes
Bile Sample every:
30 minutes
Cancel
Accept Changes

6

STATIC PARAMETERS

Arrival time OPR:	01:01
Time start back table (out of ice):	01:20
Time start back table flush:	01:47
Time start oxygenation (100% O2):	
Time start portal perfusion:	02:06
Time start arterial perfusion:	02:09
Start Flush:	03:15
Start portal reperfusion:	03:39
Start arterial reperfusion:	03:45
End perfusion:	

WEIGHT

Current weight: 1500g

Start weight:	End weight:
1500 g	g

Appendix E. Small Improvements

A list of the small improvements and suggestions that users made during the evaluation.

- Oxygen flow can be set to above 1000 mL/min in extreme cases
- Changing the amount of mL in manual addition popup makes the interface crash
- In some places heparin is in mL and in others mg
- Include the ability to also set a timer in reminders with a manual description
- hep**A**tic -> spelling
- When a popup opens the page behind it still scrolls up and down
- “Accept” button in control panel
- “0” values in the perfusion graphs are the pump failing to make a measurement, these can be excluded from the graphs.
- Include a marker for the moment where the decision to transplant should be made at minute 270
- The liver does not look like a button
- Change the time increments in the automatic planner so that it increments in steps of whole minutes
- Think about what will happen if you add 4 medicines at the same time point
- Increase thickness of blue “current” line
- Change background colour of the graphs for different temperatures (DOPE, rewarming, NMP), maybe as a gradient
- Bile production values are missing
- Settings for HOPE (only AH perfused)
- Add histology number and donor times to static parameters
- Add T_{return} label under the temperature in the toolbar
- Add minutes under elapsed time

Appendix F. Evaluation Protocol

Evaluation interview protocol

1. 5 – 10 minutes exploring the interface (thinking aloud). Explain thinking aloud beforehand. These questions can be used to probe participants when they stop talking:

- Wat denkt u?
- Waar zoekt u nu naar? Waar kijkt u naar?
- Als u daarop zou klikken wat verwacht u dat er zal gebeuren?

2. Performing tasks, time how long it takes

1. Voeg heparin toe
2. U heeft zelf iets met de hand toegevoegd, voeg een marker toe op het grafiek: wat, hoeveel mL en wanneer
3. Stel de interface in zodat het een veneus flow van 520 mL/min onderhoudt en elk uur 2 mL heparin wordt toegevoegd
4. U ergert zich aan een waarschuwing die telkens afgaat, verander dit alarm zodat hij pas bij een andere waarde afgaat
5. Bekijk alle pH grafieken voor AH, VP en gal

Situatie:

- Kijk rond de interface en zoek wat er fout gaat met het orgaan en neem actie door iets toe te voegen dat dit kan herstellen
    - *pH is te laag voeg HCO3 toe*

3. General questions

- Mist u bepaalde informatie? Zo ja, welke?
- Is er iets die u graag anders weergegeven zou willen zien?
- Wat vindt u van de kleuren?
- Wat vindt u van de overview pagina?
    - Zou u daar nog iets in één oogopslag willen zien?
    - Zou u nog iets anders aanpakken?
- Wat denkt over toolbar bovenin elke pagina?
    - Zou u daar nog iets willen zien?
- Wat denkt u over de verdeling van de grafieken (bloedgassen/elektrolyten)? Zou u een andere verdeling maken?
- Wat vindt u over hoe de grafieken gefilterd kunnen worden?
- Andere opmerkingen

4. Parameters importance ranking

- Uit deze lijst, geef een ranking aan de top 5 meest belangrijke parameters (en waar) om te zien

5. System Usability Scale (SUS) Questionnaire + 2 extra questions:

- Het was makkelijk om de info te vinden die ik zocht
- Ik zou deze informatie vertrouwen

Parameter	**Ranking**	**AH, VP or Bile?**
Lactate		
Glucose		
Na		
K		
Cl		
Ca		
pH		
HCO3		
pO2		
sO2		
CO2		
BEC		
Hb		
CO2 Hb		
Met Hb		
H+ Hb		
O2 Hb		
tbilirubin		
AH glucose* AH lactate		
Bile glucose/AH glucose		
Bile glucose – AH glucose		
Bile HCO3 – AH HCO3		
Bile pH – AH pH		

1. I think that I would like to use this system frequently.

   1 2 3 4 5

2. I found the system unnecessarily complex.

   1 2 3 4 5

3. I thought the system was easy to use.

4. I think that I would need the support of a technical person to be able to use this system.

   1 2 3 4 5

5. I found the various functions in this system were well integrated.

   1 2 3 4 5

6. I thought there was too much inconsistency in this system.

7. I would imagine that most people would learn to use this system very quickly.

   1 2 3 4 5

8. I found the system very cumbersome to use.

9. I felt very confident using the system.

10. I needed to learn a lot of things before I could get going with this system.

11. It was easy to find the information I was looking for

    1 2 3 4 5

12. I would trust this information

    1 2 3 4 5