An eye-movement monitoring device for premature babies

Enhancing current sleep-monitoring systems to benefit premature babies

C. Kruissel

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Thesis committee:
Prof. Dr. Ir. W. Serdijn, TU Delft
Dr. D. Dodou, TU Delft
Dr. J. Dudink, UMCU

TU Delft

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by

C. Kruissel

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Student number:	4549856	
Thesis committee:	Prof. Dr. Ir. W. Serdijn,	TU Delft, supervisor
	Dr. D. Dodou,	TU Delft
	Dr. J. Dudink,	University Medical Centre Utrecht

TU Delft

Abstract

This document lays out the design and development of a specialized device aimed at monitoring the eye movements of premature babies, which creates an opportunity to create better sleep-monitoring systems.

Monitoring sleep has great significance, especially for premature babies, because it allows for the adaptation of care to accommodate for better and more sleep. Different sleep stages can be identified, but the identification does differ for adults compared to premature babies. Different characteristics including brain activity, heart rate, respiration, eye movement and face and body movements are linked to those sleep stages.

Eye movement is a characteristic that could be used more optimally for the creation of a sleep-monitoring system. Eye movement can be tracked using different methods, but electrooculography shows the greatest promise. For this specific method, different options exist concerning electrode placement and materials. The use of this system for premature babies during sleep also creates limitations related to the fragility of the skin of prematurely born babies. Furthermore, these babies normally lie in the Neonatal Intensive Care Unit, creating additional context-specific considerations.

Different research methods were used, resulting in a complete picture of the steps taken after premature birth occurs. These steps are portrayed in a scenario. The requirements and wishes drawn from these are used to develop ideas. During the development, a choice was made to create two parts for the device, namely the shell and the electronics module.

In the final design, the shell contains specialized electrode places, named snap-rings, as well as features that create adaptability and additional details to accommodate the use of multiple devices that are already being used on premature babies. The electronics module includes an electrode configuration that can be placed into the snap-rings in the shell. The electrode protrudes the snap-ring and is pushed onto the skin. The force needed to place the electrode is decreased by using a material with a low Young's modulus, ensuring contact between the electrode and the skin without causing damage to it. This novel configuration enables the use of dry electrodes, eliminating the need for gels and adhesives.

Some recommendations are given, which concern further the development of the device, the eventual certification and the embedding of the device within a system that monitors sleep.

Overall, a complete overview of the concept design of a device that can monitor eye movement of premature babies is given, which creates an opportunity for the improvement of sleep monitoring systems for these babies.

Preface

This master thesis report contains the documentation of the development of a device that can measure the eye movement of premature babies in an effort to contribute to current sleep monitoring systems. It has been a pleasure working on this project to enrich and put to use my knowledge of the biomedical field while getting the opportunity to gain experience in the development of medical devices. The project has given me the opportunity to show what tools the master's degree in Biomedical Engineering has given me and created a great starting point for future opportunities that might come my way.

I would like to express my gratitude towards all people who have supported me throughout this project. A special mention of gratitude is aimed towards Prof. Dr. Ir. Wouter Serdijn, my supervisor during my thesis, but more importantly, the person who guided me and gave me feedback and tools to complete the project. Furthermore, I would like to thank Dr. Jeroen Dudink, who presented the opportunity for this master thesis project and created a link with many other relevant persons who could provide me with even more insights on my project. I would also like to specifically mention Wouter Berendshot, who embarked on this project simultaneously with us, which turned out to create the perfect division between a physical device design and more extensive research on the signal processing that could be done with the data from this device. The list of people that I would like to thank as well is endless, so last but not least, a great thank you to all my friends and family who have been involved not only in this project but throughout my studies.

I look forward to completing this journey during my master's thesis defence on the 30th of October, 2023.

Claudia Kruissel
Delft, September 15, 2023

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Introduction

Different studies on the role of sleep have been performed uncovering its diverse functions that play an important role in multiple aspects of a patient's health such as energy conservation, cognitive performance and neural development [1, 2, 3]. Sleep is involved in brain differentiation; it plays a critical role in learning and memory and it is important to maintain brain plasticity [4]. The amount of sleep reaches a maximum during fetal and neonatal life [2]. This greater amount of sleep has been linked to the maturation of the brain [5, 6].

The many functions that sleep has give it great importance. The need for sleep in brain development makes its importance even greater for preterm babies, i.e. babies born before 37 weeks of gestation. To be able to adapt general and elective care for preterm babies and their environment, especially in intensive care, in a way that enhances the sleep amount or quality, it is necessary to monitor their sleep. Within Chapter 2, Literature Research, research on sleep and how to monitor it can be found.

By identifying which characteristics can be used to monitor sleep and selecting the characteristics that are not currently used or not used most optimally, an opportunity can be created to use the selected characteristic in creating a new method or support and enhance an existing method for sleep monitoring. From this analysis, a goal was formulated for the project that is portrayed in this report. This goal is to develop a device that monitors the eye movement of premature babies. For the background research, the different ways to monitor eye movement that already exist are described in Chapter 2, Literature Research, as well.

To be able to create a neonatal eye-tracking device for sleep analysis, the design approach that can be found in Chapter 3, Project Approach, was taken. This approach was based on a design cycle with four phases: analyse, design, build and test. In addition to the literature research, some research within the real-life context of this research was conducted in different ways as laid out in Chapter 4. Some of this field research was done at University Medical Centre Utrecht (UMCU). This research was the foundation for the requirements and wishes setup for the design of the device. These can be found in Chapter 5.

Within Chapter 6, the development towards the final design is elaborated. Design choices are explained and the reasoning for the final design is shown. The design consists of multiple parts, including a novel electrode configuration. The resulting design concept itself will then be presented in Chapter 7. After the design is presented, the assumptions and choices will be discussed in Chapter 8, followed by a conclusion and recommendations for future development of the device in Chapter 9 and 10 respectively.

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Literature research

Within this chapter, the current practice for sleep monitoring will be combined with knowledge of the physiological and contextual restrictions and specific needs of premature babies, eventually highlighting opportunities that exist to create a device or adapt and enhance an existing device for sleep monitoring in premature babies.

2.1. Sleep stages

Sleep can be divided into different stages, which is done differently for adults compared to neonates. A study performed by Cabon et al. [7] used five stages: quiet sleep, active sleep, drowsiness, quiet alert and active alert. In a study for sleep in preterm infants, active sleep and quiet sleep were also identified, but the other states were called intermediate sleep, arousal and non-sleep state of wake [3]. A commonly used description of sleep stages uses the distinction between rapid eye movement (REM) and non-rapid eye movement (NREM) sleep. For premature babies, the sleep stages REM and NREM are considered to be the equivalent of active sleep and quiet sleep respectively [2, 8]. Initially, REM sleep is the dominant type of sleep stage. Approaching full term, REM and NREM take up an equal amount of time. By 8 months of age, NREM becomes approximately 80% of sleep time. NREM is often said to be the part of sleep that serves energy conservation and nervous system recuperation [1]. REM sleep is considered to be the type of sleep that plays a big role in brain maturation and development [9]. The main distinction between REM and NREM can be found in the brain activity that occurs, but specific characterization was also attributed to rapid eye movements and a decrease of tension in the posterior muscles [4, 10]. The separation of sleep stages is complex and needs a set of multiple characteristics to make the stages identifiable. Being able to identify sleep stages can create advantages in tracking sleep and adjusting care to the baby's sleep stage.

2.2. Sleep stage identification

For preterm babies, the characteristics dividing sleep into the different stages are different from that of adults. Multiple studies have identified these characteristics at different ages. The most commonly used characteristics used for sleep staging are brain activity, eye movement, heart rate, heart-rate variability, muscle activity, brain and body temperature and respiration [4, 11].

2.2.1. Brain activity

Brain activity can be measured using an electroencephalogram (EEG). Brain activity during sleep is related to the development of the brain at all ages [4]. During REM sleep, the firing of ganglion cells in different systems takes place to create connections between the brain and sensory organs [4]. NREM is often characterized as the stage in which there is little mental activity, necessary for energy conservation [12]. Using an EEG on adults, NREM can be divided into 3 stages: N1, N2 and N3. REM sleep however typically portrays one basic pattern [4]. Between 20 and 28 weeks of gestational age (WoGA), the EEG wave patterns do not show as they do after 28 WoGA [4]. Different rest and activity cycles can still take

place, but the distinct EEG patterns do not occur. Between 28 and 36-38 WoGA, the specific brain activity patterns evolve from discontinuous to more continuous patterns [3, 4]. The EEG patterns that are similar to those of adults, which distinguish the sleep stages, only appear after 3 to 4 months of life for infants born in full term. The assessment of EEGs during sleep for premature babies is often done manually by physicians, which is very time-consuming [13]. There are however developments in algorithms that analyse the EEGs automatically. Specifically, the immature development of the brain makes this a complicated task [13].

2.2.2. Heart rate

Heart rate and heart-rate variability differ for preterm babies compared to adults in that their absolute value is different, but the patterns occurring during sleep are often similar [3]. REM sleep in preterm babies is characterized by variations in heart rate, whereas NREM sleep for these babies is accompanied by a more regular heart rate [2]. In a study by Harper, Schechtman and Kluge [14], an accuracy of sleep classification in infants of 82% was obtained when using just cardiac variables. These variables were heart rate, heart-rate variability and cardiac interbeat-interval variation.

2.2.3. Respiration

Respiration often offers reliable variables to determine sleep stages in preterm infants, since they also portray differences in those stages. Breathing of preterm babies during REM sleep is more irregular than during NREM sleep [3]. When Harper, Schechtman and Kluge [14] used just respiratory measures, which were respiratory rate and respiratory variability, the accuracy of sleep-stage classification was 80.0%. When combining both earlier mentioned cardiac measures with respiratory measures, the accuracy increased to 84.8%. This shows great promise in using these two types of characteristics for the monitoring of sleep in premature babies since these characteristics are relatively easy to measure and detection systems for them are often already in place.

2.2.4. Eye movement

The eye movement in preterm babies mostly distinguishes sleep stages from the wake and arousal stages; the wake and arousal stages normally happen with open eyes that are focused and don't show rapid eye movements, whereas the first two occur with closed eyes [3]. A distinction can be made between REM and NREM sleep in that REM sleep is the period in which, as the name suggests, rapid eye movements occur [3]. Furthermore, the first manifestations of REM sleep are movements of the eyelids and body, indicating that this is one of the first clues that can distinguish sleep stages in preterm babies [4].

2.2.5. Face and body movements

Extensive analysis of face and body movements can also show a noticeable distinction between sleep stages. The study of Cabon et al. [7] used audio and video recordings to assess vocalizations, eye state and body motion to identify sleep stages. A study by Lopez [15] used infrared-triggered cameras to record data that was used to determine different events during sleep. The biggest disadvantage of identifying sleep stages using this method is the need for human assessment of each characteristic at each point in time. Besides this, even though atonia of the muscles is named as a characteristic of REM sleep, it does not occur until 2 to 3 months of age and is only intermittent in preterm infants [4]. The cause for this can be attributed to the role of brain development that REM has for preterm infants. During their sleep, activity-dependent developmental processes take place, meaning the brain activates the muscles with the intent of developing its control over them [10]. This perceived difference that is related to age makes this variable hard to monitor and conclusions based on them would be somewhat unreliable.

2.2.6. Opportunity for sleep classification

Considering all different characteristics related to sleep, especially in preterm infants, a mix of different measurements should allow for a proper identification of sleep stages. The differences in those characteristics between preterm babies and adults lead us to believe that using a subset of heart rate, respiration rate and eye movements shows a lot of promise in determining the sleep stages of preterm babies. Since heart rate and respiration rate are characteristics of vital functions that are often already

measured, adding a proper measurement of eye movement would create a more reliable system. A method to measure the eye movement of premature babies should therefore be developed.

2.3. Eye movement tracking

Eye tracking in adults can be done in different ways and multiple reasons to do so exist. Different studies have been done where relative and absolute movements of the eye were studied [16]. An overview of different eye-tracking methods can be found in Figure 2.1.

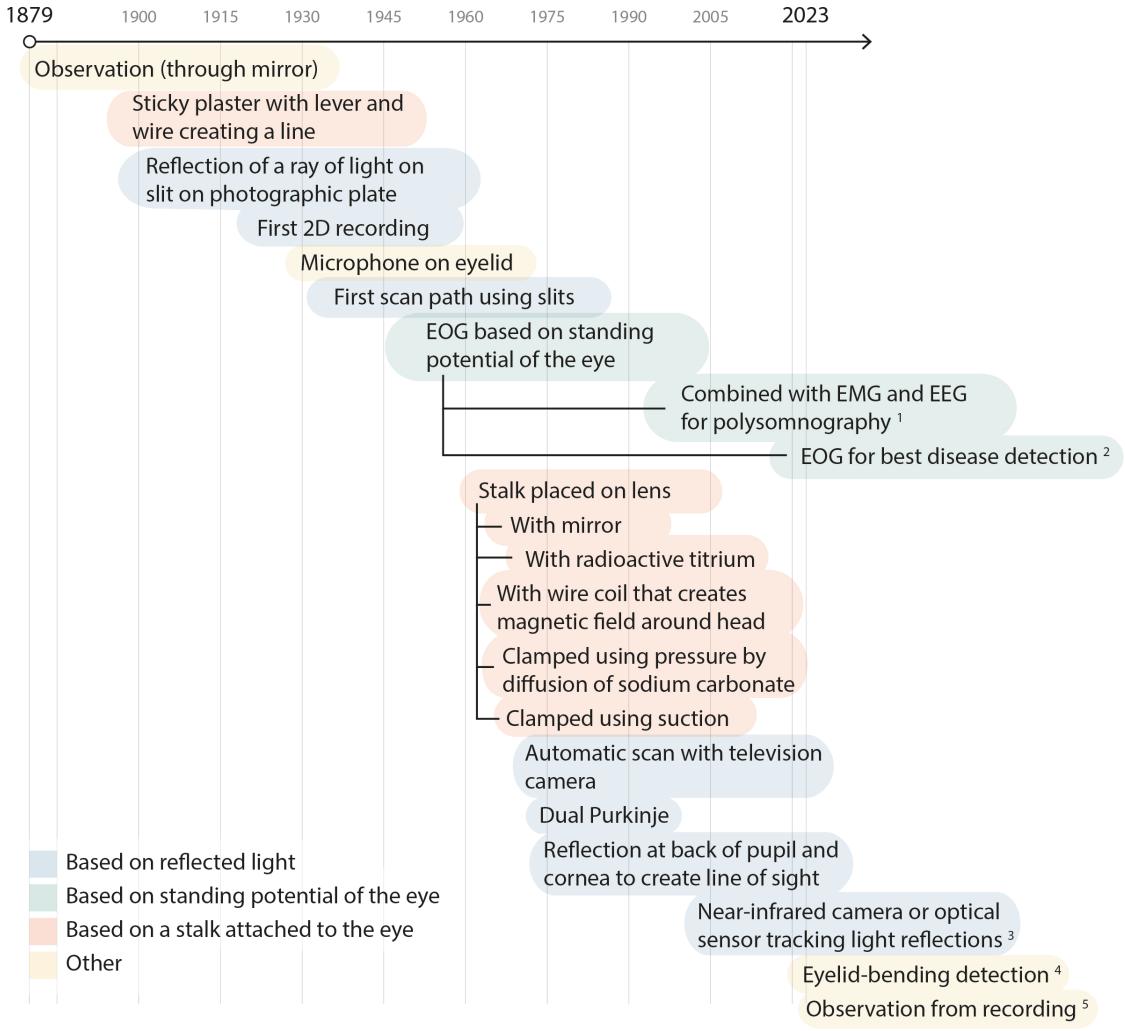


Figure 2.1: Eye movement tracking methods in history grouped per type of method [16]
[1] [17] [18] [2] [19] [3] [15] [20] [4] [21] [22] [5] [7]

During sleep, the eyelids are mostly closed, and any eye movement during this period is therefore not based on the fixation on external focus points. Measuring eye movement relative to the head would support a system that measures sleep or sleep stages. An analysis of the different eye-movement tracking methods can be performed. The different methods can be distinguished by the principles they are based on.

2.3.1. Methods using observation

Some of the very first studies going back to the 1870s were done simply using observation to see how the eye was moving, in which a mirror could be used to observe the eye while performing a task such as reading [16]. Studies identifying REM sleep do so by identifying rapid eye movements by visual inspection [23]. Some studies using ultrasonography were done, by which even eye movement of babies in utero was observed [24]. Some studies that needed more robust results focus more on the state of the eyelid than on movement of the eye itself. These also use simple observation and annotation [7]. In these studies, the most important distinction is made between open and closed eyes. This method of observation and annotation is also used in current polysomnographies [25]. Their biggest disadvantage is that these studies are extremely time-consuming and need specially trained personnel, which in turn makes them expensive [23, 26]. Current methods often use more precise and more automated measurements. In the future, AI and machine learning could show promise in automatic analysis of for example live images.

2.3.2. Methods based on reflection of light

Many methods have been developed and used in which the reflection of light on the eye, either via the cornea, the pupil or both, is the phenomenon that is measured. These types of measurements have been performed since the early 20^{th} century up until now [16]. Using the combination of reflection on the cornea and pupil makes it possible to calculate the line of sight [16, 27]. It is also possible to apply this principle to a setup that uses infrared light [20]. When enough light shines on the eye, the contrast between the different parts of the eye such as the pupil, iris and sclerae are detectable and can therefore also show eye movement [16]. For all possible methods using the reflection of light, an open eye and some type of illumination are needed, whereas as described in the characteristics for sleep stages, the eyes are closed during sleep. This means that, even though this category of measurements is one of the most used methods for identifying eye movement, it is not applicable to measuring eye movement during sleep.

2.3.3. Methods using protruding stalk on eye

Several methods exist in which a type of stalk protruding outwards was attached to the eye on which something could be attached that was measurable and therefore showed eye movement [16]. Differences within studies were related to how the stalk was attached to the eye and what kind of attachment was placed on the stalk, where properties such as magnetic field or level of radioactivity could be used [16]. The limitation that they all have in common is the invasiveness of attaching something to the eyeball and, similarly to the methods based on reflection, the need for an open eye. This type of method therefore does not show ideal conditions for measuring eye movement during sleep.

2.3.4. Using a microphone

In 1928, a study was done in which a microphone was placed on top of the eyelid [16]. Since the eye is not perfectly round, but bulges a little bit in the ‘front’ of the eye, it can record whenever this bulge bumps into the microphone [16]. This study is often considered one of the first studies that could detect so-called saccadic eye movements [28]. Placing a microphone on top of the eyelid might be complicated in the setting in which premature babies are found. Besides this, movement artefacts and disruption by sound from the surroundings will interfere greatly with the ability to get proper measurements [16].

2.3.5. Using piezoelectric elements

Recently, in the early 2020s, some studies using piezoelectric elements were used to detect the movement of the eyelid [21, 22]. This method is based on the detection of movement in the skin around the eye, which arches when moving the eyelid. Using the piezoelectric elements removes the need for the eye to be open since the elements are placed right next to the eye on the surrounding skin [21, 22]. A disadvantage that does occur for some common piezoelectric materials, such as lead zirconate titanate (PZT), is that they contain lead [29]. Exposure to too much lead can be toxic and lead is a material that can be absorbed through the skin [30]. Even when choosing piezoelectric materials that do not contain lead, this method to track eye movement is relatively new and underdeveloped, which decreases its reliability. The relatively immature development of this technique combined with the possible health

risks that could occur with some specific materials, this method would currently be unfavourable for the tracking of eye movements in premature babies.

2.3.6. EOG

A very commonly used eye-movement tracking method is based on the standing potential of the eye. The first studies describing this potential emerged during the 1950s and led to the development of the electrooculogram (EOG) [31]. The EOG has been used for different purposes such as determining neurological disorders, diseases of the eye or measuring eye movement [17, 19, 32, 33, 34, 35, 36, 37, 38]. The measurement is done using electrodes that are placed in a specific configuration around the eye. This would remove the need for the eyes to be open during measurements. The signal detected by an EOG can be affected by artefacts, such as muscle potentials, small electromagnetic disturbances from cables or surrounding power line interference [36]. On the other hand, the method is non-invasive, cost-efficient, easy to acquire and easy to be processed in real-time [36]. Since this method is also used in current clinical practice, it has already proved to be a reliable method in other settings [37]. These reasons show why this method has great potential to be used for measuring eye movement in premature babies.

2.4. The electrooculogram

2.4.1. Biological phenomenon

EOG can be used for different kinds of studies. An EOG, just like an electroencephalogram (EEG), electromyogram (EMG), electrocardiogram (ECG)) and other methods, uses an electrophysiological potential that occurs within the eye [33]. This potential is the transepithelial potential of the retinal pigment epithelium, that exists between the cornea and the Bruchs membrane found in the back of the eye [19]. The cornea is positively charged where the retina is negatively charged which together contributes to creating this potential difference [34]. The changes in resistance between these membranes alter the transepithelial potential and thus the standing potential [37]. This change in resistance has its origin in the pigment epithelium of the retina [19]. The measured signal can be influenced in two ways: a change in retinal stimulation and a change in eye position.

2.4.2. Change in retinal stimulation

The measured potential can be influenced by retinal stimulation [33]. Retinal stimulation can occur because of adaptation to a change in ambient illumination [37]. A normal response to light that changes the potential requires a normal pigment epithelium and normal mid-retinal function [19]. Using this principle for the EOG, different studies can be performed. A commonly performed procedure is to measure the light peak:dark trough (LP:DT) ratio [19, 37]. Following the standard from the International Society for Clinical Electrophysiology of vision on EOGs, this ratio can be measured by alternating a dark adaptation phase with a light adaptation phase, of which respectively the minimum and maximum amplitude of the standing potential are compared [19, 37]. This ratio is affected in diseases such as diffuse disorders of the retinal pigment epithelium or disorders of the photoreceptor layer of the retina [37]. Most disorders lead to both an abnormal EOG and electroretinogram, but some only show in an abnormal EOG or abnormal LP:DT ratio, such as Best disease [37, 19]. This application of EOG uses the response of the eye to light and is therefore not useful in determining eye movement.

2.4.3. Changes in movement

The change in potential can also be caused by eye movement since the movement of the eye shifts the potential by movement of the positive cornea [33, 19]. The magnitude of the eye movement in this case is linearly proportional to the standing potential and thus the EOG amplitude [37, 36]. The sign of this potential change shows the direction of the movement of the eye, which indicates that both the amount of movement and direction of movement can be measured with the EOG [36]. The voltage swing that is created by the movement of the eye can reach approximately 2 to 5 mV in adults [19].

In multiple studies, this ability to detect eye movement so precisely that you can detect its direction was used for human-computer/machine interface systems. Within these studies, a set of different directions could be measured. Guo et al. [39] were able to detect three types of movement in the eyes, Banerjee et al. [36] and Heo, Yoon and Park [40] detected 6 types of movement. Wu et al.

[34] managed to differentiate between 8 movements and the study that showed the most differentiated detection of eye movements was that of Phukpattaranont et al. [35], where 10 types of movement were distinguished. These different directions were up, down, right, left, up-right, up-left, down-right, down-left, clockwise and counterclockwise. This detection is based on the shape of the waveform that is created by the signal. Using methods that distinguish different eye movements can help create systems in which those movements control a computer or machine. Examples of things that can be controlled are neural-prosthetic devices, the cursor of a computer mouse, a virtual keyboard, an automatic sequential row-column scanner and a wheelchair [36, 40].

Not all applications of EOG that want to detect movement instead of illumination changes take the actual direction of the movement into account. Zhang et al. [38] only differentiated between a blink, a saccade and the fixation of the eye, to determine fatigue in the user. This system would potentially help detect driver fatigue in future applications.

Other variables related to eye movement can also be derived from the EOG. In a study by Takahashi and Atsumi [17] the number, frequency, interval, duration, rotation, velocity and power of eye movements were also measured. By measuring these variables, it could also be determined whether an eye movement belonged to a rapid-eye-movement burst, which was defined by the time between two successive eye movements [17]. In this study, 69.8% of all EMs were found to belong to these bursts. Since REM sleep is described and recognised by rapid eye movement, determining the direction of the eye movements is of less importance [41, 3]. The variables named in Takahashi and Atsumi's [17] study however could help determine sleep stages and especially the recognition of REM and EM bursts.

2.4.4. Electrode placement

Different applications of the EOG require different placement of the electrodes that do the measurements. Figure 2.2 gives an overview of different electrode placements used in different studies.

The placement of the EOG electrodes determines how many movements can be distinguished. Multiple options for a ground electrode have also been used and are often not a restriction in the setup of the device. Overall, placing the electrodes closer to the eye will always create a higher measured voltage [37].

For an EOG to be able to detect all movement, and if necessary its direction, the measurement is done in two directions, which splits up the EOG into a vertical EOG and a horizontal EOG. Normally this is done by placing an electrode on the two outer canthi and two electrodes periorbitally as shown in Figure 2.2a [17, 35]. The measurements of these can be combined to measure movements in multiple directions [35].

For an EOG that is used to determine the LP:DT ratio, only a single set of measuring electrodes is necessary. Placing one electrode on the outer canthus and one on the inner canthus of one eye will give information on the LP:DT ratio of that eye [19]. This placement, as portrayed in Figure 2.2b is used as the standard for this application [37]. It is also sufficiently accurate if the EOG only needs to be able to detect the movement of the eyes horizontally [39]. For some applications only measuring the horizontal movement of the eye is enough since this movement is affected the least by artefacts like eye-lid movement [17]. Besides this, over half of the eye movements happen horizontally [17].

Later on, forehead EOGs have been studied as well to accommodate for applications in which the eyes should not be covered or crossed by the device [40, 38]. Shown in Figure 2.2c, placing two electrodes in line horizontally and two in line vertically, the eye movement can still be detected as shown by Zhang et al. [38]. Further evolution of this technique has even created a setup in which the positive electrode is shared for the vertical and horizontal measurement as can be seen in Figure 2.2d [40]. Even though this setup accommodates easier wearable systems and correlates with regular EOG electrode placement with a relatively high factor between 0.78 and 0.88 in different studies, it also has some drawbacks [40, 38]. The discrepancy that exists between the potential from the up movement and the down movement of the eyes requires multiple thresholds to properly assess those movements [40]. There is more fluctuation and baseline drift in the forehead EOG and amplitudes and signal qualities are lower than with conventional placement [38]. Even considering this, the EOG waveforms are often still relatively identifiable [40].

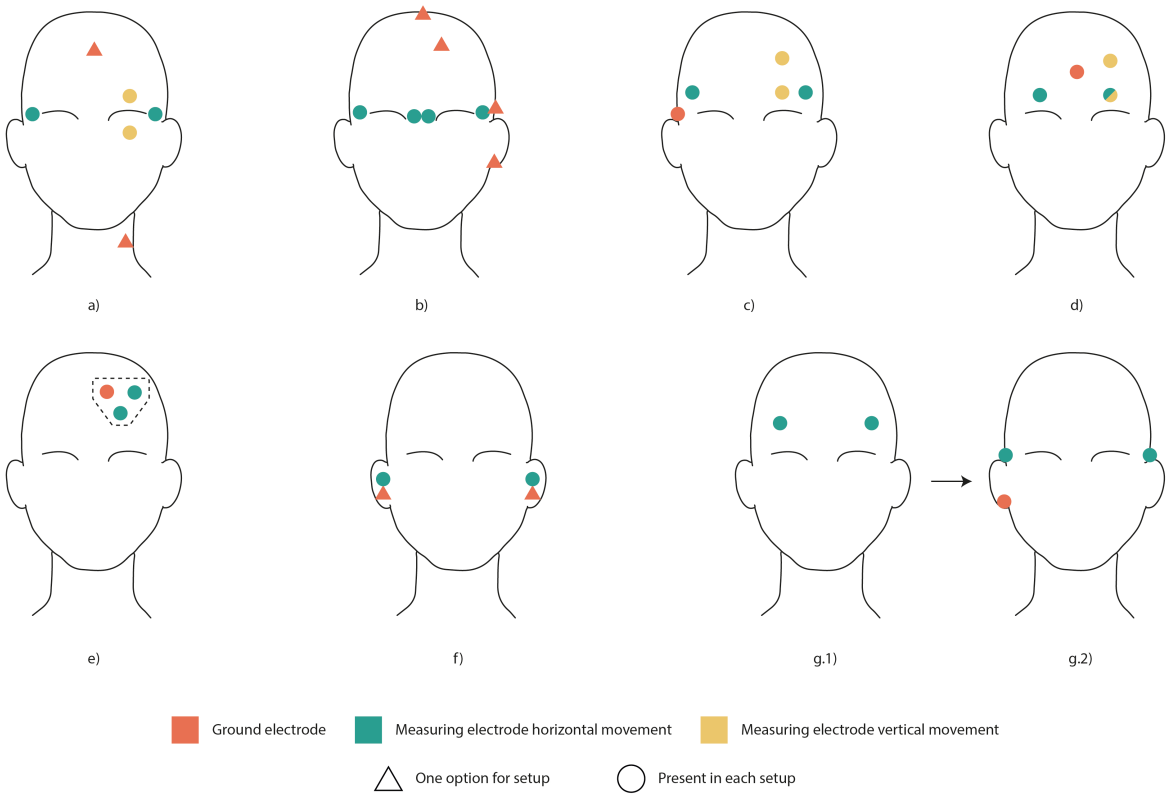


Figure 2.2: Placement options for EOG electrodes a) Standard two-directional placement [17, 35, 36], b) Standard placement for LT:DP ratio determination [37, 19], c) Standard forehead placement [38], d) Forehead placement with shared positive electrode [40], e) Triangle patch for electrodes [39], f) Electrodes inside earbuds [42], g) EEG electrodes comparison between placement on F7 and F8 in the frontal region and the placement of electrodes behind the ears [43]

Belkacem et al. [43] have also investigated the use of EEG electrodes to get the signals for the EOG and create a setup that doesn't interrupt the field of sight. The two different setups are shown in Figure 2.2g. The main drawback of this placement was related to drawbacks in facial muscle artefacts. Besides this, EEG data has more variability and has a non-stationary nature [43]. More unconventional placements have also been studied, such as those of Guo et al. [39] and Manabe, Fukumoto and Yagi [42], which often showed worse signal quality than other discussed setups. They have tried a triangular patch and earbuds as shown in Figures 2.2e and 2.2f.

The most promising configurations for using an EOG to detect eye movement in premature babies would be the conventional and forehead placement. More tests would need to be done to determine whether using those setups would create sufficiently reliable data. Furthermore, using only electrodes that monitor horizontal movement would create benefits in both development and usability of a device, but verification steps would also need to be performed to see if using only the horizontal component of eye movements is enough to enhance a sleep detection system.

2.4.5. Electrical system of EOG

Within a system that uses EOG, three main parts can be distinguished. These have been depicted in Figure 2.3.

The EOG uses electrodes to measure the potential difference and uses other electrical modules that need to be powered [40, 44]. The data is acquired in a way that it can later be processed [34, 36, 39]. Within data acquisition, a digital signal is created that can be analysed, which for an EOG means at least an amplifier, multiple filters and an analog-to-digital converter are needed [36, 37, 39, 40, 44]. An algorithm can be used that will process the data to form useful information for the application that the

EOG was done for initially. Specific properties of some of the components needed for this system have been described in previous studies. A list of these can be found in Appendix A.

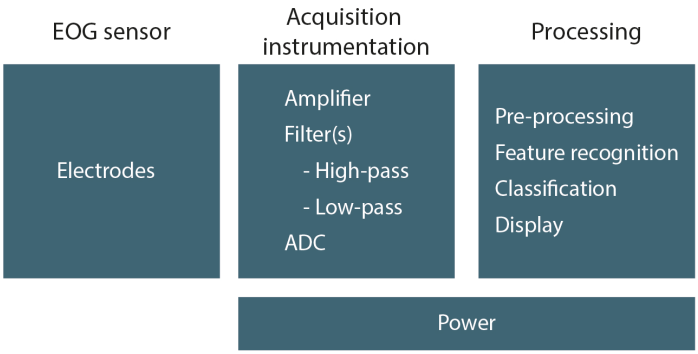


Figure 2.3: Components of an EOG system

An electrical circuit can be made in which the interaction between the skin and an electrode, for example, an EOG electrode, is modeled. It can be found in Figure 2.4.

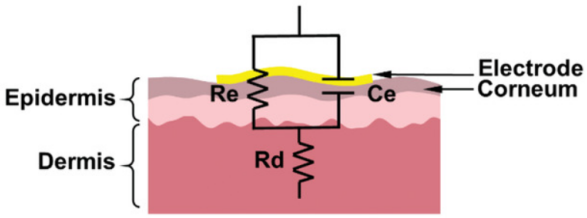


Figure 2.4: Representation of electrical interface for on-skin electrodes, often described as parallel circuit [33]

The interface of the skin and the electrode, as depicted, is considered to be a parallel circuit with a resistance due to leakage, Re, an interface resistance, Rd and a capacitance, Ce [33]. To be able to have a sufficient signal-to-noise ratio (SNR), the capacitance should be high, whereas the interface should have a low resistance [33]. Choices in hardware can influence these properties and optimize the system. Further elaboration on electrode choices will be discussed in Section 2.5.1.

2.5. Limitations from premature babies

It has been established that measuring eye movements will add greatly to measuring sleep and EOG shows the most promise in creating a device to measure eye movement in premature babies. It is important to determine what limitations arise from this specific target group to be able to create a system that can be used on them.

2.5.1. Skin

One of the aspects that is different in premature babies is their skin. The skin functions as a barrier that is critical for water and gas exchanges during fetal life [45]. The skin normally consists of the stratum corneum, viable epidermis and dermis [45]. Epidermal maturation however normally only completes around 34 WoGA, meaning preterm infants regularly have an underdeveloped epidermis and stratum corneum [46]. Even after a baby makes it to full term, it still undergoes a functional and structural skin maturation process [46]. Disruption of the skin barrier can lead to multiple conditions, such as dehydration, hypothermia or even poisoning from absorption of toxic agents [45]. The fragile skin of an infant is also more susceptible to chemical irritation or infection [46].

2.5.2. Adhesion to skin

Since their skin is very fragile, it plays a big influence in deciding which materials can be used but also how devices or sensors can be attached. A basis for practice that was published in 1999 already

describes how adhesive application and removal should be adapted for the care of premature babies [47]. A study by Lund et al. [48] in 1986 and a study by Dollison and Beckstrand [49] in 1995 had already investigated the use of a pectin-based barrier, showing that careful consideration of the way an electrode is attached to the skin has been prioritized since early use on preterm babies. Biocompatible adhesives exist, such as tapes and medical liquid bandages [33]. Multiple studies on microstructures to create so-called dry adhesives are being done as well, in which the aim is to create structures that mimic existing biological structures that show great adhesiveness, such as gecko feet or clingfish discs [33]. Another method is to create a pressure-sensitive adhesive, which bonds only when pressure is applied [33]. Finding a method for adhesion which can be reversed or controlled, for example by applying water, would reduce the risk for skin breakage or pain when detaching.

2.5.3. Electrodes

The fragility of a baby's skin under 34 WoGA causes all electrodes that are in contact with the skin to be considered obtrusive [3]. Therefore, a need for careful consideration of different types of electrodes exists. The different electrical properties need to fit the needs for an EOG while protecting the skin of the baby where the electrodes need to be placed. In an extensive study by Werth et al. [3], the electrodes used were split into three categories: normal electrodes, dry electrodes and capacitive electrodes.

Normal electrodes are often also called gel electrodes because they use a gel to create better conduction between the electrode and the skin [3]. This gel however can dry which can cause the impedance to increase [3]. This is why this type of electrode is not considered to work well for long-term applications [39]. Besides this, there is an increased risk for inflammation at the site of contact and some toxicological concerns have been raised about gels that are used [3].

Dry electrodes are made of different kinds of materials that don't require skin abrading to reduce skin resistance and don't have the need for a conductive gel [3]. The material is able to follow the shape of the skin contour without creating a high-impedance gap between the electrode and skin [3]. The impedance compared to that of normal electrodes is somewhat higher because the conduction is mostly enabled by a layer of moisture instead of the conductive gel for the normal electrodes [3]. This difference causes smaller signal amplitudes to be reached, but the total amount of noise in these electrodes is lower because of for example a lower thermal noise, creating a higher signal-to-noise ratio [3]. A recent development even created a nano needle array, where small punctures in the skin allow little needles to create a very good contact area [3]. The punctures are so small that they are considered non-invasive by some researchers and the infection risk stays minimal.

Capacitive electrodes use capacitive coupling without needing contact with the skin [3]. Problems that can occur for this type of electrodes are its sensitivity to movement and dielectric artefacts [3]. The processing system needed around these electrodes is also more complex due to the small amplitude of the signal which requires an amplifier circuit with very low noise [3]. Some instances have occurred where a contactless device was created with similar signal and noise amplitudes as gel electrodes, but overall, they show more complex requirements for proper readout [3].

2.5.4. Electrode materials

For current EOG setups, the most conventional electrode is the Ag/AgCl electrode [36]. This is an example of a normal electrode, which means it needs gel to reduce the impedance. It is often chosen for its negligible drift and absent polarization potential [36]. This material however is rigid meaning signal quality decreases during motion [36]. It is desirable to find better alternatives. This is how new on-skin electrodes arose. The main properties that are important for these electrodes are conductivity and stretchability, but studies have also taken into account softness, adhesion to the skin, breathability and biocompatibility [33]. Since the skin has a fracture strain of at least 15% and in some places even more, it is advantageous if the material placed on the skin for measurement has a similar fracture strain [33]. Flexible electronics with a stretchability of up to 400% were developed [33]. Since these new on-skin electrodes are often dry electrodes, they require a biocompatible nature for them to be applicable in long-term measurements. Specific materials for on-skin electrodes have been analysed by Wu et al. [33]. A summary of these categories of materials can be found in Table 2.1.

Material	Advantages	Disadvantages
Metal thin film	• Conductivity • Mechanic properties • State-of-the-art manufacturing for low cost • Low modulus elastomer substrate can promote softness and stretchability	• Low breakage strain • Large modulus • Likely to cause skin irritation and allergy after long direct exposure
Carbon (based on carbon nanotubules)	• Flexibility • Conductivity • Constant conductivity • No skin irritation/biocompatibility • Comparable impedance to standard Ag/AgCL	• Some processes are very environmentally unfriendly
Metallic nanomaterials	• Conductivity • In combination with elastic polymer substrate, better properties • Highly conformal contact • Possible to make biocompatible • Possible to make robust and durable	• Brittle • Impedance increased with tensile strain

Table 2.1: Comparison of commonly used materials for electrodes [33]

Metal thin films, carbon and metallic nanomaterials cover a large amount of the on-skin electrodes that have been developed, but specific cases also used other materials. Conductive polymers have occasionally been used for their biocompatibility, ease of deposition, relatively high conductivity and a relatively high SNR [33]. A composite with paper has also been tested which showed promise for a long-term high signal quality [33]. Important for all of these electrodes is that using an array is often desirable to avoid limited input, using estimation accuracy and reducing the impact of movement and performance degradation by one electrode [33].

For the purpose of creating a device that can measure the eye movement of premature babies, a few possibilities exist. Biocompatible on-skin electrodes seem to be a development that will benefit systems for premature babies greatly. Within this project, however, a novel setup can create an opportunity for devices to use currently existing dry electrodes to be used on these babies already.

As shown earlier, the signals measured by the electrode need to be acquired and processed. The chips used to provide parts that can process the signals cannot be made from soft materials since those normally have a low computational performance [33]. This means an integrated device needs to be created with a hard chip but soft materials for the electrodes.

Multiple options exist for electrode type and material. Current clinical practice would suggest using the

standard Ag/AgCl electrodes, but during development, dry electrodes should be considered as well to take into account the biological requirements of premature babies.

2.5.5. NICU

Premature babies often lie in the Neonatal Intensive Care Unit (NICU). An analysis of this environment has been done by Vitale, Chirico and Lentini [50] with the aim of reducing unwanted sensory stimulation. Premature babies in this environment are already monitored for multiple biological signals. Creating wireless devices is often done to reduce clumsy and restrictive wiring while increasing patient mobility and creating the possibility of controlling and monitoring several devices from one monitor [51]. Wireless EOGs have already been developed. In the study of Debbarma et al. [44], a low energy Bluetooth module was used. Wu et al. [34] used a consumer wireless recording device and Heo et al. [40] achieved transmission through a Bluetooth 2.0 module. A device to record the eye movement of premature babies should therefore preferably be made wireless as well.

A proper examination of current practice within the NICU is necessary to create a device that can measure the eye movement of premature babies without interrupting or being interrupted by other processes. An example of such a high-impact process that takes place in the NICU is the treatment for jaundice. Even in full-term newborns, jaundice occurs in as many as 30-50% [52]. Preterm infants have an even higher risk of this and other liver-related complications, due to the immaturity of the liver [53]. Jaundice in preterm babies is often treated by using phototherapy in which the eyes are covered with a mask to protect them from the light exposure [54]. The use of this mask potentially greatly influences the possibilities for a device that tracks eye movement. During field research, more specific requirements on the procedures and environment for premature babies are found.

3

Project Approach

As the literature research has shown, a device tracking eye movement of premature babies is desirable. To develop such a device, multiple steps need to be taken. A design cycle creates a framework for such a project that can lead to a promising design, which is feasible and desirable. The design cycle roughly portraying this project documented in this report is shown in Figure 3.1.

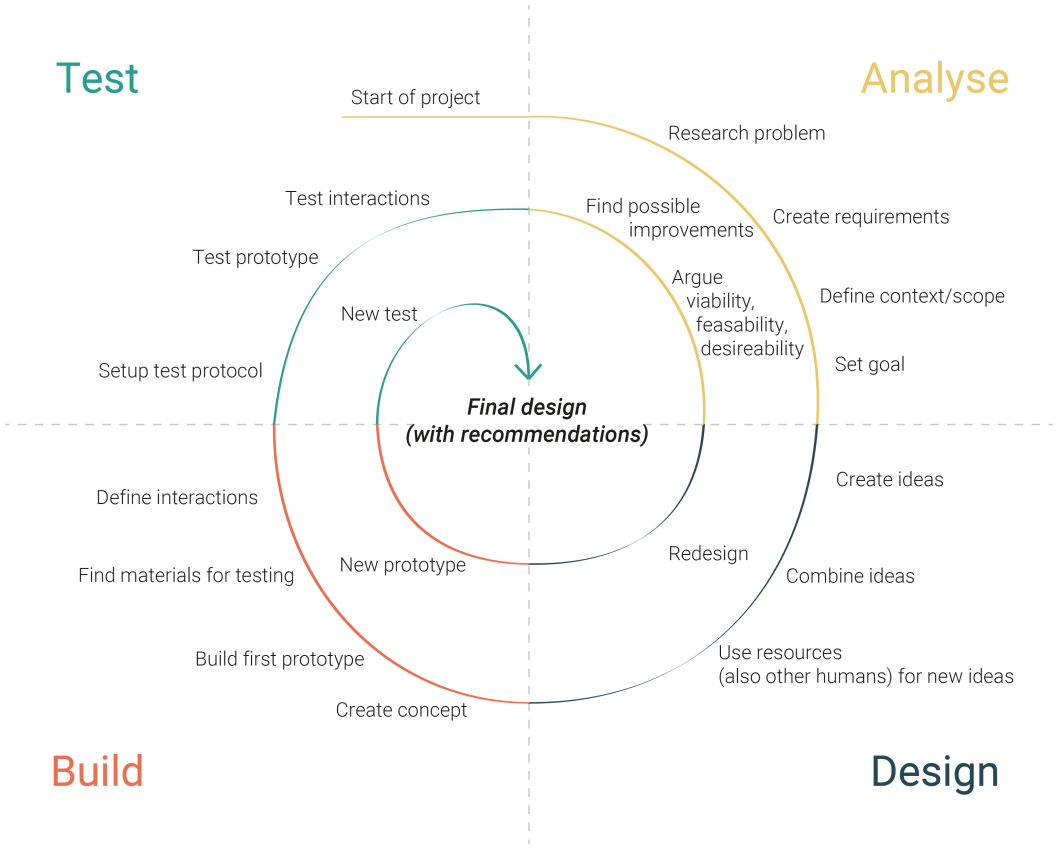


Figure 3.1: Design cycle for a development project of a device created to follow as an approach for this thesis

This cycle is a general representation that could be applied to the development of any device, but always consists of four phases; Analyse, Design, Build and Test [55]. For this project specific, in the Analyse phase different kinds of research were done. This research consisted of literature research and field research. Findings from the research help create a solid base for the desirability of the device. A design goal can be set by finding the problems or missing knowledge within a specific scope or context,

which in this case is about monitoring sleep in premature babies. The research also helps formulate requirements and wishes for the device.

The problem or problems that need to be solved have now been identified and a solid setup for the design phase of this cycle is finished. In the Design phase, ideas are created and combined which leads to creating a concept. By generating multiple ideas which are compared, a better argumentation is created for the chosen concept. Using input from other people and sources will increase the variety of ideas, increasing the likeliness of a thought-out concept. By using existing knowledge as a foundation for ideation, the feasibility of the design is increased.

During the Build phase, it is important to expand on a concept in a way that it becomes suitable for a test phase. Often this is done using prototypes or models. These can also be theoretical or technical models. Within this project, different ways of showing the idea are used, including visualisations and prototyping. By fulfilling a build phase, the ease of communication about a design increases.

The Test phase then verifies whether a concept fulfils the requirements and goal that were already determined in the earlier phases of the cycle. Verifying the design within this test phase and possibly implementing or identifying improvements strengthens its feasibility. Tests could be done with physical prototypes, but they can also be tested within theoretical frameworks, by applying modelling, scientific reasoning or expert validation. For this project, these latter three are mainly used.

This cycle can be followed multiple times, or small iterations can be done during one of the steps in the cycle. This leads to a final design including recommendations for further development or testing.

4

Field research

To complement the literature research and create a solid foundation for the creation of a device that can monitor eye movement of premature babies, field research was necessary. Different kinds of field research have been performed to include all stakeholders in this project. When developing a product or system, it is important to take all stakeholders into account [56]. A stakeholder overview has been created for this project which can be seen in Figure 4.1.

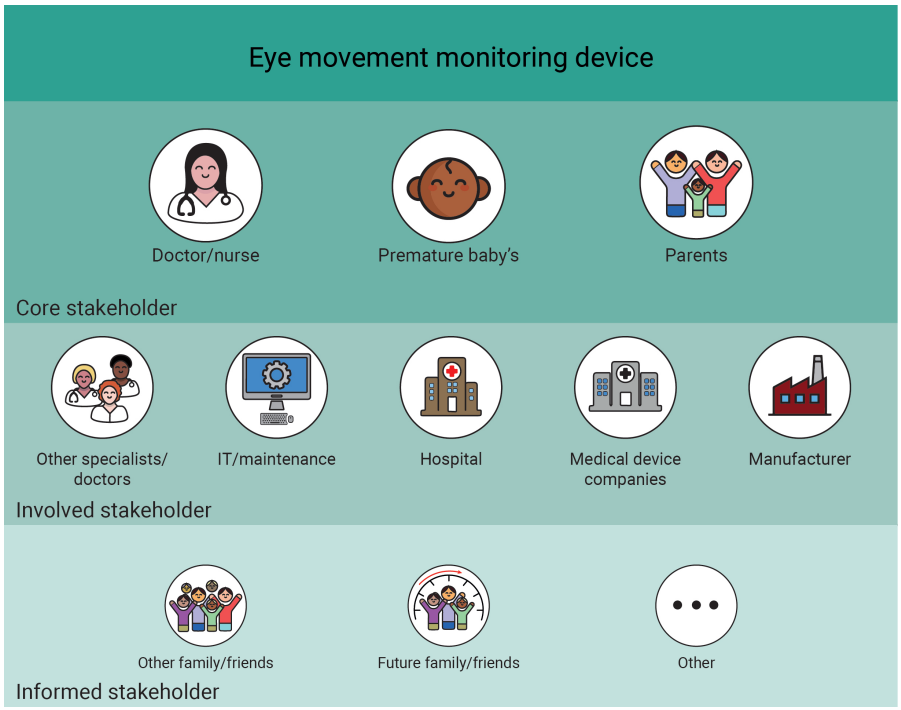


Figure 4.1: Stakeholder overview

Stakeholders can be categorized in different ways. For example, when building a product, the stakeholders could be identified as the customer or users, the industries or markets, the suppliers and the investors [57]. For this project, however, it was chosen to split the stakeholders into the core stakeholders, the involved stakeholders and the informed stakeholders. Core stakeholders would be directly impacted by this device and its use. Involved stakeholders are impacted but indirectly and involved stakeholders only experience minimal impact and mostly simply get updated about the device. For the earlier stages of development of a device, the core stakeholders are most important to keep in mind. The three core stakeholders within this project are the patients on whom the system will be used, thus premature babies, the parents of those babies and the users of the device, thus the doctors, nurses

and some other staff on the NICU floor. Each of these stakeholders will be taken into account using different approaches, which will be elaborated throughout this chapter.

4.1. Survey

To include parents who are part of the core stakeholders of an eye monitoring device for premature babies, a survey was conducted. The purpose of the survey was to understand how parents would want to be able to interact with the system and what influence the system can have on their emotions. The survey and responses can be found in appendices B and C respectively. Some important findings can be derived from these answers. The answers to the statements were divided for some topics but were not for others. The answers have been represented in graphs in Figure 4.2. To the statement 'Whenever possible, I want to be involved in actions concerning the devices around my baby.', different kinds of answers have been given, implicating that if a new device is developed, the actions or involvement of non-medical personnel needs to be taken into account. Ideally, for these parents, all devices would be developed in a way that they could contribute during their use, but they are not necessary for the use, since not all parents want to be involved. More importantly, when looking at the statement 'I want to be able to see the values measured on my baby by myself.', most respondents agreed at least to some degree. This means that the output of any new system should not be incorporated within the system itself, but should be an actual output that is shared with parents, or with medical personnel who could in turn share that output with the parents.

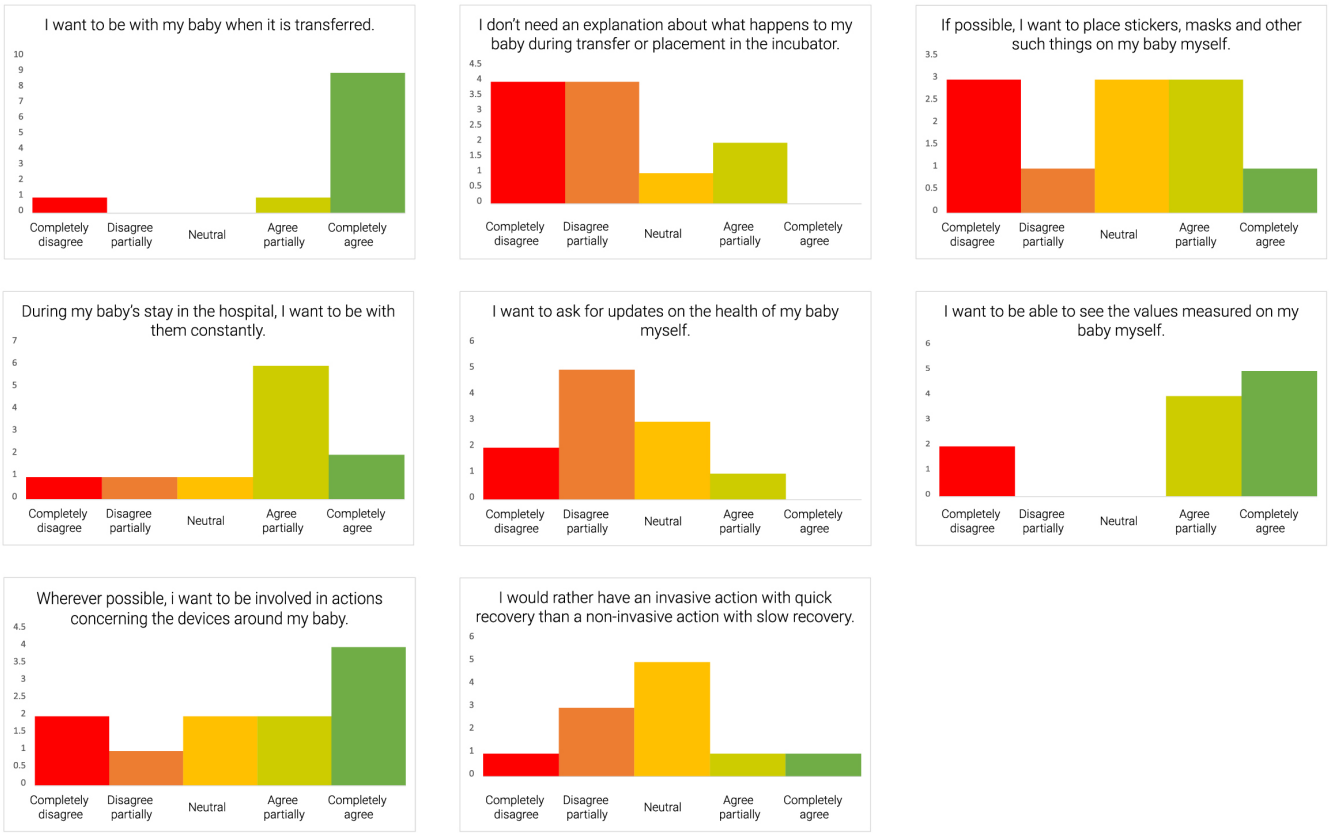


Figure 4.2: Responses to statements in the survey for parents

In Figure 4.3, the answers of the parents who have responded with the answer 'Yes' to the question 'Has your child been admitted to the hospital in the first 10 weeks of after birth?' are shown. Interestingly, these parents seem to tend to answer the statements concerning involvement with an answer that would increase their involvement and knowledge. This slight shift in answers compared to the complete pool of answers could indicate that when actually being in the situation, the need for involvement and

knowledge grows compared to when thinking about it rather theoretically. This only strengthens the idea that when a new device is developed, the use of it should be as simple as possible to create opportunities for the parents to be involved and the output should be something that can be shared with those parents.

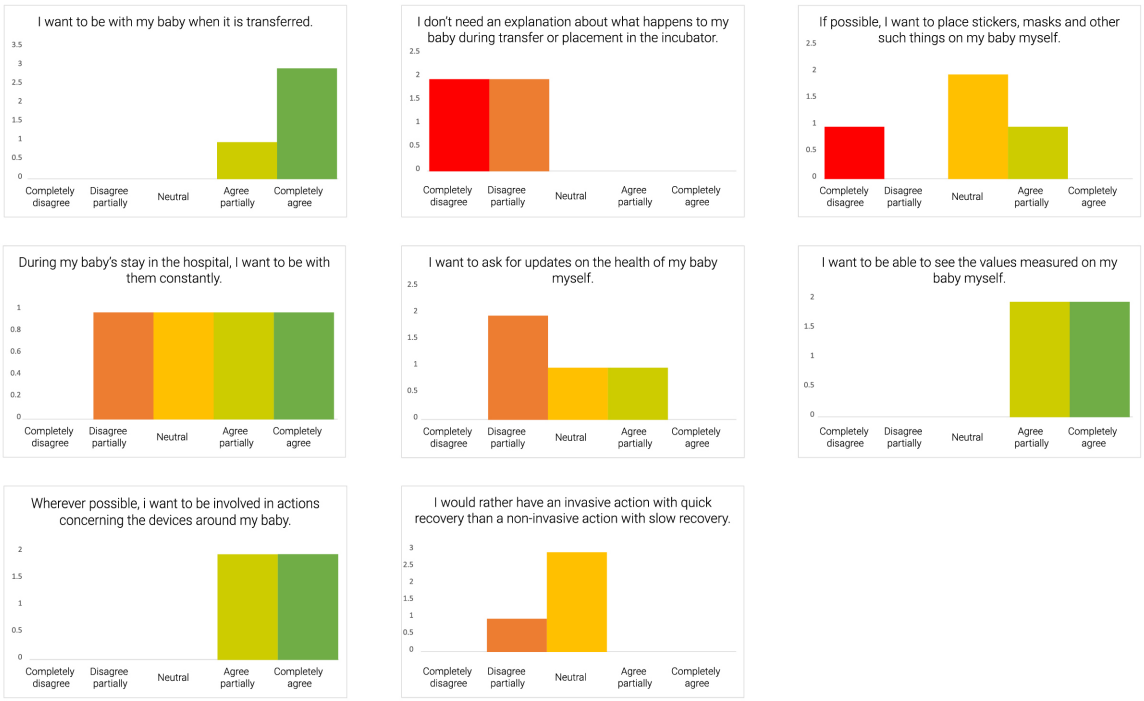


Figure 4.3: Responses to statements in the survey for parents who have had a child admitted to the hospital within 10 weeks after birth

Some of the remarks that were given on the other questions in the survey showed that they want to be informed, but prioritize the baby's health. For example, most of the respondents indicate that they would like regular updates on their baby, except when there is a big change in the situation. In that case they want to be informed immediately. This regular interval of updates is specifically described by some as needing to be at least once a day. A new device or system should therefore also provide information to show a status when asked and show whether a situation changes or not. This would also mean that it can not just give a number or status of that moment, it would need to show the history of measurements as well. This finding is especially important when designing the output interface.

In Figure 4.4, the answers concerning the most bothersome aspect of this situation are portrayed. The most given answer was that the feeling of not being able to change the situation is the worst part. Fortunately, medicine and advances in technology have an increasing influence on the survival rate of premature babies. By creating technology that is understandable and interpretable for the parents, this feeling of powerlessness might decrease.

4.2. Interviews

After this, an interview was conducted. The participant was a mother of a child who had been born roughly a month before the interview and had to be admitted to the NICU due to a need for phototherapy. Even though the reason for the baby being admitted to the NICU was not premature birth, it was assumed that the experiences of a parent of any baby that lies in the NICU can give a general insight into this circumstance. This interview intended to get a better idea of what happens when the baby is in the NICU and how a parent would feel about different parts of that process. Furthermore, some topics were discussed concerning the type, format and content of information that was given and some early insights were obtained on the project from a parent's perspective.

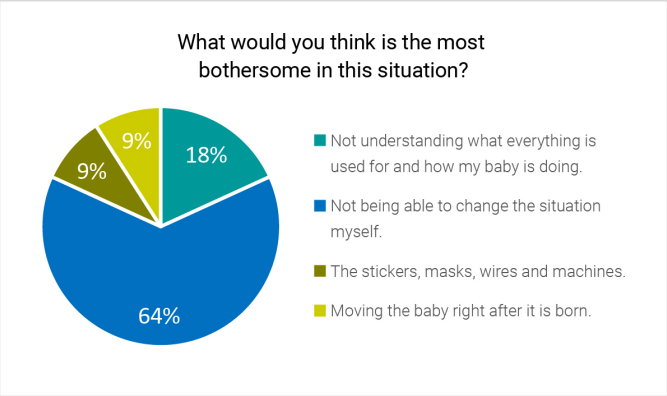


Figure 4.4: Answers to the survey on the question ”What would you think is the most bothersome in this situation?”

From this interview, some interesting findings can be noted. First of all, the respondent noted that information like whether the baby is asleep or not is to some more valuable than the more factual data like heartbeat since sleep is a phenomenon that is linked to rest. If the baby sleeps well, a parent would feel that the baby is not under any stress, which would in turn make the parent feel better. This shows that, besides the earlier mentioned clinical advantages of monitoring sleep, there are also advantages in how the state of the baby is perceived by non-medical parties.

Another conclusion from the interview is that the way the information is portrayed for non-medical parties such as parents or family members is very important. For example, the respondent pointed out that graphs with thresholds are more understandable for them compared to numbers, since they also show whether or not a variable is changing and if it is in the desired range.

During the interview, it was also mentioned that touching the baby is allowed, but touching the bare skin of the body is not preferred. Rather touching the head of the baby or any clothing is advised. Handling the baby for example to change a diaper or give a bottle of milk is sometimes allowed, but everything is always discussed and if necessary done together with the nurse. A device that monitors the sleep of a baby will rarely pose a threat to the health of the baby when misplaced or not functioning properly. Nevertheless, parents touching the device should be taken into account and any risks should be considered.

4.3. Observation NICU

Besides the literature research that was conducted on some of the needs and requirements of premature babies, an analysis of the environment in which they lay was done to create a better understanding of the devices, interruptions and workflow that would affect the use of the device that would measure eye movement. This analysis was done over the course of two visits to the NICU and some small interviews with employees of the department.

During the first visit, a baby was born at 25 WoGA, meaning he was born extremely premature. This created the opportunity to observe the steps taken right after birth. Besides the general steps outlined in for example protocols, this observation allowed looking at details that might matter for the development of a new device. During this visit, the following observations important observations were made:

- The baby is usually put on its back with the head straight up for the first 72 hours after birth.
- After the first 72 hours, the baby is normally placed on their belly with their face to the side.
- The first step is always to establish oxygenation.
- Stickers or adhesives are not used on extremely premature babies in the first few days of their lives, instead, a bonnet is placed to which for example a breathing device can be attached using a specific type of velcro.

- A phototherapy mask is never placed right away. It is normally placed after an estimated 24 hours, because of the lack of functioning of the baby's liver. The mother has preserved the breakdown of bilirubin in the baby, but after birth, the premature baby's liver often does not perform well enough.
- Sometimes, the ventilator uses a setting called HFO, which sometimes causes slight shaking of the table and therefore of the baby.
- Some problems that seem to exist are the pressure on the cheeks of the baby caused by the straps that keep the Nasal Continuous Positive Airway Pressure (nCPAP) device in place and the fact that the cap to which the nCPAP device is attached needs to be moved or removed for the application of multiple different devices.

In another visit, more in-depth information was obtained about the steps after birth during interviews with two staff members of the NICU floor. Important findings of this visit were:

- The first steps to take are always to clear the airway and place a saturation sensor. Babies born before 32 WoGA almost always need respiratory support. Most of the babies, approximately 9 out of 10, do not need invasive ventilation but only non-invasive respiratory support. This is often given using the nCPAP, but can also be done using NIPPV.
- The currently used head cap needs to be placed in a certain direction.
- The nurses are always the ones handling the devices, but some parents do help, or move small parts if they feel they should.
- Sleep is an easy-to-grasp concept, which is also nice for parents.
- Devices to take into account are the near-infrared spectroscopy (NIRS) sensor, EEG sensors, and photo-therapy mask.
- Pressure spots on the skin are a huge problem.
- Ears should not be covered because of dirt that gathers behind them.
- Babies often seem to sleep especially when they lie with their parents, which is called kangaroo care or skin-to-skin care.
- A lot of wires, tubes and more are already present and get tangled easily.

For the field research, a package of materials that is ready for use when a baby is born prematurely was analysed. This package can be seen in Figure 4.5. The package mostly contains materials that are used for the installation of the nCPAP machine, highlighting the importance of getting this device installed first. Analysing the materials gave a better understanding of what steps are currently taken when a baby is born prematurely.

Figure 4.5: Package with materials for when a baby is born prematurely

The bonnets that are placed on the heads of babies that are attached to the nCPAP device come in different sizes that are dependent on head circumference. This is why a measuring string is included in the package, with which the head circumference can be measured and therefore the right bonnet can be chosen. A choice needs to be made for the use of a mask or a prong. According to the staff of the NICU, the babies often respond worse to the prong, so a preference exists for using a mask. Both when using a prong and when using a mask, the attachment is held in place by two straps, that have a special type of velcro on their endings that adheres to the bonnet. The tube attached to the mask or prong has to be secured, which is done with a strap on top of the head. If the angle of the mask causes it to lift slightly up, the breathing support might not work optimally, which is when a foam triangle is used below the strap on top of the head, to lift the tube and change the angle of the mask. To get a better understanding of these steps, they were performed on a baby doll. In Figure 4.6 this setup is shown, which also gives a better view of the final situation when all steps are completed.

Figure 4.6: Result of reenactment of steps taken for nCPAP instalment right after premature birth of baby

4.4. Protocols

Within the setting in which these babies lie, multiple protocols are applicable, including national and hospital guidelines. These protocols largely determine which steps need to be taken to ensure the baby's safety and prioritize the right devices or procedures. Within the UMCU, these protocols are stored in one place. Analysing them creates a full overview of what steps are supposed to be taken according to the national guidelines and how they are specified within the hospital, therefore indicating clearly what steps and devices need to be taken into account in the development of an eye-movement monitoring device.

The specific protocols that were used were:

- Landelijke aanbeveling: Extreme prematuur (R. Knol, R.F. Kornelisse en A.A. Kroon (Erasmus MC-Sophia))
  National recommendation Extreme premature
- Verpleegkundig Protocol - Extreem prematuur, assisteren bij de opvang na de geboorte (UMCU)
  Nursing protocol - Extreme premature, assist at care after birth
- Verpleegkundig Protocol - Extreem prematuur, verzorging (UMCU)
  Nursing protocol, Extreme premature, care
- Zorgpad premature patiënt (AD < 32 weken): medisch (UMCU)
  Care path premature patient (AD < 32 weeks): medical
- Verpleegkundig Protocol - nCPAP/nIPPV met behulp van een Neojetsysteem aan de Leoniplus, aansluiten en verzorging bij pasgeborenen (UMCU)
  Nursing protocol - nCPAP/nIPPV with help of Neojetsystem on Leoniplus, installation and care for newborns
- Verpleegkundig Protocol - NIRS en Bedbase registratie bij pasgeborenen, aansluiten van (UMCU)
  Nursing protocol - NIRS and Bedbase registration for newborns, installation
- Verpleegkundig Protocol - Fototherapie, verplegen van een pasgeborene met behulp van een lamp (UMCU)

Nursing protocol - Phototherapy, nursing a newborn with the help of a lamp

- Protocol ongeconjugeerde hyperbilirubinemia (UMCU)
  Protocol unconjugated hyperbilirubinemia
- Verpleegkundig Protocol - aEEG monitor (CFM) bij pasgeborenen, aansluiten van (UMCU)
  Nursing protocol - aEEG monitor (CFM) for newborns, installation

4.5. Scenario

Using the protocols, observation and interviews, a scenario for the birth of premature babies within the UMCU was created. This scenario is portrayed in Figure 4.8 on Page 24. Visualising a scenario can be helpful to determine which parts of the process have crucial requirements, but also which steps could be improved upon.

From this scenario, it can be seen that multiple devices are attached to the head or face, which influences the placement of a device that uses EOG and could also influence the performance of such a device. The main parts important to take into account are the use of the bonnet for the breathing device, the breathing device itself, a NIRS sensor, possibly EEG electrodes, a phototherapy mask and the use of an echo device, which are portrayed in Steps 3a, 3b, 12 and 14.

Within this scenario, some steps are also more time-sensitive than others. During an interview, it was highlighted that clearing the airway, installing the breathing support device and installing a saturation meter, which happens in Steps 3 to 5, always take priority and need to happen carefully, but quickly.

Furthermore, it can be noted that the placement of any devices on the head after the placement of a breathing support device, as shown in Step 12 is somewhat devious. This step can be divided into 3 steps which are portrayed in Figure 4.7. A previously placed bonnet needs to be removed or repositioned before any other devices can be placed on the head. Similarly, when trying to make an echo of the head, as in Step 14, the bonnet needs to be pulled forward to reach the skin. In the current setup, this way of working is necessary, because the placement of the breathing support device takes priority over the placement of any other devices.

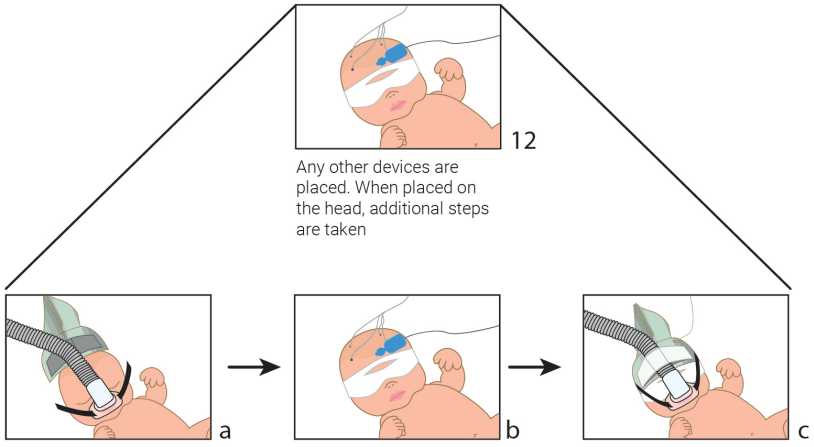


Figure 4.7: Step 12 of the scenario, visualised in smaller steps

The field research, which was a combination of interviews, surveys, observations and analysis of documents, has led to a scenario, which is an overview of current practice, portraying what happens when a baby is born prematurely. This creates an opportunity to identify requirements and wishes for a new device, which is in this case a device that monitors the eye movement of these babies.

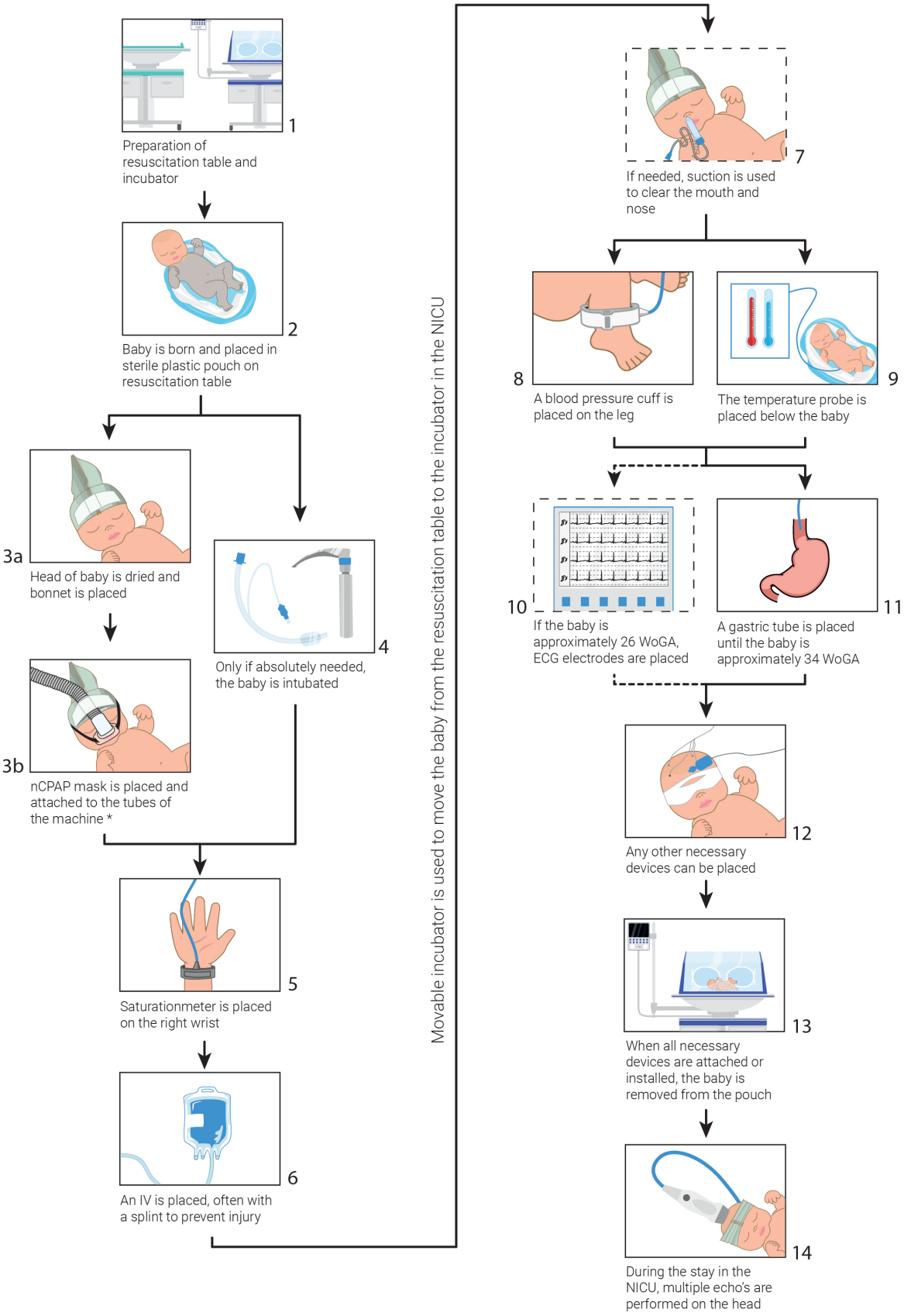


Figure 4.8: Scenario portraying steps taken after the birth of a premature baby
*Different types of breathing support exist and are used. Within the UMCU this is often the nCPAP or nIPPV, which are both part of the Neojet system that is attached to the Leoniplus monitoring device

5

Requirements and wishes

Conducting the necessary literature and field research has led to a list of requirements and wishes that would need to be fulfilled to create a device that takes the core stakeholders, the goal of the device and the context in which it is placed into account. These requirements and wishes are the initial ones, necessary to create a first technical concept, after which verification and further development would create a more elaborate list. This list is portrayed below.

5.1. Requirements

For the requirements, it was chosen to focus on three categories, which are functional, patient-specific and context-specific requirements. Requirements could also be drawn up concerning for example storage or manufacturing, but for the first development stage of this device, the three chosen categories are the most important.

Functional:

- Has to obtain an EOG signal that can be read by medical professionals
- Has to be able to measure signals between 0.1 Hz and 6.2 Hz (these values have later been determined to be the filter frequencies of a standard EOG device [58])
- Has to be able to sense an EOG signal for 48 hours

Patient-specific:

- Has to be suitable for head circumferences between 21 and 33 cm (these are the measurements that currently used bonnets are suitable for)
- Has to be able to place the sensors in the right position relative to the eye for premature babies
- Should not require a different head position than positions the baby is currently put into, which include: lying on the back, face up and lying on their belly, face to the side
- Cannot have any adhesive touching the skin of the patient
- Should not need conductive gel touching the skin of the patient

Context-specific:

- Cannot delay the time before a patient is given any breathing support (e.g. nCPAP device or ventilation)
- Has to be usable on a patient for which any or multiple of the following are also in use:
  - breathing support device (at least the Neojet nCPAP device)
  - IV in the arm, foot or through the belly button

  - NIRS sensor
  - EEG electrodes
  - ECG electrodes
  - Photo-therapy mask

5.2. Wishes

Some wishes exist for the development of this device, which would create a product that satisfies the needs of the users. The following were directly obtained from the literature research and field research that was done.

- Should be installable with as few actions as possible
- Should be easy to use for any NICU staff
- Should have a signal-to-noise ratio that allows for reliable analysis of the output by an expert user, ideally this ratio is optimized to make this analysis as easy as possible
- Should fit the heads of babies from 28 to 40 WoGA that fit between the 3rd and 97th percentile, thus heads with a circumference from 23.0 cm to 38.5 cm [59].
- Is wireless
- Is reusable

6

Development

6.1. Ideation

To start the development of a device that can monitor the eye movement of premature babies, an ideation phase took place.

A design method called How-Tos was used to split the problem that this device should solve into multiple parts [60]. By formulating these different problem statements as questions, early ideation can be stimulated. Addressing the different problems in a broader sense will allow the participants of the session to answer the questions freely. This avoids a constricted vision and will allow for more ideas to be generated. A How-Tos session can be done individually or in groups, depending on the involved parties in the project. All participants should however have a basic understanding of the problem statements. The questions that were chosen for this session were:

1. How can you track eye movement? *This question was mostly answered by literature research*
2. How can you attach something to the skin?
3. How can you conduct signals?
4. How can you keep something in one place?

These questions were based on the obstacles that exist for creating a device now or obtaining a regular EOG from a premature baby. The list below entails the most promising answers of this session.

1. How can you track eye movement?
    - The literature research had already pointed out that for this specific context, EOG is the most promising method for eye-movement tracking.
2. How can you attach something to the skin?
    - The fragility of a premature baby's skin eliminated a lot of ideas, leaving two options: directly applied pressure or created pressure by a wrap around the item that is to be attached to something.
3. How can you conduct signals?
    - The information needed to answer this question was already laid out in literature research, by looking at the different categories of electrodes. The answer suitable for this specific context would be the use of dry electrodes which make use of a small layer of naturally occurring moisture.
4. How can you keep something in one place?
    - The answers that fulfil the requirements, again keeping in mind the fragility of the skin, all use some type of pressure. Some specific ideas were:
        - A cap

- A band (or bandage)
- A clamp

During an ideation session with some nurses from the NICU floor, some of the areas on the baby's head that are already occupied or influenced by other devices were identified. This was done with the help of a baby doll on which the areas were pointed out. Similarly to the procedure done during the field research, the nCPAP device was installed again to see which parts of the head were occupied by this device. Marking all the areas on the head resulted in the visual representation shown in Figure 6.1. This creates a better overview of which parts of the head need to be taken into consideration, but also which are still available to possibly place parts of the new device on. Some additional comments on the available space on the head were given as well. Especially the fontanel and the cranial sutures require careful consideration. The fontanel is relatively large and the cranial sutures are not closed to account for the growth of the baby, meaning these parts of the skull should be avoided [61]. Furthermore, the aim of an EEG often determines the amount of EEG electrodes that are necessary, which means that the black dots merely represent the fact that these need to be taken into account [62].

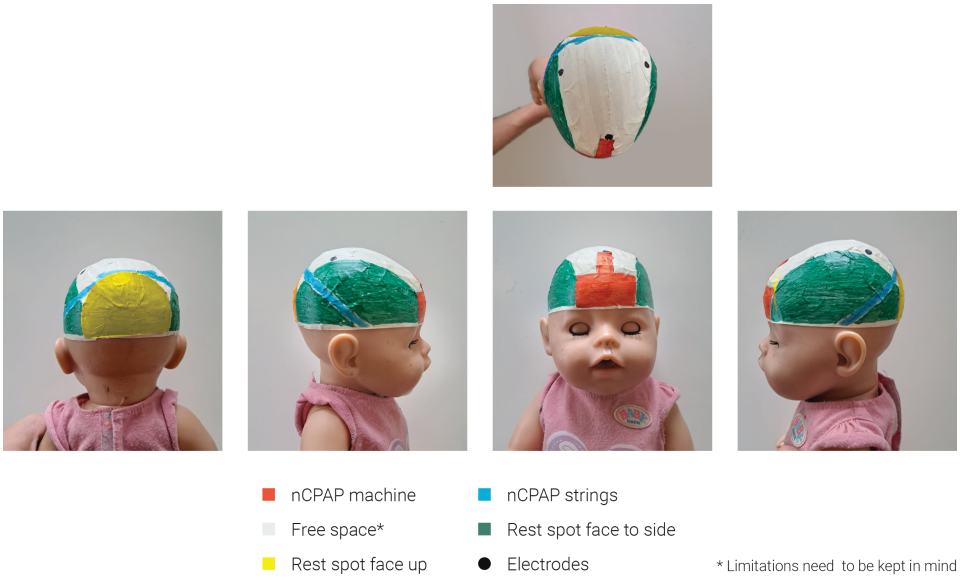


Figure 6.1: Visual representation of occupied areas on the head of a premature baby

From this session, some answers were chosen that would be able to fulfil the earlier mentioned requirements and could be combined to form ideas for the device. Individual as well as cooperative ideation sessions were held. As a basis for these ideation sessions, some heads were drawn and printed on which drawings could be made as a starting point. The sketches can be found in appendix D. By using the same types of heads as the ones on which the different possibilities for electrode placement were portrayed, it was possible to think of concepts that would be able to keep those electrodes in place, while keeping the features of the face in mind. During these sessions, the placement of electrodes for both vertical and horizontal movement was kept in mind.

During these ideation sessions, both the requirements and the created scenario were kept in mind which created some drawings and ideas for the setup of this device. For a lot of the ideas, however, the main problem that would occur is the installation time. This is why it was chosen to create the device as two separate parts as will be explained below.

6.2. Division of device

One of the requirements that was laid out earlier pointed out that the amount of time it takes to get to the step where a breathing device is installed should not become longer because of the use of this new device. This requirement created an obstacle during ideation since EOG electrodes need to be placed on the face, which is hard to reach when the breathing device is already installed. This has led to the idea of creating a device that has two parts: a shell, which is the part that will be placed on the

patient's head without any device yet attached or active, and an electronics module, which will include the electrodes and the electronic parts that need to be installed or attached to start the measurement. Within the earlier shown scenario, the placement of the shell would replace the placement of the bonnet. To fulfil the requirement, the placement of this shell should therefore not take any longer than the placement of the bonnet. Consequently, the shell that is made needs to take over the function of the bonnet, which is keeping the nCPAP device in place. This idea can be applied to most of the earlier created ideas, but it needs to be taken into account that the electronics part needs to be attachable to the shell after the nCPAP device is placed. This is why some further development of both these parts was still required.

6.3. Shell development

For shell development, 3D physical models were created. The earlier mentioned baby doll was used to test different shapes. These shapes were mostly derived from earlier ideation while trying to cover the places on which electrodes are placed and keeping the earlier identified areas of the head in mind. By creating 3D physical models, a better understanding of the complex shape of the head is gained while a feel for the different materials is developed. The designs that were created can be split into three categories that are shown in Figure 6.2. They are either shaped like a bonnet or form a web-like structure or are like an adjusted headband. More pictures of the models can be found in Appendix E. Since the placement of the shell happens before the placement of the nCPAP device and replaces the currently used nCPAP bonnet, it needs to cover the functionality of the nCPAP bonnet. This means that using a similar material and shape as those of the original bonnet provides a benefit in the ease of use of the shell.

(a) Bonnet-based design idea (b) Web-based design idea (c) Mask or headband-based design idea

Figure 6.2: Measurements of bonnet prototype

Some of the currently used devices for babies also use some type of hardcovers to protect parts of the baby. For example, the Infant EarCup™ by Sanibel™ is a see-through hard shell that is placed over the ears of the baby. By creating a 3D physical model, it could be determined if additional features such as those hardcovers would be needed for the shell itself to stay in place. Adding this to the bonnet however would take away a big part of its adaptability, and would increase the risk of pressure points which could damage the skin of the baby. It was therefore determined that creating a shell that does not require hard materials is better.

To further develop the idea for the shells, other choices need to be made as well. One important aspect of the shell is the type of material that is used. Since the shells need to keep the electrodes in place, as well as the breathing device, the shell should be placed tightly on the head. This does however come with a limitation. The skull of a baby is not fully formed yet, meaning it is still very malleable [61]. Any pressure on the head can therefore lead to both reversible and irreversible distortions. A balance needs to be found between creating a bonnet that keeps devices in place and that keeps the pressure on the skull as low as possible. To create a tight fit without exerting too much pressure, a material with stretch should be used. As was already explained in Chapter 2, Literature Research, the skin of premature babies is very fragile, which is why the material should also not aggravate the skin of the baby. This is why the first 3D physical models were made using materials that are currently already used in devices and applications for premature babies. The two materials that are already used and

contain enough stretch are the materials of the nCPAP bonnet and the material of the phototherapy mask. These were considered good options for the development of the shell.

The material of the phototherapy mask presents with similar stretch properties as the bonnet. The material is however a bit more coarse, meaning it is somewhat harder to shape for detailed applications and might create more friction on the skin. This friction does make sure that the fabric moves less but lead to the irritation of the skin. During the creation of the 3D physical models, the bonnet-like shapes were easier to make from the material of the nCPAP bonnet, whereas a web-like shape was easier to make with the phototherapy mask material. To be able to ensure the shell does not exert too much pressure on the head of the baby, while still providing support for the nCPAP device, the sizes could be related to the sizes of the nCPAP bonnet, meaning they are also related to the head circumference. The easiest way to ensure this is to take the same material as used for the bonnets. Its stretch percentage could be calculated using the following formula.

$$\frac{\text{(distance of material when stretched-distance of material unstretched)}}{\text{distance of material when unstretched}} * 100\% = \text{stretch percentage}$$

The stretch percentage of the nCPAP bonnet is 93.3%. The stretch percentage of the material used in the phototherapy mask is 100.0%, which is not very different from the nCPAP bonnet but could provide a different amount of support for the nCPAP device itself. For the final design, it was chosen to use the same material as currently present in the nCPAP device, ensuring safety and ease of handling.

Considering all findings during the creation of 3D physical models and keeping the requirements and wishes in mind, it was chosen to focus on the development of a specialized bonnet instead of a web-like shape. This ensures compatibility with other devices, such as the nCPAP device, which creates an additional advantage. During observation, one finding showed that the rubber part of the nCPAP mask or prong often pushes into the skin. Considering the higher friction this material creates, this would often damage the skin in that spot, which caused the NICU staff to place a piece of tissue between the material and the skin. Using a shell shaped like a bonnet, but pulled down further over the cheeks will already provide an additional protective layer for those points on the cheek on which the rubber part of the nCPAP mask is placed. This avoids damage to the skin without needing to place a separate protective material in an additional step. Furthermore, the steps within the scenario that was shown in Chapter 4, will differ the least when using this type of design, enhancing the ease of implementation. Specifically Steps 3a and 3b, the placement of the bonnet and nCPAP device, only differ in the fact that the bonnet is shaped differently, but the amount of time for placing the bonnet and ease of use are comparable, which was also stated as a requirement earlier on.

To be able to create a shell and ensure that the electrodes for the EOG are placed correctly, some adjustability needs to be enabled. Figure 6.3 portrays the distances that would need to be adjustable for the electrodes to fit different faces. The important distances to adapt are those that place the horizontal and vertical electrodes in the correct position relatively to the eyes. This placement can also be achieved by moving the electrodes relatively from each other and then repositioning the whole system.

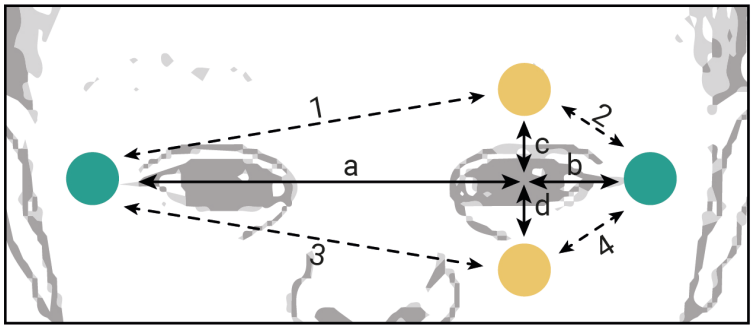
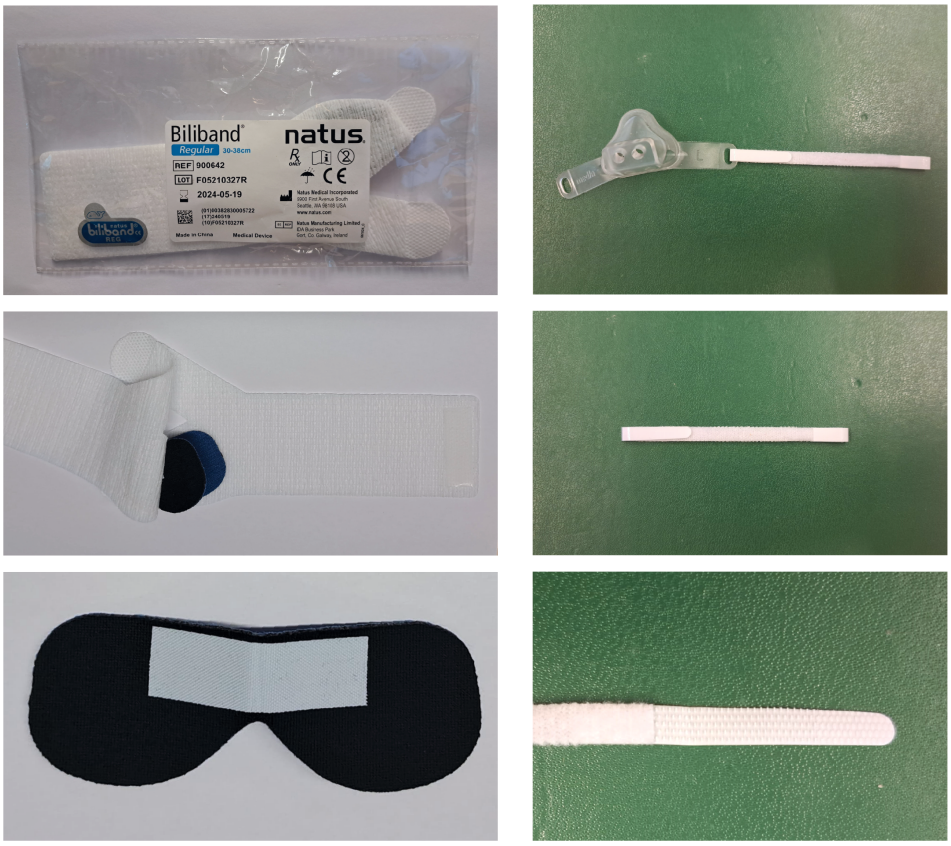


Figure 6.3: Distances between electrodes. Distance a and b need to be correct to place the horizontal electrodes and distance c and d to place the vertical electrodes. Within a shell, distances 1,2,3 and 4 could also be made adjustable to achieve the same amount of adaptability.

To create places on the shell that are adjustable, there needs to be a way to connect the material to itself at the places of adjustment. This can easily be achieved using the specific type of velcro that is currently already being used in some applications for premature babies, as was observed during the field research. The strings that are used to place the nCPAP device also use this velcro, showing that it attaches perfectly to the material of the bonnet. The blackout material that is on the inner side of the phototherapy mask is also attached to the headband using the same type of velcro, showing that it also attaches to this material perfectly. Figure 6.4a shows the velcro in the phototherapy mask, and Figure 6.4b shows the velcro in the strap of the nCPAP device.



(a) Velcro used in phototherapy mask of the Biliband ®

(b) Velcro used in straps for the nCPAP device

Figure 6.4: Current velcro applications

Using this velcro, different options for adjustability exist. Some of the options have been portrayed in Figure 6.5. However, when needing an additional piece of solid material, the chance of that piece being pushed onto the skin or creating some kind of damage or pressure on the skin is increased. This is why in the current design, material is just able to be stretched on top of each other without needing a ring or extra part. The last option in Figure 6.5 shows this configuration, enabling vertical and horizontal adjustment. Besides the adjustability to enable the electrode placement, it is also important that the initial configuration of the bonnet fits each baby, as the adjustment step only takes place after the placement of the nCPAP device. Again, this is to avoid creating a delay before the nCPAP device is in place. This means that the hole created surrounding the eyes should be set to maximum, with the straps already fastened.

Besides adjusting the shell to accommodate for the proper placement of the electrodes, the attachment of the electrodes to the bonnet is also important. Different methods of attachment were thought of, including buttonholes, straps or sacks. For the final concept, a special type of electrode combined with a placement ring could be used to attach the electrodes. The complete setup of this system is explained in Section 6.4.

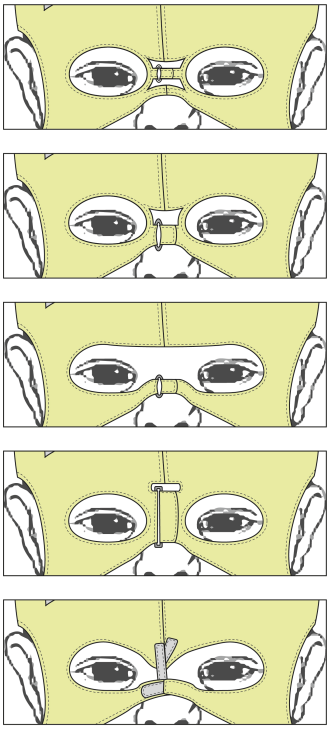


Figure 6.5: Exploration of options for adjustability

During field research, it was pointed out that the current nCPAP bonnet does not only need to be pulled up to accommodate the placement of certain devices or sensors, but it often also needs to be pulled down to create space for an echo. In the current bonnets, the width of the bonnet increases with the size of the bonnet. As explained before, the bonnet size is dependent on head circumference. The height of the bonnets however does not show any relation to the bonnet size and therefore is not dependent on head circumference. In Figure 6.6, the relation between these variables is portrayed. The data on which this graph is based can be found in Appendix F. A smaller height of the bonnet will create easier access to the top of the head for an echo. The staff of the NICU did point out that the material that covers the head helps keep the baby warm, so the material should still be able to fit over the head. The height of the bonnet should therefore keep the height of the head in mind to be able to cover it while being as short as possible to accommodate the echo better.

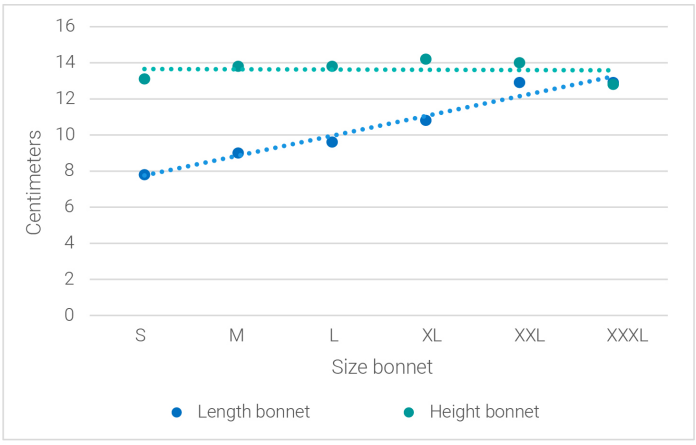


Figure 6.6: Width and height of nCPAP bonnet compared to size of bonnet

During the development of the final concept, different aspects needed to be kept in mind, mostly laid out in the earlier set of requirements and wishes. Final adaptations were made to accommodate for the requirement regarding other devices that need to be able to function or be used simultaneously with this device and thus while this specialized bonnet is used. In the bonnet, a window will be created that can provide ease of application of a NIRS sensor. Initially, an idea was created in which a small part of the bonnet was removed to create a place with exposed skin for the NIRS sensor. When developing a prototype, however, the limited space on the heads of the babies showed that this would not be possible. This is why a window is created in the shape of a slit along the edge of the large velcro strip that holds the nCPAP tube in place. The velcro strip is sturdier and does not stretch out as much as the material of the bonnet itself. This provides a more secure edge to the slit that can be folded open when placing the NIRS sensor. The edges of the slit will slightly overlap, using the earlier mentioned special type of velcro to make sure it closes. By using velcro, and not for example a button or zipper, any wire necessary for the NIRS sensor can protrude the bonnet at the desired place on the slit. The slit is placed on the outer side of the velcro strip, to ensure that the nCPAP device does not need to be removed to be able to open up the window. The slit exists on both sides of the head since the NIRS sensor can be placed on both sides as well. When the bonnet is first placed on the head, the slits are both closed. Just like the straps for adjustability are already in a predetermined position, the slits need to be closed so they do not need attention before the nCPAP device is placed. This avoids creating a delay in the placement of the device. The slit could also serve other purposes, like the placement of EEG electrodes or other devices, depending on their placement on the head. Figure 6.7 shows where this window would be placed and how it would roughly look when opened.

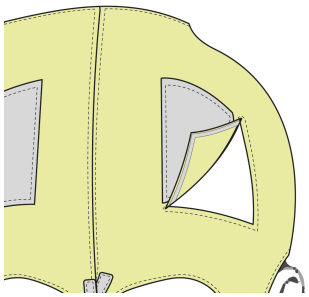
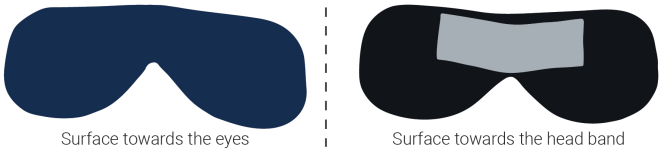
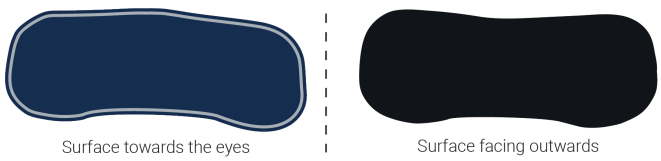


Figure 6.7: Window for placement of NIRS sensor and possibly other devices

The currently used phototherapy mask was also taken into account. Currently, the staff on the NICU floor often takes the part of the mask that actually blocks light and places it underneath the bonnet and the nCPAP tubes manually. Since the new specialized bonnet already extends past the eyes, a new shape of this blackout part of the mask can be created that has an edge of the same velcro that is used already for other parts of the bonnet, so it can simply be placed on top of the mask. This also removes the need for the headband to be used and prevents large movements or interruptions for the nCPAP. The change in the shape of the phototherapy blackout material is shown in Figure 6.8.



(a) Light-blocking material from currently used phototherapy mask



(b) Light-blocking material for new setup, no headband is required for this attachment

Figure 6.8: Redesign of phototherapy mask

To be able to test and help develop the different parts of the specialized bonnet that have been explained, a simple bonnet that fits an adult head was used. This bonnet is shown by itself and while worn by an adult in Figure 6.9. This bigger bonnet was made of a fabric with the same ratio of materials as the nCPAP bonnets, which are made of a material blend of 95% polyamid and 5% elastan [63]. The stretch percentage of the fabric for the prototype was 76.7%. The stretch percentage of the nCPAP bonnet was 93.3%, which means the prototype will show less stretch than the final design will.

Figure 6.9: Working prototype to test stretch properties and adjustability of bonnets

Using this model, characteristics such as adjustability were easier to understand and follow. By using the sizes of the currently used nCPAP bonnets, the relationship between head circumference could be determined. Finding a linear relation in these provides the possibility of determining the size of a bonnet for an adult-sized head. Figure 6.10 shows the sizes of the currently existing bonnets in relation to the head circumference they are meant for, including a linear trend line to determine what the size of the prototype bonnet needs to be. The data on which this graph was based can be found in Appendix F. It was chosen to look at the corresponding maximum head circumferences belonging to the sizes, in order for the prototype to be as tight as it would be on a baby. The person on which this model was used had a head circumference of 58cm, meaning the bonnet's width had to be 21.5 cm.

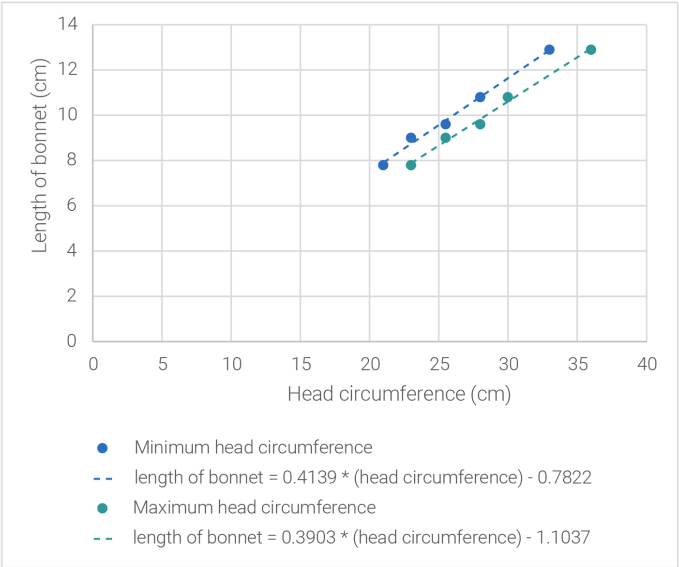


Figure 6.10: Head circumference in relation to length of bonnet, including trend line for linear relation

Further along in the development, a model that would fit the head of the baby doll was also made, including all features mentioned in this chapter. The only adaptation made was that the EOG in the prototype was created for the measurement of only horizontal eye movement. This prototype helped verify that the ideas are possible to put into a physical model and also made communication about the design easier. Figure 6.11 shows this model.

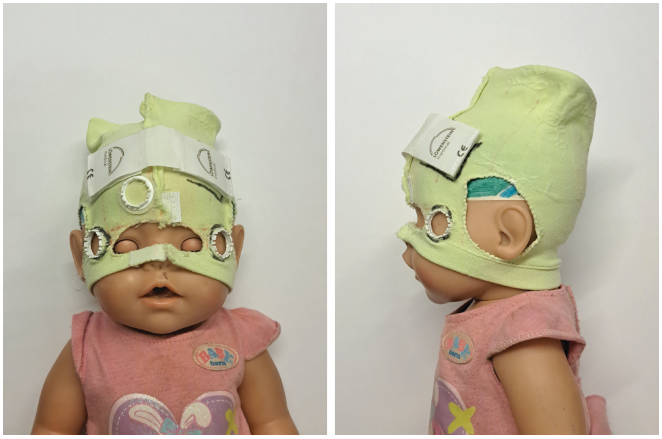
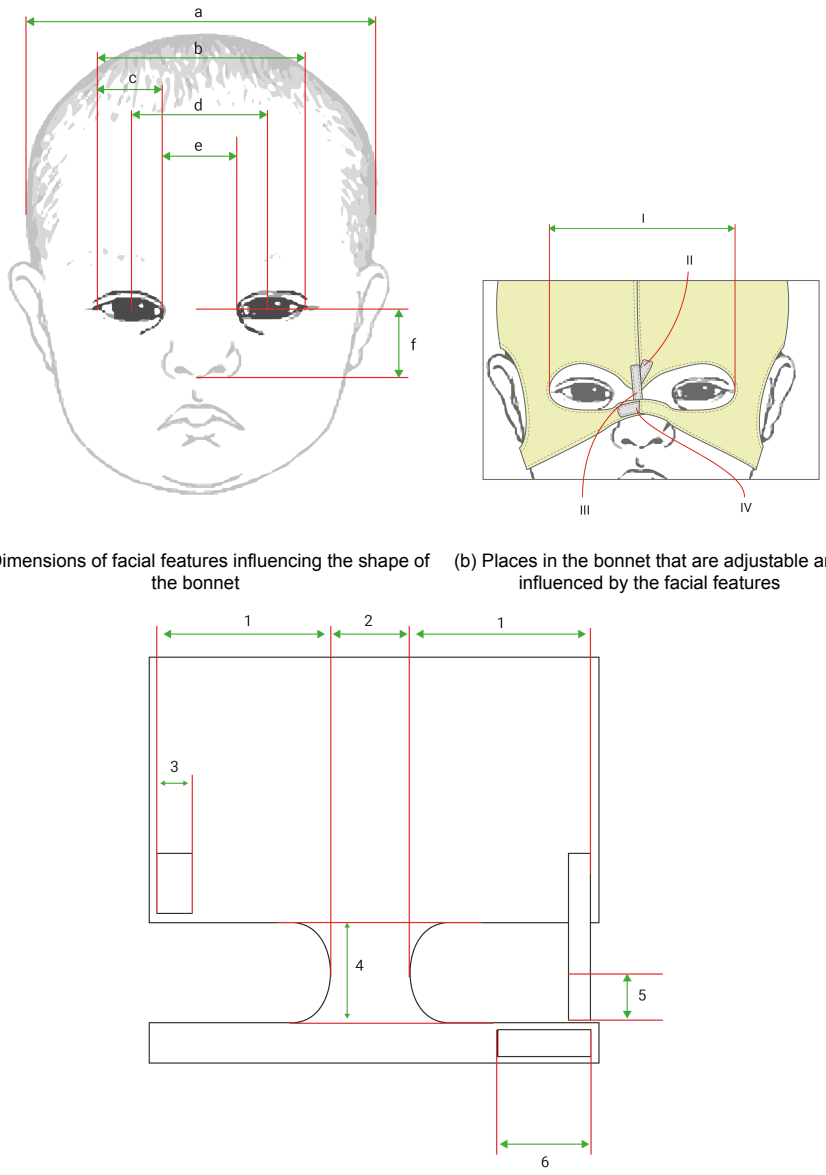


Figure 6.11: Prototype used to test ideas and ease communication about the ideas

The material needed to make the bonnet has a specific shape before assembling it. In Figure 6.12, this shape is shown, including the important measurements. For the measurements, the sizes that the shell needs to be able to adapt to are those of babies ranging from 28 to 40 WoGA. To make the different sizes of bonnet compatible with the differences in eye position and facial features, the adjustability of the shell needs to correspond to the size of the bonnet. An example design was created for a bonnet that would fit a baby that is born at 28 WoGA. Table 6.1 shows the dimensions needed to create the shape in Figure 6.12c. The tables showing all dimensions of Figures 6.12a, 6.12b and 6.12c can be found in Appendix G.

Table 6.1: Dimensions of the shape in Figure 6.12c, based on the sizes for a baby of 28 WoGA [59]

Dimension in Fig. 6.12c	**Related to this dimension in Fig. 6.12b**	**Related to this dimension in Fig. 6.12a**	**Value**
1	I	b	2.5 cm
2	I	a	≈ 21.8 cm
3	II	e	0.6 cm
4	n.a.	n.a.	1.5 cm
5	III	f	1.2 cm
6	IV	e	1.2 cm



(a) Dimensions of facial features influencing the shape of the bonnet

(b) Places in the bonnet that are adjustable and influenced by the facial features

(c) Shape of the bonnet before assembling, including specific dimensions

Figure 6.12: Measurements of facial features and adjustable parts that determine the shape of the bonnet before assembly

This specialized bonnet replaced the currently used bonnet that comes with the nCPAP device. Since the bonnet is adapted, not only to accommodate the EOG but also to tackle some of the more devious steps that need to be taken, some of the steps of the created scenario in Chapter 4 have now changed. This change in steps is shown in Figure 6.13.

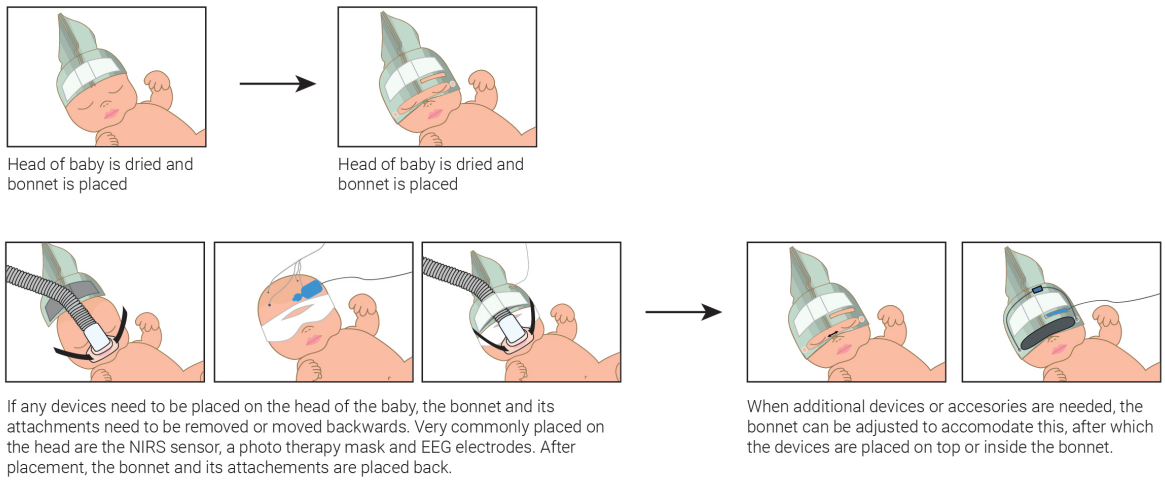


Figure 6.13: Steps of the scenario after premature birth that have changed with the new design

The final design and its features are laid out shortly again in Chapter 7.

6.4. Electronics development

6.4.1. EOG exploration

For some preliminary tests, a special module was obtained called the MaM Sense [58]. The MaM Sense is an all-in-one biomedical sensor including electrodes and a printed circuit board (PCB), that can be used to obtain three different types of electrophysiological signals, namely EOG, ECG and EMG. The board was created to be compatible with Arduino boards and signals can be read using an Arduino, but also using other tools like Excel. The device is not for use in medical settings, but rather focused on developers, for the purpose of prototyping or early testing, which makes the module perfect for this project. MaM High Tech provides a schematic of the PCB including specifications of the filters and amplifiers in the PCB. Figure 6.14 shows this configuration.

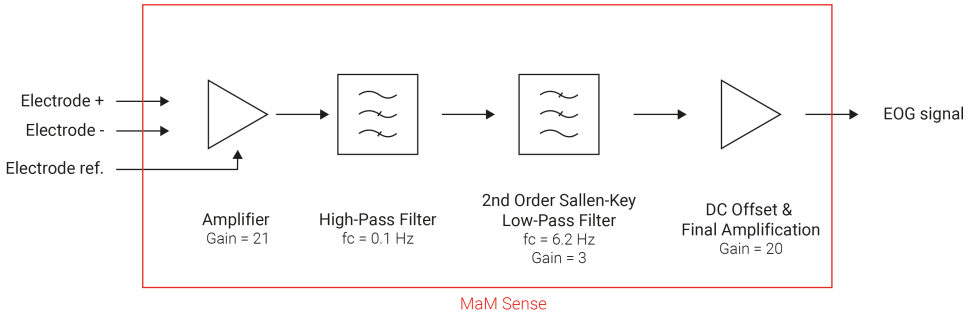


Figure 6.14: System block diagram of the PCB in the MaM Sense

Since this system has a rather simple interface and is a ready-to-use system, it is very useful for testing and prototyping. Some drawbacks that need to be taken into account are the fact that this system, when used to obtain an EOG, only uses two measuring electrodes, placed horizontally in line with the eyes, whereas earlier research showed that using 4 electrodes provides a more complete data set on eye movement. Besides this, the electrodes delivered with the MaM Sense are standard wet electrodes, with a gel and an adhesive to attach the electrodes. The tests performed were executed using these electrodes, but as mentioned before, in the final design concept, dry electrodes would be preferable.

A test setup was created to be able to analyse the usage of an EOG system and possibly discover findings that need to be taken into account for the development and design of a device that uses EOG. To be able to do a test with the MaM Senso module, some testing was done to identify how the module itself affects the signal and see whether it works properly. These confirmational tests can be found in Appendix H.

After the basic testing, a test was performed in which the electrodes were placed on a test person. This test was done to analyse whether specific steps or usage need to be taken into account for the creation of a new device. Figure 6.15 shows the electronics setup used for this test.

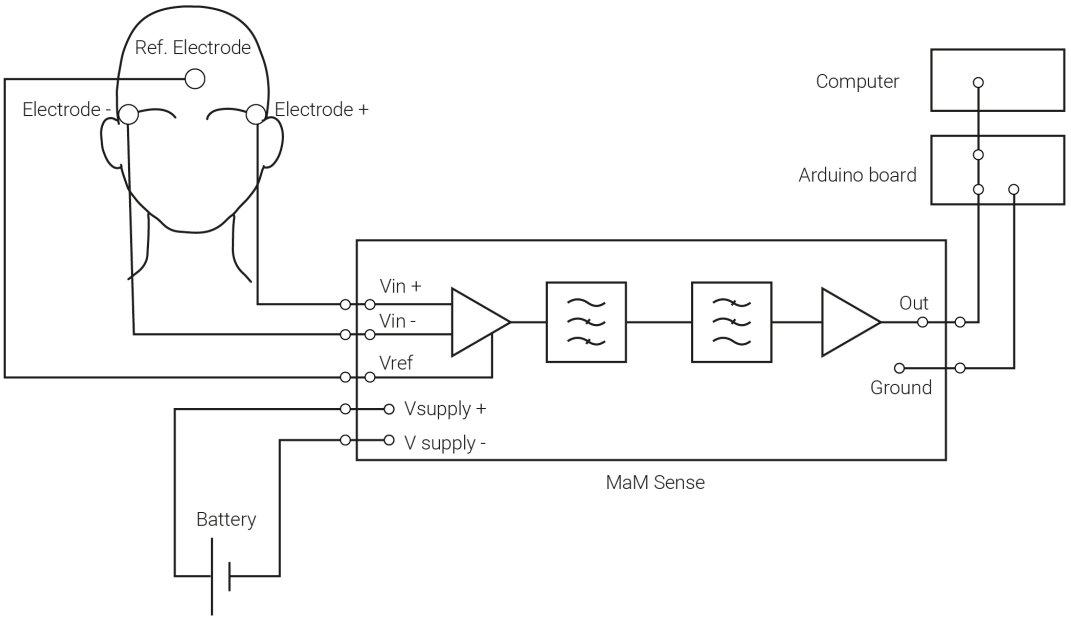
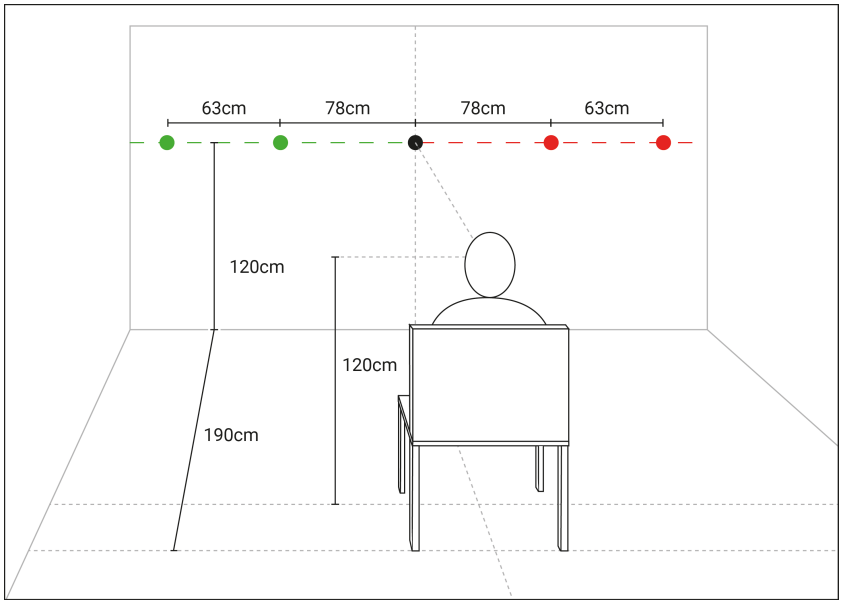
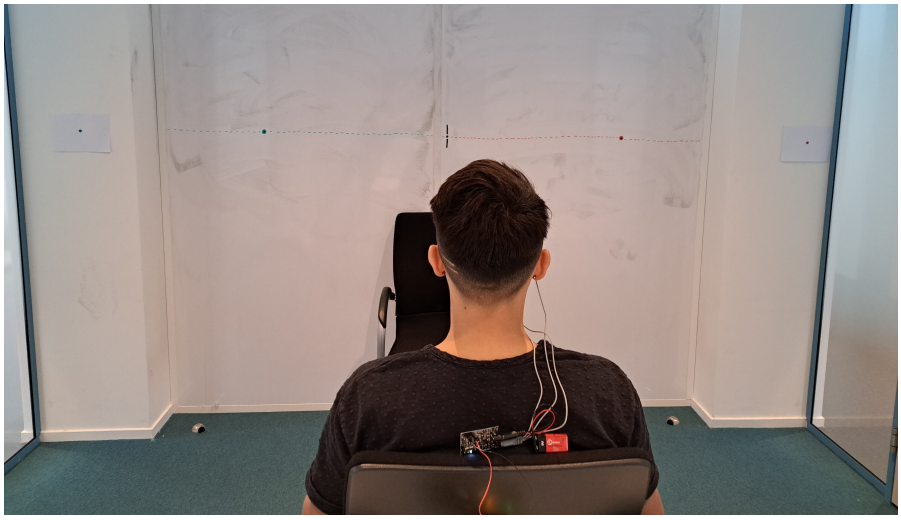


Figure 6.15: Test setup of the MaM Sense for analysis of the use EOG using a test person

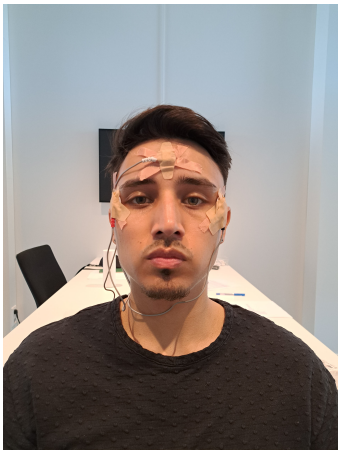
The overall test setup is shown in Figure 6.16. Figure 6.16a shows the setup as planned with the dimensions that were eventually used in the real setup. The real setup is shown in Figure 6.16b. To control the eye movement of the test person as much as possible, different coloured dots and a line to guide the sight of the test person were used. Since the MaM Sense only uses two electrodes placed horizontally and a reference electrode, the eye movement can only be measured in a horizontal direction. The placement of these electrodes on the test person is shown in Figure 6.16c. This is why the guideline and dots were placed on a horizontal line at the height of the test person's eyes. This height was measured while the test person sat on the chair in the room. The coloured dots are placed at an equal distance to the right and left of the middle black dot, which is right in front of the test person. The coloured dots on the far side of the guideline were placed towards the edge of the visual field. A camera was placed directly in front of the test person and a simultaneous recording of the serial plotter of Arduino IDE was made. This would provide the possibility of comparing the registered eye movement with the change in the measured value. The full test plan that was used to execute this test can be found in Appendix I.



(a) Planned setup with distances of real-life setup



(b) Actual setup with a participant at the time of testing



(c) Placement of electrodes on the head of the participant

Figure 6.16: Initial test setup for testing the MaM Sense and basic principles of an EOG

The first run of this test showed no relation between the eye movement and the measured values. The provided electrodes of the MaM Sense have an adhesive and already contain some conductive gel. However, the electrodes were repositioned before conducting the test, which decreased the strength of the adhesive. As shown in Figure 6.16c, some bandages were used to keep the electrodes in their place, but the shape of the skin, which is not straight, and the weaker force of the bandages did not provide enough pressure to ensure proper connection between the electrode and the skin. This is why a second run of the test was done, in which additional pressure was provided to the electrodes next to the eyes manually. The electrodes themselves are encased by a non-conductive material, so besides enhancing the contact between the test person and the electrodes, this should not have a big impact. When the same test plan was followed, the different movements of the eye were detectable. The main finding of this test is that a certain pressure is needed to ensure proper conductance between electrodes and skin. Furthermore, this specific setup needed a specific order of activation of the MaM Sense and the Arduino board in order to function properly. This is however related to the fact that the MaM Sense is created for developers. If a specialized board would be created for a device for the measurement of eye movement in premature babies, it should be designed in a fool-proof way, making it easy to switch on and off.

6.4.2. Electrode exploration

As explained in Chapter 2, Literature Research, different electrodes exist for different applications. Within the UMCU, different kinds of electrodes are also being used, depending not only on the application but also on the age of the patient. Different electrodes obtained from the UMCU and commercial websites were analysed.

Most of these electrodes still rely on some type of adhesive and gel, which is why these electrodes are generally supplied with the adhesive and gel already on the electrodes. An interesting feature of a device that monitors eye movement is the use of a snap electrode. It might help create a shell and electronics module that can be separated from each other. Furthermore, it is interesting to see that in most applications, the electrode material itself is roughly the same size, but the size of the padding or adhesive that surrounds it varies. During a visit to the UMCU to observe a polysomnography, the use of some cup electrodes was observed. These electrodes are a lot smaller and need manual application of a gel, a paste and a small piece of tape.

One application that stood out is that of Sentec. Sentec uses a snap system for their sensors of the V-Sign™ and OxiVenT™ which are both used as PCO_2 sensors. The snap system consists of a snap-ring and an electrode that snap into each other. The snap-ring uses an adhesive edge that is placed on the skin, after which the sensors are placed and kept in place by small snap-fits on the circumference of the ring. Figure 6.17 shows the ring and sensor of Sentec. This application was used to further develop the device.

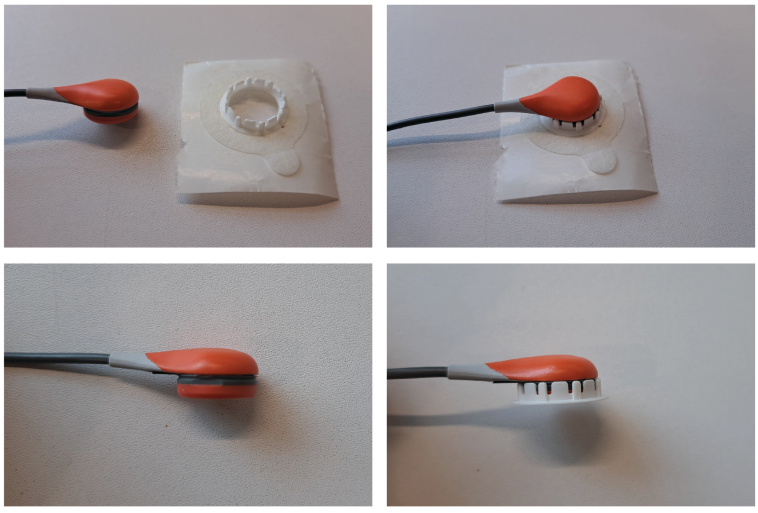


Figure 6.17: The sensor and snap-ring developed by Sentec to accommodate the use of the V-Sign™ and OxiVenT™

6.4.3. Electrode setup

This described electrode application creates a possibility for creating a shell that is separate from the electronics module. The snap-ring can be sown in the bonnet, creating the place for the EOG electrodes, which can be placed into the rings when the EOG is actually performed. A problem however arises when simply placing the sensor in the snap-fit ring if it is on the same plane as the bonnet. This situation is portrayed in Figure 6.19a. The surface of the face next to an eye is usually not straight or convex, but rather slightly concave, meaning the electrode might not be in contact with the face properly. The electrode can be made in a way that it protrudes the snap-ring, but since the distance to the skin is variable, depending on how the face is shaped and where the sensor is placed, this could mean that the hard electrode is pushed into the skin. Even if the skin is fully developed, this type of pressure is not preferred, and as mentioned multiple times, the skin of premature babies is even more fragile and susceptible to pressure points.

To deal with this problem, a system was made that makes sure the electrode is in contact with the skin without exerting too much pressure on it. When pushing the electrode through the snap-ring by adding a layer of material in between the snap-ring and the electrode, a force will act on the skin, since the electrode is being pushed onto it. Changing the stiffness of the layer of material that pushes the electrode further down, this force can be decreased. In a simplified setup as shown in Figure 6.18, a few layers of material are in play, namely the skin, the electrode and the material that pushes the electrode down. The force that acts on the skin will be the same as the force that pushes the electrode down. To ensure contact between the electrode and skin, the height of the layer of material and the electrode needs to be slightly bigger than the gap between the snap-ring and the skin. In the most simplified scenario, it could be assumed that both the electrode and the skin are non-compressible, meaning only the material pushing the electrode down will deform from the compression force to make the layers fit in the gap.

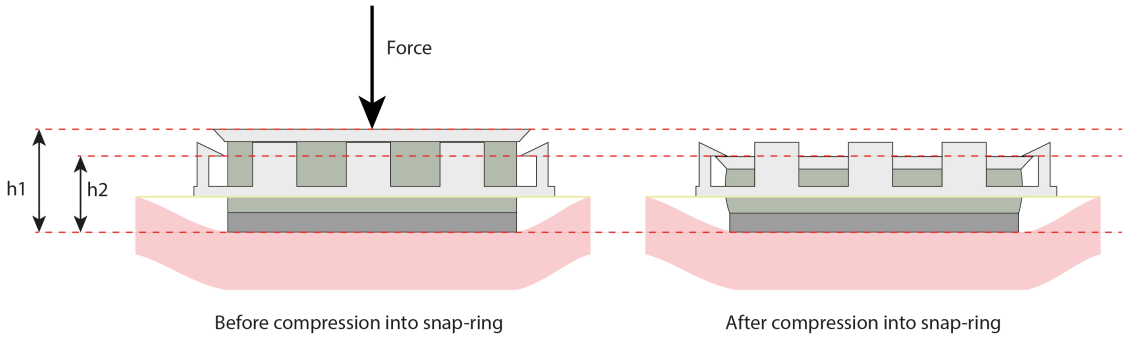


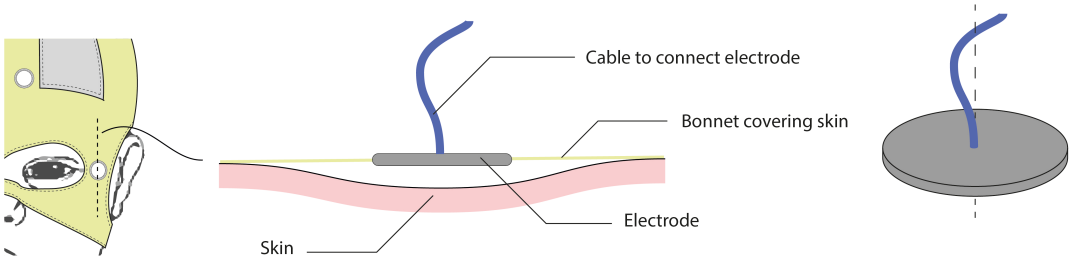
Figure 6.18: Visualisation of the compression of the electrode and the attached material layers, h1 is the original height of the electrode including attached materials, h2 is the height after compressing the material to fit the electrode including the attached materials between the snap-ring and the skin

Using the equations for stress and strain, it can derived that replacing the material layer that pushes the electrode down with a material that has a lower Young's modulus and therefore is less stiff, will decrease the force that is needed to create the compression of the material and therefore decrease the force that acts upon the skin.

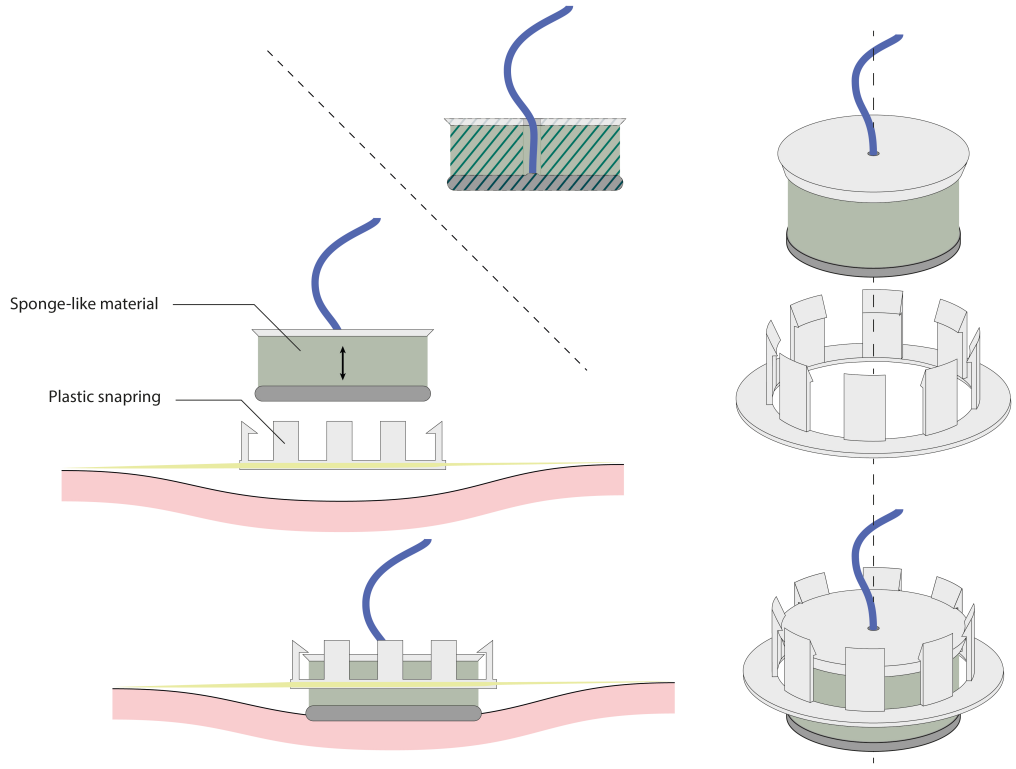
A more realistic, yet still simplified model, would be to take into account the compressibility of the skin and the electrode. However, since the skin and electrode in both scenarios are the same, the result is still that the force needed to create the compression is still lower when using a material with a lower Young's modulus. The derivation of the equations for this simplified model can be found in Appendix J.

The Young's modulus is described as the property that indicates the stiffness of a material. Sponge-like materials have a special structure that decreases their stiffness. This is why the use of a sponge-like material can mimic a lower Young's modulus and therefore function as the bridging material between the snap-ring and electrode while lowering the amount of force needed to make the electrode and material fit.

The addition of a sponge-like layer therefore seems to provide a solution. Figure 6.19b shows this novel setup for electrodes that are used on fragile skin. The electrode fits inside a snap-ring, similar to the Sentec sensors, but uses the damping properties of the sponge-like structure to decrease the pressure on the skin.



(a) Situation when an electrode is attached directly onto the bonnet



(b) Situation using new electrode and snap-ring configuration

Figure 6.19: Change in electrode configuration

To enhance communication concerning this idea, an elementary prototype was created. This was done by using an existing electrode, of which all adhesives and gel were removed, and adding a layer of sponge-like material and a layer of hard material to be able to snap into the snap-ring. Both surround the wire of the electrode so as to not interrupt its connection with the electrode material. This basic

prototype is shown in Figure 6.20.

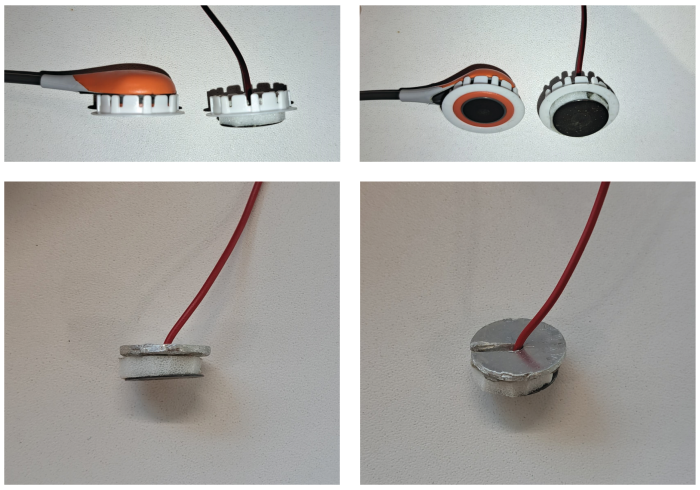


Figure 6.20: Basic prototype for novel electrode configuration in which the electrode protrudes the snap-ring but can be compressed due to a sponge-like material layer, the figure shows the basic prototype beside the Sentec application, showing the way the electrode now protrudes the snap-ring

Since the electrode can now be placed inside the bonnet and proper contact between the electrode and skin is ensured, the need for an adhesive is cancelled out. By using this setup for the electrode and combining it with an electrode material that can be used as a dry electrode, as explained earlier in Chapter 2, Literature Research, the need for any added fluids like gels or conductive pastes can be avoided.

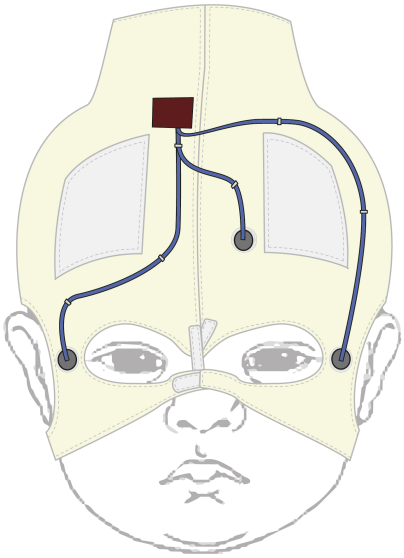
6.4.4. Wireless setup

One of the wishes that was expressed by the staff of the NICU during the field research, was the wish for a wireless setup. In this device, wireless is meant as no additional wires or tubes running from the baby to a monitor, since they might get tangled with all the present wires and tubes. An EOG uses at least three measuring points, two for the detection of eye movement and one as a reference. The electrodes measure a potential difference, which means they have to be connected to each other. A completely wireless system is therefore not possible, but using one transmitting module to which all three measuring points are connected is possible. This does create the need for three wires that run between the electrodes and the transmitting module, but by placing the transmitting module close to the measuring points, the wires are limited in length and do not run to an external monitor, decreasing the change of them getting tangled or mistaken for other wires. Figure 6.21 shows what this kind of setup could look like.

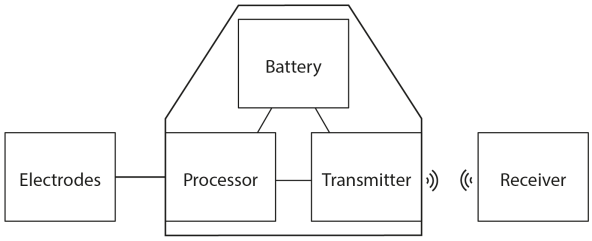
To be able to lead the wires to the transmitting box without bothering for example eye-sight, the wires could have some type of adhering material that keeps them in the right spot. For this specific design, this way of guiding the wires has been portrayed with the same velcro that has been used already and has proven to adhere to the bonnet. This would be a relatively easy setup, as shown in Figure 6.21c with a lot of space for adaptability and repositioning. The transmitting module itself will be contained in a small case, which should prevent other signals from interfering due to direct contact with the electronics.

Since multiple positions of the baby's head are possible, as explained in Chapter 4, the space to place a transmitting module is quite limited. By creating a transmitting box around it that can be placed and repositioned on the bonnet easily, it can be moved if needed. One way to achieve this would be to use the same specific velcro again, which would allow positioning and repositioning based on the situation.

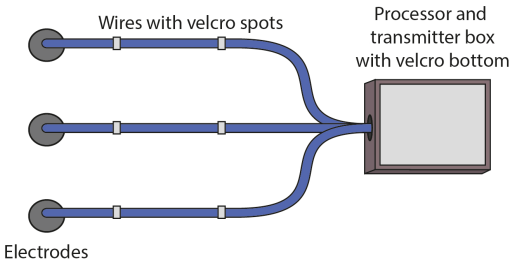
Currently, simple transmitters and receivers can be created in very small sizes. Alongside the MaM Sense module, a setup was created in an attempt to make it wireless. This was done using the MaM



(a) Rough representation of the placement of the wires and box containing the transmitting module



(b) Connections between different parts of the electronics of the device



(c) Connection between electrodes and transmitting module

Figure 6.21: Transmitting module within the setup of the electronics part of the device

Sense together with an Arduino Nano board and an HC-05 Bluetooth module. Using these three different modules would already create a wireless system that can transmit the received data from the MaM Sense to a device like a computer. In this case, the MaM sense functions as a signal processing unit and the Arduino Nano and HC-05 allow transmitting the signal. Each of the three modules can be seen in Figure 6.22. If a customized PCB was made that would place the amplifiers, filters and transmitter on one board, without additional unused modules, the size of the board would decrease a lot, suggesting a final design for a box that contains this board would not be too big to place on the head of the baby. The weight of these three modules together is 19.8 grams. Since the board will be a lot smaller when made specialized for this device, the weight will also be a lot lower, suggesting the box that will be placed on the head will not be a problem in size or weight.

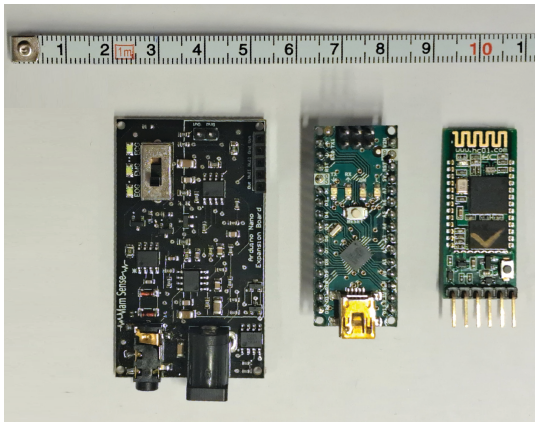


Figure 6.22: MaM Sense, Arduino Nano and HC-05 module, which formed a basic setup for a wireless EOG prototype

Further development of some of the parts of both the shell and the electronics could be done. In Chapter 10, the recommendations for further development have been laid out.

7

Final concept design

The device has been split into two parts; a shell and an electronics module. An overview of the final design that has already been explained thoroughly is shown in this chapter, solely highlighting the different aspects of the design again.

7.1. Shell

The final shell that was created into a prototype is portrayed in Figure 7. Different features of this shell will be highlighted.

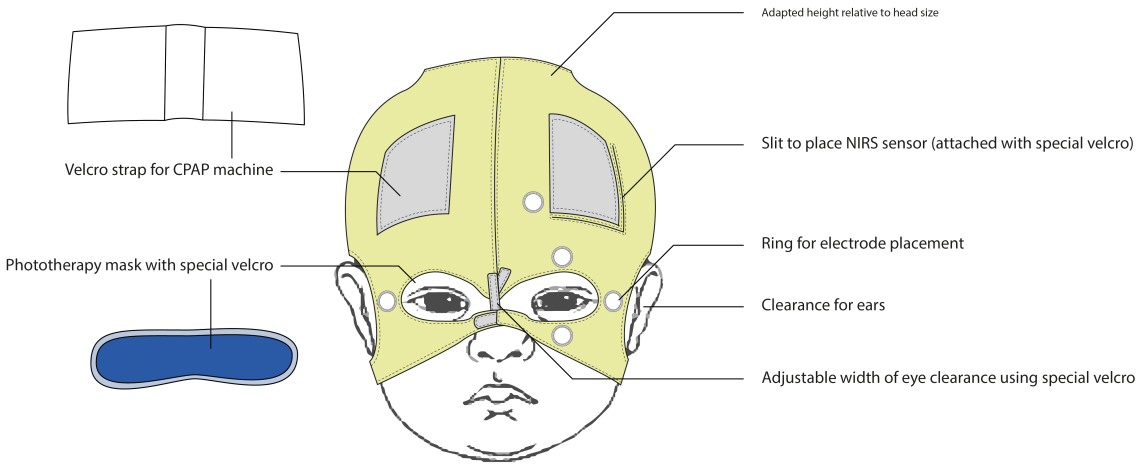


Figure 7.1: Final design concept of the shell

7.1.1. Electrode placement

The shell of this current design is a specialised bonnet for premature babies. Within this bonnet, special places are created in which electrodes for an EOG can be placed.

7.1.2. Sizes and adaptability

The bonnet itself has two points that create adaptability to perfect the placement of the electrodes: one to adjust the distance of the gap that crosses the eye horizontally, and one to adjust the distance of the same gap vertically. The height of the bonnet also depends on the size of the head to enable making an echo while covering the head. Different sizes will exist that depend on sizes such as head circumference and distances between the eyes' features.

7.1.3. nCPAP support

The bonnet is made of the same material as the one currently in use. This means that the support that the current bonnet provides for keeping the nCPAP device in place can still be given. The tube of the device is placed underneath a strap on the forehead of the baby. The velcro on the straps of the device that are attached to the mask or prong is attached to the bonnet. When placing the bonnet, the nose is kept clear, ensuring that placement of the mask or prong of the nCPAP device is still possible. Pressure points on the cheeks from the straps of the nCPAP device are decreased since the bonnet runs underneath these points. The friction that is currently caused by the rubber directly touching the skin of the baby is also prevented. When necessary, the strap of the specialized bonnet that is normally placed on the upper lip of the baby can also be placed on top of the mask, which helps prevent lifting of the upper part of the mask.

7.1.4. Other devices

Besides all critical devices, other devices are sometimes also used. A slit is made in the bonnet that can be opened and closed, allowing users to expose the skin for placement of a NIRS sensor or other types of sensors.

The phototherapy mask consists of a material that blocks out light and an edge with velcro, which enables placement of the material directly on top of the bonnet, covering the eyes completely.

7.2. Electronics

Besides the shell, an electronics module was designed that would enable the device to extract an EOG. Within this module, different parts can be found, namely the electrodes, a signal processing unit and a transmitting and receiving module. A simplified visualisation of this system is shown in Figure 7.2.

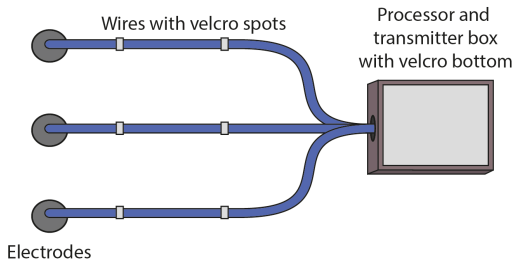


Figure 7.2: Electronics module of the eye-movement monitoring device

7.2.1. Electrodes

In Figure 7.3 the electrode configuration that was designed specifically for this device is shown. The electrode consists of the electrode itself, a sponge-like material with a relatively low Young's modulus and a plastic ring. The plastic ring fits inside a snap-ring that is placed inside the bonnet.

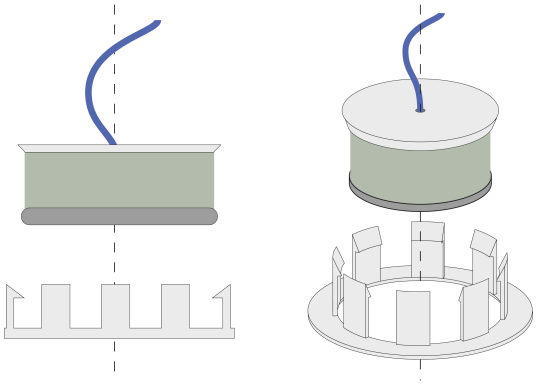


Figure 7.3: New electrode configuration

7.2.2. Wireless device

The electrodes are attached to a signal processing module which is then connected to a transmitting module. The transmitting module can send the signal from the electrodes to a receiving module. The signal processing and transmitting module can be found in a compact box that has one side covered with velcro. The signal processing and transmitting modules need to be powered. The receiving module would be part of the device or machine that eventually visualises or imports the data.

8

Discussion

The proposed design consisting of a shell and electronics module was created with the purpose of developing a device that can measure the eye movement of premature babies. By developing such a device, a sleep monitoring system can be enhanced or created which eventually can be used to support the sleep cycles of these babies by altering for example treatment plans.

The requirements, wishes and scenario in Chapters 4 and 5 were based on field research that was conducted within the UMCU. This has caused a lot of design decisions to have been based on information that might be specific to the UMCU. For the creation of the scenario, some national guidelines were used as well, so this current design should not interfere with those, but specific opinions of staff or specific steps taken at the UMCU might differ from those at other institutions.

Furthermore, within the development process for this design, some choices were based on the currently used materials within the UMCU. The material of the bonnet and the snap-ring of the electrodes both already exist within the UMCU. This choice was made to ensure the safety of the baby and existing knowledge for the end user, which is the NICU staff. For practical purposes, it might however be true that better materials or applications exist that might enhance this design even further.

Within the device, the electronics module uses a method that already exists and is used, namely EOG. This method records the movement of the eyes in one or more directions, depending on the placement of the electrodes. Within the current prototype, two horizontally placed electrodes and a reference electrode are used to measure the horizontal movement of the eyes. This was assumed to give a measurement of the movement of the eyes accurately enough to be able to distinguish different eye movement phases that belong to the different sleep stages. During the observation of a polysomnogram within the UMCU, only two electrodes for the movement of the eyes were used as well, suggesting this indeed gives a sufficiently accurate reading. It has however been shown that using four electrodes creates a more complete dataset. The final design concept therefore does still incorporate electrodes in both the horizontal and vertical directions.

As explained in the literature research, a lot of different electrodes exist, but dry electrodes, or electrodes that do not need adhesive or gel to function, would be beneficial, especially for the fragile skin of premature babies. A novel concept was proposed which would use pressure to ensure proper contact between the electrode and the skin without exerting too much pressure on this skin. The novelty of this design was evaluated using questions from the invention disclosure forms of the Netherlands Organisation for Scientific Research (NWO) and the World Intellectual Property Organisation (WIPO) [64, 65]. The relevant questions from these forms have been taken and answered, which can be found in Appendix K.

The following devices were identified as crucial in Chapter 5, Requirements and Wishes, and taken care of in the design:

Breathing support device, especially nCPAP device The specialized bonnet completely covers the function of the current nCPAP bonnet. It is made of the same material, ensuring the same type of

support for the attachment of the straps of the nCPAP device. Furthermore, the strap that is present on the current bonnet is placed on the specialized bonnet as well. The strap is placed higher on the bonnet, but since the bonnet itself is pulled further down over the face of the baby, the relative position to the face is the same. An interview with a nurse from the NICU pointed out that the strap that runs over the nose could even be used to secure the mask from the nCPAP device. As described in Chapter 4, Field Research, a triangular foam piece is currently used when the mask lifts too much due to an improper angle of the tubing. The strap could help prevent the mask from lifting as well.

IV in the arm, foot, or through the belly button The current design should not interfere with an IV, independent of which site the IV is placed at. The shell is placed on the head and when the electronics module is attached, it is placed solely on top of the bonnet, using a wireless connection to transfer the measured data.

NIRS sensor The NIRS sensor is placed on the top of the forehead. The slits that were added to the front of the bonnet, which can be opened and closed using velcro, accommodate for the placement of this sensor and enable the user to still apply it on either side of the head. This removes the need for removing the whole bonnet and moving the nCPAP device, which in current practice is necessary. This shows that, even though the main function of this specialized bonnet is to provide the option of performing an EOG, it also makes the task of applying a NIRS sensor less devious. The nCPAP bonnet currently is moved a lot when trying to place any additional device, so it was assumed that the movement caused by a slit in the bonnet is less and will therefore not exceed the amount of disturbance that is allowed.

EEG electrodes In current practice, nurses and NICU staff puncture small holes through the bonnets to be able to place EEG electrodes if need be. In the new bonnet, the same type of material is used. This means this method of EEG electrode placement is still possible. The EOG electrodes are not in the places where EEG electrodes are normally found. Furthermore, the wireless module for transmitting the EOG data can be placed rather freely somewhere on the forehead. Using a proper encasing for this electronics module should ensure that interference is limited.

ECG electrodes ECG electrodes are not placed on the head or face, so these will not be interfered with by the use of the shell or placement of EOG electrodes. The transmitting module should not interfere with the signal that is received by the ECG electrodes.

Phototherapy mask The phototherapy mask was adapted to avoid the need to move the nCPAP tube. During an interview with a neonatologist, it was pointed out that it might still be hard to place the mask underneath the tube of the nCPAP device. Since the current mask is also placed manually but needs to be placed underneath the mask as well, it was assumed that, though it still requires some additional effort, the placement of the mask is still easier for the new mask than with the currently used one.

Some expert interviews were conducted to verify the plausibility of the new use of the bonnet. These interviews were done with 4 staff members of the NICU floor of the UMCU and one neonatologist. They were asked to share their opinion on the design and the functionality of the shell and the device as a whole. Initial reactions were positive, though overall some hesitance especially regarding safety and ease of use was visible. Though each of the staff members expressed that this hesitance mostly arose because the design is still in a concept phase and the actual use of a fully functioning prototype is the only way to show them what the usage would actually be like. Some optimism was shown in the fact that the bonnet would accommodate other devices relatively better. A suggestion was made by one staff member that the feeding tube, which is currently placed on the cheek might even also be placed on the bonnet. This idea however was not encouraged a lot by the other interviewed members, since the feeding tube relies a lot more on stable fixation. Overall, the staff members would encourage the development of the bonnet and also see its value in creating a system that monitors sleep.

9

Conclusion

Since sleep plays an important role in different ways, especially in brain development for premature babies, a method to track it is desirable. Tracking eye movement has been shown to have great potential in enhancing or creating a system that can do this. Different methods to track eye movement already exist, where the EOG is most applicable for this specific purpose and setting.

Through the use of literature research, field research, ideation sessions and scenario analysis, a design was created for a device that can monitor the eye movement of premature babies using EOG. The device consists of two parts, namely a shell and an electronics module. The shell was designed to hold the electronics module that enables an EOG. Further adaptations were made to the shell to make its use fit within a scenario on the NICU floor. These adaptations made the device compatible with a scenario in which other devices, such as the nCPAP device, the NIRS sensor and the phototherapy mask can still be used. Choices were made concerning its fabric and adjustability and a plan was laid out for the creation of different sizes.

The electronics module is created with two main parts; the electrode configuration and a processing, transmitting and receiving module. The electrode configuration was adapted in a way that adhesives and gel are not necessary, creating space for dry electrodes and therefore protecting the fragile skin of premature babies. Using a new innovative configuration, including a sponge-like layer of material, the electrode is pushed onto the skin with enough pressure to ensure proper contact, while avoiding too much pressure that would damage the skin of the baby. This new configuration shows potential in enhancing the use of dry electrodes and even shows promise for other applications.

Some assumptions were made to create this final concept design, but overall choices were made to create a design ready to be advanced to the next stages. Early prototypes were already created and different aspects of the problem, the context and the stakeholders were taken into account. Current practice and knowledge were combined with new insights and a new type of electrode configuration to create a system that, when developed further, can help babies born prematurely by ensuring better sleep habits, which could eventually lead to improved brain development. Further recommendations can be found in Chapter 10.

10 Recommendations

Within this report, a final concept design is shown for a device that can measure eye movement of premature babies, which could eventually be used to enhance sleep monitoring systems for these babies. Some parts of the design would need additional verification and other steps would need to be taken as well before it could become a device usable in a clinical setting.

An important aspect of the development of medical devices is their certification. The certification for a medical device in Europe can be achieved by following the Medical Device Regulation (MDR) [66, 67]. When successfully fulfilling a conformity assessment, a CE mark is awarded. To be able to decide on a conformity assessment route, the classification of the device needs to be determined as well. The shell and electronics module could be certified separately, which might provide an advantage for the certification of the shell. The MDR states: "'active device' means any device, the operation of which depends on a source of energy other than that generated by the human body for that purpose, or by gravity, and which acts by changing the density of or converting that energy. Devices intended to transmit energy, substances or other elements between an active device and the patient, without any significant change, shall not be deemed to be active devices." Since the electronics module requires a power source, it would be seen as an active device. The shell separately from the electronics module however is not an active device. The shell without the electronics module, however, does not fulfil the purpose of the whole system. A strategy should be created to get the proper certification to be able to use the whole system in a clinical setting.

Besides the MDR, certain standards, such as those from the International Standards Organisation (ISO) exist, which help get MDR certified. During an interview with a staff member of the Medical Technology & Clinical Physics cluster (MTKF), some of these ISO standards were already named that would most likely apply to a device like the one developed in this report. The most important one would be ISO 60601, for electronic safety, but further along in development standards concerning software or risk management would also be relevant.

Further development of the design itself is also needed. The EOG electrodes that were explored and used for this design have not been tested within a prototype. The use of dry electrodes is still limited in current clinical settings but could provide great advantages for premature babies. The configuration in the current design already provides a setup that ensures contact with the skin without excessive pressure on the skin, but the electrode material and shape still need further development to ensure proper conduction of the signal.

The setup for the electrode itself was already proven to work better if a material is used with a sponge-like structure. To be able to make this setup work properly, tests would need to be conducted to find the right shape, thickness and Young's modulus of the material. The goal would be to find a sponge-like material that finds the balance between using pressure to keep the electrode in the right place and decreasing the pressure in a way that prevents skin damage or pressure points. Along with the development of dry electrodes, this way of placing the electrodes could provide a benefit for multiple

systems, each of which would need to have its own special setup of sponge-like material with electrode and snap-ring shape.

As explained, the shell is a specialised bonnet that should be created in a set of different sizes. In the design, it was said that these sizes could be the same as those of the nCPAP bonnets, but other features such as the adjustability of the bonnets are also dependent on the size that a specific patient needs. The dimensions used in the design were based on literature, but actual sizing and perfection of the adjustability of those sizes would be necessary to ensure each patient would fit one of the available bonnets.

The bonnet was not only enhanced to enable the EOG but simultaneously an attempt was made to make some of the steps that needed to be taken to use other devices less devious. In further development cycles, an even more thorough analysis of the devices used could be done to enhance the bonnet even further, creating a full system of devices and accessories that enable instead of disturb each other.

The part of this design that needs further development to fulfil one of the earlier stated wishes is the part that makes the system wireless. Currently, a relatively easy and simple setup was thought of which requires a small transmitting module that will be placed inside a little box. Multiple possible solutions however exist that enable wireless transmission of data. The actual configuration of this part of the electronics module would need further development.

Furthermore, within the current prototype, only the horizontal movement of the eyes is measured, whereas the final design concept still shows the measuring points for both horizontal and vertical movement of the eyes. Tests would need to be done to determine which of these fit the context and desired output best. Where more electrodes might be beneficial to create a better output, a design that measures solely one direction could benefit the ease of use of the device.

Once the development of the technical design and the documents for certification allow it, trials should be set up to be able to verify the reliability of the system. This way the output of the system gains value and could be used for the sleep monitoring system. If the device itself works properly, the output could simply be visualised on a screen and analysed by specialists who will draw conclusions from it. This is what happens in for example current polysomnographies as well. However, as stated, a goal of this project was to find a way to enhance sleep monitoring systems. Once this device is developed, its data could be integrated into a system that monitors and recognizes sleep. This can create opportunities to adapt care for premature babies according to their sleep states. All steps for integrating this system in such a setup still need to be performed.

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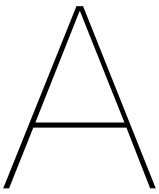


EOG properties

The following properties were named in studies that used EOG or analysed it. They give a general idea of what the orders of magnitude of these values are.

- time constant - needs to be long to avoid distortions (in this study, a time constant of 3.2 seconds was used) [17]
- sampling rate - 80 Hz [17], 256 Hz [36]
- frequency range 0.1 tot 50Hz [36]
- high-pass filter - 0.1 Hz [36] - cuts off unwanted data, or 1st order 1.6 Hz, capacitor of 1 μF, resistor of 10 kohm [44]
- gain of 2000 [36] or 3000 [40]
- electrode - skin contact impedance lower than 5 kilohm [37]
- EOG amplitude between 250 and 1000 μV, essential frequency content of 30 Hz [37]
- digitizer should sample saccades at a rate of 1kHz or higher [37]
- amplification ideally is DC amplification but causes baseline drift [37]
- AC coupling with 0.1 Hz high pass and 30 Hz low pass filter is recommended [37]
- bandwidth of 0.05-35Hz [40] or 0.1 tot 500 Hz [44]
- ADC [40] with 16 bit resolution and 256 Hz sampling rate [40] or AC with sampling of input at 200 Hz, resolution of 10 bits [44]
- high input impedance, high common-mode rejection ratio [44]
- low power amplifier with input impedance of 10Gohm [44]
- low pass filter with a gain around 1, cut off frequency of 47 Hz, leaving 1.6 to 47 Hz [44]
- information transfer rate of 13 bits/min [39]

B

Parents survey

The following information and questions were given to the participants of the survey. The information was provided in Dutch. For this report, a translation of all questions and information is given in italic text. Red text shows what happens within the survey when choosing certain options or fulfilling certain questions. This translation was created by a person who possesses an International Baccalaureate English Diploma.

Scriptie Claudia Kruissel *Thesis Claudia Kruissel*

Allereerst wil ik je graag bedanken dat je de tijd neemt om deze vragenlijst in te vullen. Ik zal even kort introduceren waar ik deze vragenlijst voor heb gemaakt. Voor mijn master opleiding Biomedical Engineering probeer ik een apparaat te ontwikkelen dat kan helpen met het monitoren van slaap in veel te vroeg geboren baby's. Een belangrijk onderdeel daarvan is het meten van de oogbewegingen. Bij het ontwikkelen van het apparaat wil ik niet alleen een goed werkend apparaat maken, maar ook zorgen dat alle betrokkenen een zo goed mogelijke ervaring hebben. Vandaar dat ik graag de mening van ouders erbij wil betrekken. Mocht je je niet prettig voelen bij het beantwoorden van een vraag, dan kan je deze altijd overslaan. Verder ben je altijd vrij om te stoppen met de vragenlijst. Voor vragen kun je contact met me opnemen via *voeg email adres in* of *voeg telefoonnummer in*.

*Firstly I would like to thank you for taking the time to fill in this questionnaire. I will shortly introduce why I made this questionnaire. For my master's degree in Biomedical Engineering, I am trying to develop a device that can help monitor sleep of very premature babies. An important part of this is the measurement of eye movement. Throughout the development, I do not only want the device to work well, but I want to make sure all involved people have an experience that is as nice as possible. This is why I would like to involve the opinion of parents. In case you do not feel comfortable answering a question, you can always skip it. Furthermore, you are always welcome to stop the questionnaire. For any questions, you can contact me through *insert email* or *insert phone number*.*

Next section

Algemene informatie *General information*

Hoeveel kinderen heeft u? *How many children do you have?*

- Geen kinderen *No children* When this answer is chosen, the respondent is redirected to the end of the questionnaire
- 1
- 2
- 3
- 4

- Meer dan 4 *More than 4*

Wat is uw geslacht? *What is your gender?*

- Vrouw *Female*
- Man *Male*
- Anders... *Other...*

Next section

Algemene informatie over uw kind/kinderen *General information about your child/children*

Hoe oud is uw kind/zijn uw kinderen? *How old is your child/are your children?*

Wat was de duur van uw kortste zwangerschap in weken? *What was the duration of your shortest pregnancy in weeks?*

Zijn er complicaties opgetreden tijdens de zwangerschap? Zo ja, welke? *Were there any complications during the pregnancy? If yes, which?*

Zijn er complicaties opgetreden tijdens de geboorte? Zo ja, welke? *Were there any complications during birth? If yes, which?*

Waar is uw kind geboren? *Where was your child born?*

- In het ziekenhuis *In the hospital*
- Thuis *At home*
- Anders... *Other...*

Is uw kind opgenomen geweest in het ziekenhuis in de eerste 10 weken na de geboorte? *Has your child ever been admitted to the hospital within the first 10 weeks after birth?*

- Ja *Yes*
- Nee *No*
- Anders... *Other...*

Next section

Situatieschets *Situation discription*

Als u doorklikt zult u een klein scenario lezen. Hierbij is ook een foto geplaatst van een baby die zich in de beschreven situatie bevindt, zodat de situatie duidelijker wordt. Mocht u erg gevoelig zijn voor beelden van zieke kinderen, kies hieronder dan voor de vragenlijst zonder foto. *If you move on to the next section, you will read a small scenario. Alongside it, a picture is placed portraying a baby in the described situation, to enhance the clarity of the situation. If you happen to be sensitive to imagery of sick children, choose the option for questionnaire without picture below.*

Met welke vragenlijst wilt u doorgaan? *With which questionnaire would you like to proceed.*

- Vragenlijst met foto *Questionnaire with picture*
- Vragenlijst zonder foto *Questionnaire without picture* When choosing this option, the next section is provided without picture

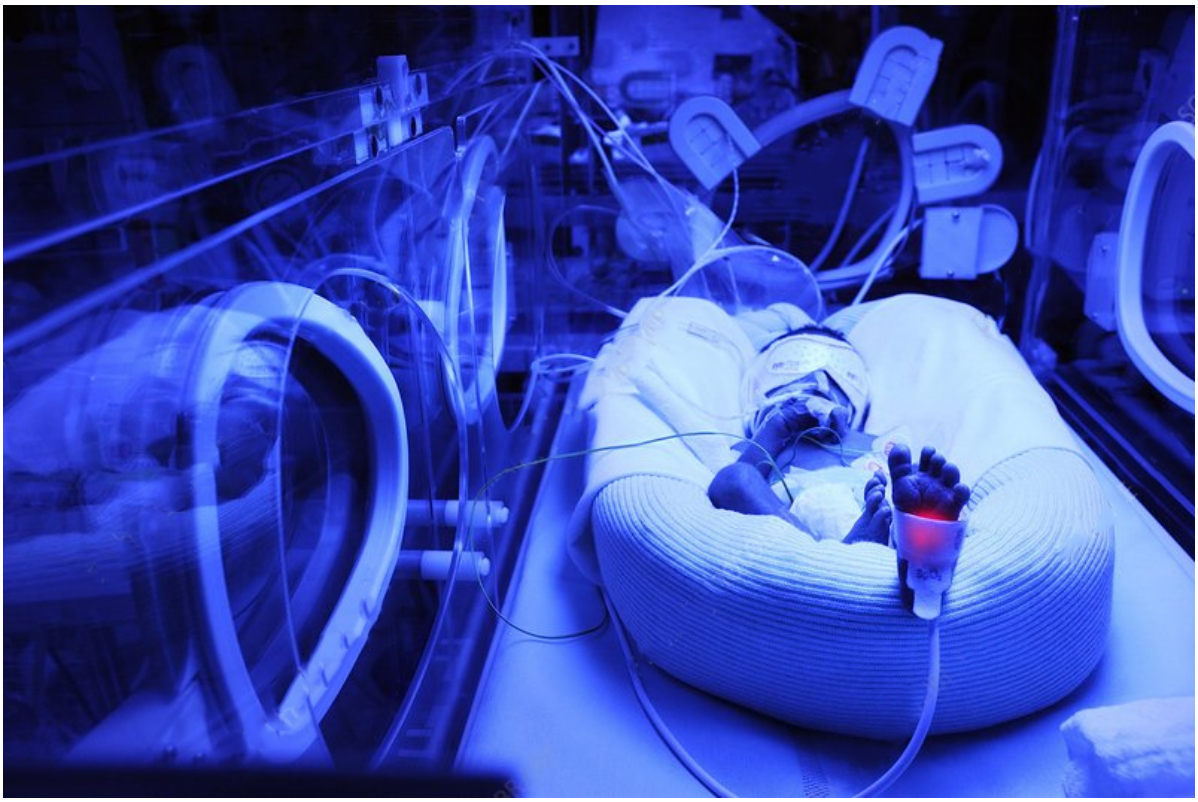
Next section

Situatieschets *Situation description*

Voor de rest van de vragen wil ik u vragen om u in te leven in de volgende situatie. Mocht u zich niet prettig voelen bij het beantwoorden van een vraag, of willen stoppen met de vragenlijst, dan mag dat altijd. *For the remainder of the questions I want to ask you to imagine yourself in the following situation.*

If you do not feel comfortable answering a question or want to stop the questionnaire, you can always choose to do so.

Uw baby is te vroeg geboren en is hierdoor nog niet sterk genoeg. De baby wordt daarom opgenomen in het ziekenhuis en moet in een couveuse liggen. De baby wordt snel meegenomen om aangesloten te worden aan verschillende meetapparaten en krijgt een infuus. Daarnaast krijgt de baby ook een maskertje omdat de baby onder een felle lamp gelegd moet worden voor lichttherapie. De foto hieronder geeft weer in wat voor situatie de baby uiteindelijk ligt. *Your baby was born prematurely and is therefore not strong enough yet. The baby is therefore admitted to the hospital and needs to be put in an incubator. The baby is taken quickly to attach different kinds of measuring equipment and an IV is placed. Furthermore, the baby gets a mask, because the baby needs to be put underneath a bright light for light therapy. The picture below shows what the situation in which the baby lies looks like.*



Next section

Stellingen *Statements*

Geef bij de volgende stellingen aan in hoeverre u het ermee eens bent. *For the following statements, please indicate to what degree you agree.*

For each of the following statements, the following options were given: Volledig oneens *Completely disagree*, Deels oneens *Partially disagree*, Neutraal *Neutral*, Deels eens *Partially agree*, Volledig eens *Completely agree*

1. Ik wil bij mijn baby zijn als deze overgeplaatst wordt. *I want to be with my baby when it is transferred*
2. Aan mij hoeft niet uitgelegd te worden wat er allemaal met mijn baby gebeurt tijdens het verplaatsen en installeren in de couveuse. *I don't need an explanation about what happens to my baby during transfer or placement in the incubator.*

3. Als het kan, wil ik graag zelf plakkers/maskers en dergelijke bij mijn baby vastmaken. *If possible, I want to place stickers, masks, or other such things on my baby myself.*
4. Ik wil tijdens het verblijf van mijn baby in het ziekenhuis constant bij hem/haar zijn. *During my baby's stay in the hospital, I want to be with them constantly.*
5. Ik wil zelf om updates over de gezondheid van mijn baby vragen. *I want to ask for updates on the health of my baby myself.*
6. De gemeten waardes van mijn baby wil ik inzien. *I want to be able to see the values measured on my baby myself.*
7. Waar mogelijk wil ik zelf betrokken zijn bij handelingen aan de apparaten van mijn baby. *Wherever possible, I want to be involved in actions concerning the devices around my baby.*
8. Ik heb liever een ingrijpende behandeling met een snel herstel dan een niet-ingrijpende behandeling met langzamer herstel. *I would rather have an invasive action with quick recovery than a non-invasive action with slow recovery.*

Next section

Overige vragen *Other questions*

Nog wat vragen over de betrokkenheid en ervaring wanneer uw baby in de beschreven situatie zou komen. *Some other questions about the involvement and experience when your baby would end up in the given situation.*

Wat zou je het vervelendst vinden in deze situatie? *What would make you feel the worst about this situation?*

- Het verplaatsen van de baby meteen na zijn geboorte *The transfer of the baby right after birth*
- Zelf weinig kunnen veranderen aan de situatie *Not being able to change the situation much myself*
- De plakkers, maskers, draadjes en machines *The stickers, masks, wires and devices*
- Niet snappen waar alles voor is en hoe het met mijn baby gaat *Not understanding what everything is for and how my baby is doing*

Stel dat u betrokken mag zijn bij het plaatsen en verwijderen van apparatuur of het meten van bepaalde waardes, zou u dit dan willen en in hoeverre? Denk hierbij aan plakkers, maar ook bloed afname of het plaatsen van sensoren. *If you could be involved in placing and removing devices or measuring certain values, would you want this and to which degree? Think of stickers, but also blood withdrawal or placing sensors.*

Op welke manier wilt u op de hoogte gehouden worden van de status van de baby (wat voor informatie wilt u en hoe vaak)? *In which way would you like to be updated about the status of your baby (what kind of information would you like and how often do you want to receive it)?*

Next section

Einde vragenlijst *End of questionnaire*

Heel erg bedankt voor het invullen van de vragenlijst. Mocht u nog vragen hebben, of op de hoogte gehouden willen worden, dan kunt u contact met mij opnemen via *voeg email adres in* of *voeg telefoonnummer in*, of hieronder reageren. Vergeet alstublieft niet op verzenden te klikken om de lijst af te ronden. *Thank you very much for answering this questionnaire. If you have any questions or want to be updated on this project, you can contact me through *insert email* or *insert phone number*, or by replying below. Please don't forget to press send to finish the questionnaire.*

Opmerkingen *Remarks*

C

Parent survey answers

The following tables show the responses to a survey. Questions and answers are in Dutch.

Antwoorder	Hoeveel kinderen heeft u?	Wat is uw geslacht?	Hoe oud is uw kind?
1	1	Vrouw	3 maanden
2	2	Vrouw	
3	2	Vrouw	
4	2	Vrouw	
5	1	Man	35
6	1	Vrouw	1,5 jaar
7	2	Vrouw	
8	1	Man	21 maanden
9	1	Vrouw	21 maanden
10	2	Man	
11	1	Man	22 maanden

Antwoorder	Wat was de duur van de zwangerschap in weken?	Zijn er complicaties opgetreden tijdens de zwangerschap? Zo ja, welke?	Zijn er complicaties opgetreden tijdens de geboorte? Zo ja, welke?	Waar is uw kind geboren?	Is uw kind opgenomen geweest in het ziekenhuis in de eerste 10 weken na de geboorte?
1	38	nee	vruchtwater in de longetjes	In het ziekenhuis	Ja
2					
3					
4					
5	40	Nee	Nee	Thuis	Nee
6	37 weken	Zwangerschap diabetes,	De navelstreng was mee gegroeid aan de placenta.	In het ziekenhuis	Nee
7					
8	40	Nee	Nee	In het ziekenhuis	Nee
9	40	Nee	Nee	In het ziekenhuis	Nee
10					
11	+-38 weken	Zwangerschapsdiabetus	Navelstreng in de placenta vergroeid. Deze kwam pas los bij de baarmoedermond. Gevaar dat tijdens de bevalling deze inscheurt en een bloeding veroorzaakt.	In het ziekenhuis	Nee

Antwoorder	Hoe oud zijn uw kinderen?	Wat was de duur van de kortste zwangerschap?	Zijn er ooit complicaties opgetreden tijdens 1 van de zwangerschappen? Zo ja, welke?	Zijn er ooit complicaties opgetreden tijdens de geboorte? Zo ja, welke?	Waar zijn uw kinderen geboren? Wanneer het verschilt, kies dan de optie anders en ligt graag toe.
1					
2	24	7 maanden	Spoed keizersnee	Nee	In het ziekenhuis
3	37 en 30	38 weken	Nee	Nee	Thuis
4	38 en 34	9 maanden	Nee	Nee	Thuis
5					
6					
7	3 en 0	37 weken	Nee	Nee	In het ziekenhuis
8					
9					
10	24	7,5 maand	Ja, zuurstofgebrek	Nee	In het ziekenhuis
11					

Antwoorder	Is 1 van uw kinderen opgenomen geweest in het ziekenhuis in de eerste 10 weken na de geboorte?	Met welke vragenlijst wilt u doorgaan?	[Ik wil bij mijn baby zijn als deze overgeplaatst wordt.]	[Aan mij hoeft niet uitgelegd te worden wat er allemaal met mijn baby gebeurt tijdens het verplaatsen en installeren in de couveuse.]
1		Vragenlijst met foto	Volledig eens	Volledig oneens
2	Ja	Vragenlijst met foto	Volledig eens	Volledig oneens
3	Ja	Vragenlijst met foto	Volledig eens	Deels oneens
4	Nee	Vragenlijst met foto	Volledig eens	Volledig oneens
5		Vragenlijst met foto	Volledig eens	Volledig oneens
6		Vragenlijst met foto	Volledig eens	Deels oneens
7	Nee	Vragenlijst met foto	Volledig oneens	Deels oneens
8		Vragenlijst met foto	Volledig eens	Neutraal
9		Vragenlijst met foto	Volledig eens	Deels eens
10	Ja	Vragenlijst met foto	Deels eens	Deels oneens
11		Vragenlijst met foto	Volledig eens	Deels eens

Antwoorder	[Als het kan, wil ik graag zelf plakkers/maskers en dergelijke bij mijn baby vastmaken.]	[Ik wil tijdens het verblijf van mijn baby in het ziekenhuis constant bij hem/haar zijn.]	[Ik wil zelf om updates over de gezondheid van mijn baby vragen.]	[De gemeten waardes van mijn baby wil ik inzien.]
1	Neutraal	Volledig eens	Neutraal	Volledig eens
2	Neutraal	Deels oneens	Deels oneens	Volledig eens
3	Volledig oneens	Neutraal	Deels oneens	Deels eens
4	Volledig eens	Volledig eens	Neutraal	Volledig eens
5	Deels eens	Deels eens	Neutraal	Volledig oneens
6	Deels eens	Deels eens	Volledig oneens	Volledig eens
7	Deels oneens	Volledig oneens	Volledig oneens	Volledig oneens
8	Volledig oneens	Deels eens	Deels oneens	Volledig eens
9	Neutraal	Deels eens	Deels oneens	Deels eens
10	Deels eens	Deels eens	Deels eens	Deels eens
11	Volledig oneens	Deels eens	Deels oneens	Deels eens

Antwoorder	[Waar mogelijk wil ik zelf betrokken zijn bij handelingen aan de apparaten van mijn baby.]	[Ik heb liever een ingrijpende behandeling met een snel herstel dan een niet-ingrijpende behandeling met langzamer herstel.]	Wat zou je het vervelendst vinden in deze situatie?	Stel dat u betrokken mag zijn bij het plaatsen en verwijderen van apparatuur of het meten van bepaalde waardes, zou u dit dan willen en in hoeverre? Denk hierbij aan plakkers, maar ook bloed afname of het plaatsen van sensoren.
1	Volledig eens	Neutraal	Niet snappen waar alles voor is en hoe het met mijn baby gaat	Ik zou dit overlaten aan het ziekenhuis personeel, dan heb ik het gevoel dat het hoe dan ook juist aangesloten wordt
2	Volledig eens	Deels oneens	Zelf weinig kunnen veranderen aan de situatie	Wel zelf. Maar onder toezicht
3	Deels eens	Neutraal	Zelf weinig kunnen veranderen aan de situatie	Nee
4	Volledig eens	Volledig eens	De plakkers, maskers, draadjes en machines	Jazeker, zoveel mogelijk is.
5	Neutraal	Deels eens	Niet snappen waar alles voor is en hoe het met mijn baby gaat	Ja tot zover het mag
6	Volledig eens	Neutraal	Zelf weinig kunnen veranderen aan de situatie	Ja, bij alles waar ik betrokken bij kan zijn.
7	Volledig oneens	Deels oneens	Zelf weinig kunnen veranderen aan de situatie	Ja
8	Volledig oneens	Deels oneens	Het verplaatsen van de baby meteen na zijn geboorte	Nee, dit laat ik aan de verpleegkundige over.
9	Neutraal	Neutraal	Zelf weinig kunnen veranderen aan de situatie	Ik zou dit wel willen onder goeie begeleiding en zekerheid dat je het goed doet.
10	Deels eens	Neutraal	Zelf weinig kunnen veranderen aan de situatie	Geen behoefte om te doen.
11	Deels oneens	Volledig oneens	Zelf weinig kunnen veranderen aan de situatie	Hier zal ik graag bij willen zijn. Al is het alleen maar voor het gevoel er voor je kind te zijn.

Antwoorder	Op welke manier wilt u op de hoogte gehouden worden van de status van de baby (wat voor informatie wilt u en hoe vaak)?	Opmerkingen
1	Ik zou uitleg willen over de monitor die is aangesloten bij de baby, zodat ik die kan aflezen en weet hoe het met mijn baby gaat. Ook zou ik het fijn vinden om in ieder geval 3 keer per dag een update te krijgen van de arts/verpleegkundige.	
2	Dagelijks. En bij ernstige zo snel mogelijk	Ik wil graag op de hoogte worden gehouden
3	Alle manieren die de artsen nodig vinden op dat moment	
4	Ja, vooruitgang en ook achteruitgang.	
5	Op een vast dagelijks moment, of eerder als er belangrijke ontwikkelingen zijn	
6	Graag mondeling, 1x per dag	
7	Maakt niet uit	
8	Het liefst zo vaak mogelijk. Goed en minder goede informatie.	Succes. Mocht je nog meer vragen hebben stel ze maar. Ik heb al bijna 2 jaar een trauma van Iza Mae.
9	Zodra er iets veranderd wil ik op de hoogte zijn. Zowel positief of negatief. Ik wil er niet zelf om vragen want dan kan je als moeder wel elke 10 minuten vragen hoe het gaat. Geen bericht is stabiel.	Succes♡
10	Huidige status, voortgang, dagelijks.	Succes.
11	1 maal per dag lijkt me redelijk. Op termijn alleen wanneer er veranderingen plaats vinden.	

D

Sketches

In Figure D.1, a set of sketches created during early ideation is shown.

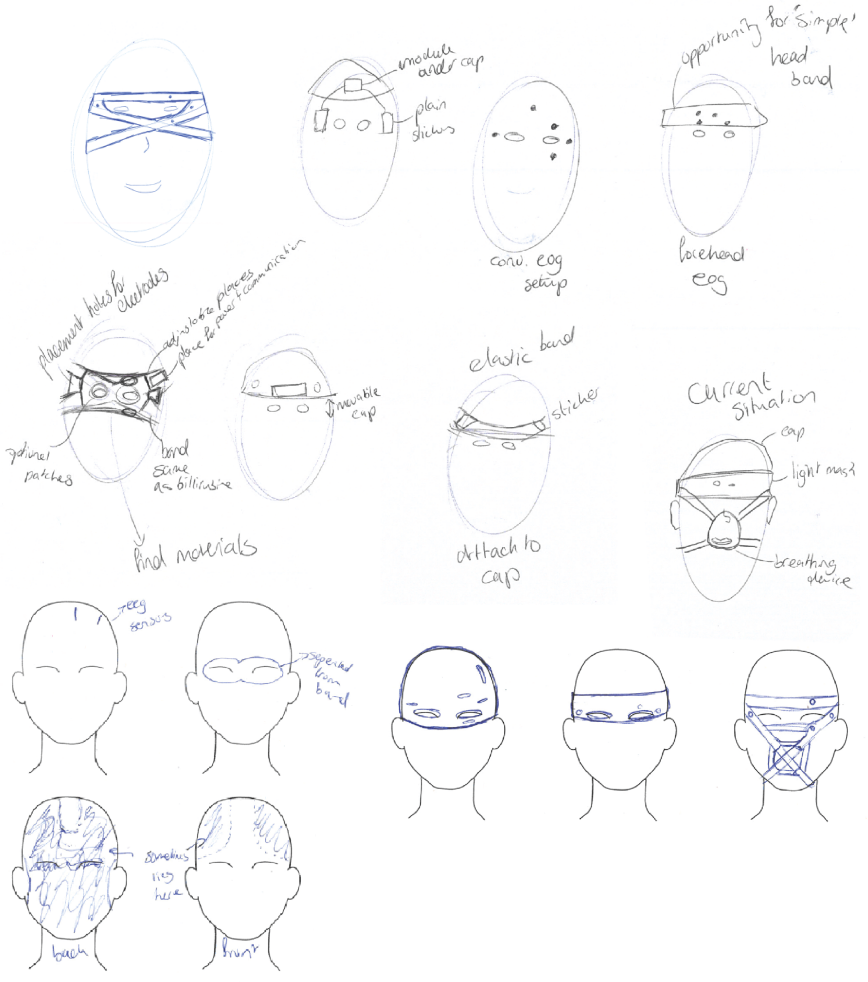


Figure D.1: Set of sketches for ideation

E

3D physical models

In Figure E.1, the 3D physical models that were used to enhance the ideation are shown.

Figure E.1: 3D physical models to enhance ideation

F

Sizes of nCPAP bonnets

The following data was used to find the relation between head circumference, bonnet size, height of the bonnet and length of the bonnet. Some data was not available, which left their respective cells blank.

Size Bonnet	Color	Max Head Circumference (cm)	Min Head Circumference (cm)	Length Bonnet (cm)	Height Bonnet (cm)	Weight (g)
XXS						
XS/micro	White	21	19			500-700
S	Yellow	23	21	7.8	13.1	700-1000
M	Red	25.5	23	9	13.8	1000-1300
L	Light Blue	28	25.5	9.6	13.8	1300-1600
XL	Orange	30	28	10.8	14.2	1600-1900
XXL	Light Green	33	30	12.9	14	1900-2400
XXXL	White Black	36	33	12.9	12.8	2400-3000

G

Measurements of baby head

The following tables show the dimensions needed to create a bonnet for a baby of 28 WoGA. The measurements were derived from a study by Fenton et al. [59].

Measurements belonging to figure 6.12a.

	What	Min. Value (cm)	Max. Value	Difference (cm)	Average value (cm)
a	Head circumference	23.9	29.6	5.7	26.8
e	Inner canthal distance	1.3	1.9	0.6	1.6
b	Outer canthal distance	3.5	4.7	1.2	4.1
d	Interpupillary distance	2.9	3.7	0.8	3.3
c	Palpebral fissure length	1.1	1.4	0.3	1.3
f	Nasal height	2.0	3.2	1.2	2.6

Measurements belonging to figure 6.12b.

	What	Value	Based on
I	Distance of gap horizontally	5.0 cm	b of fig 6.10a
II	Width of horizontally adjustable upper part	0.6 cm	e of fig 6.10a
III	Height of vertically adjustable part	1.2 cm	f of fig. 6.10a
IV	Width of horizontally adjustable lower part	1.2 cm	e of fig 6.10a

Measurements belonging to figure 6.12c.

	What	Value (cm)
1	0.5 times the distance I in fig 6.10b	2.5
2	dependent on a of fig 6.10a	21.8
3	same as II	0.6
4	height of the eye	1.5
5	distance III of fig 6.10b	1.2
6	distance IV of fig 6.10b	1.2

MaM Sense tests

Using the information from MaM High Tech, a first test setup could be made, to test the functionality of the MaM Sense module itself. For this test, an artificial signal is introduced into the electrodes, which are connected as they are intended to, to the MaM sense board. The board is then attached to an oscilloscope, to see what the output of the board is. In Figure H.1, this setup is shown.

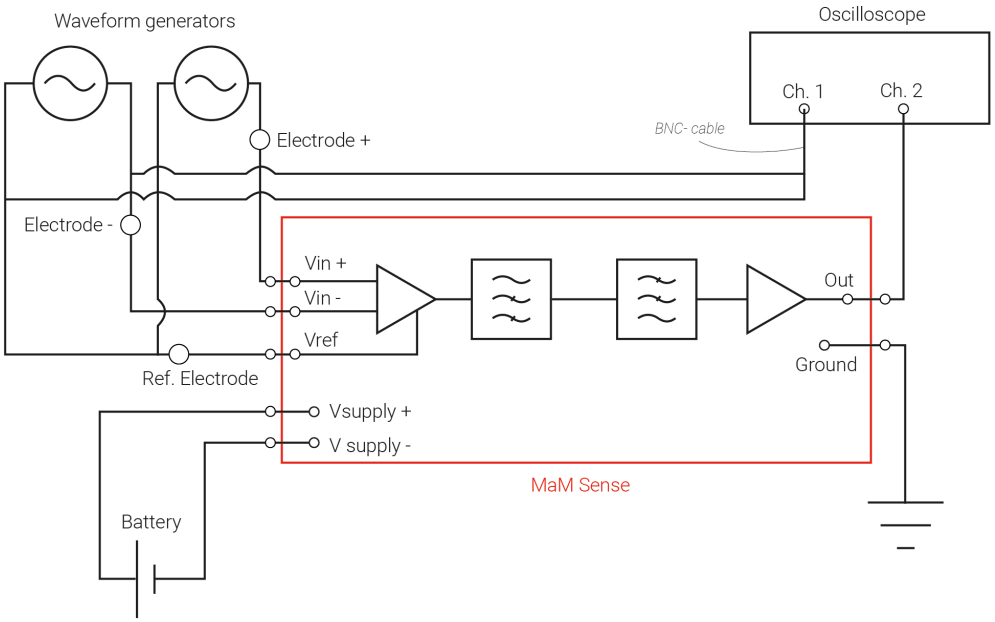


Figure H.1: Test setup for the functionality of MaM Sense module

When only using amplifiers and filters, the output signal of the MaM Sense board should not have a different shape than that of the input in the electrodes.

The results of this test showed that the waveform did not change. The amplitude of the sine wave that was introduced did grow, which can be explained by the fact that multiple amplifiers are used. A phase shift was noticed, which could be due to a delay caused by the translations of the signal and the effect that the board itself has on it. Noise was observed on the output, but a distinction between the noise and the signal itself was easily made.

After this first test to better understand the MaM Sense module itself, it was also connected to an Arduino Uno board to perform the same test. Figure H.2 shows this new, slightly different, setup. This

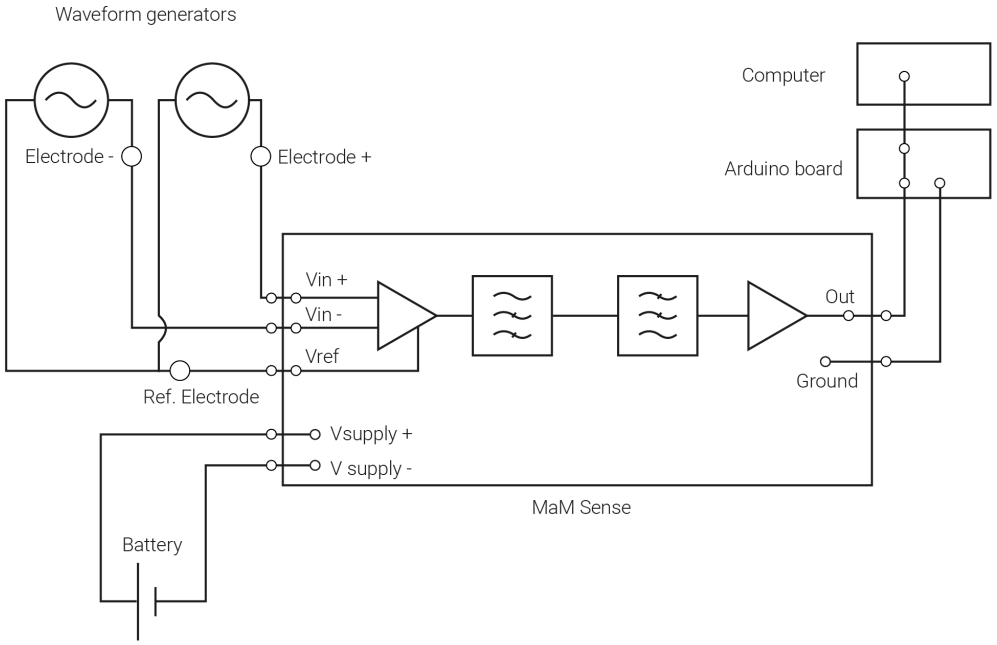


Figure H.2: New test setup to test the influence of Arduino Uno on signal

also created the need to set up an Arduino script that could read the EOG output. An Arduino script is already provided by MaM Sense, but it is created in a way that the output on the monitor of Arduino already provides textual feedback on the specific type of movement the eye makes. For these tests, the raw data for the EOG is needed. This is why a simpler script was written which is shown in Figure H.3.

This test showed roughly the same results as the first test, meaning the values followed the waveform of a sine, but the amplitude was bigger than the given signal and a certain phase shift was visible. Noise was still present, but the distinction between signal and noise was very clear.

An important finding in this new setup is that the MaM Sense and Arduino Uno do need a specific order of activation to be able to measure any values. When connecting the MaM Sense to just the Arduino Uno, it could be powered by the Arduino Uno, but the power voltage would be 5V whereas the MaM Sense needs a power supply of 9 V to function properly. The MaM Sense will only work if the 9V battery is attached when the board is already connected to the Arduino Uno board. This is a practical consideration for this specific setup, that needs to be taken into account when using it for other tests. For a final design, however, the hardware should be made foolproof and therefore only need one way to plug it in and then be able to work.

```
int fs = 100;                // Sampling rate (Hz) Don't change!
float Ts = (float)1000 / fs; //Sampling Period (ms)
//ADC COnfiguration
const byte adc_in        = A2; // ADC input pin.(For example A2 for Arduino Uno, 27 for ESP32)
const byte adc_bits      = 10; // The resolution of your MCU's ADC
const byte default_bits  = 10; // Don't change!
const float vref         = 5;  // Reference voltage of your MCU's ADC (V)
const float default_vref = 5 ; // Default reference voltage of the Arduino Uno (V) Don't Change
const float adc_scale    = pow(2, default_bits - adc_bits) * vref / default_vref;
// Scales the input signal - for arduino uno = 1
const float eog_offset   = 1.40; // DC offset of the Mam Sense Board EOG output. (V)
const float sig_offset   = round(pow(2, default_bits) * eog_offset / default_vref);

unsigned long counter = 0;
short data_buff[200];

void setup() {
  Serial.begin(9600);  //start running
}

void loop() { // loop this code

  delay(Ts);    //delay by one sampling period
  data_buff[counter%200] = round(analogRead(adc_in) * adc_scale - sig_offset);
  //read the input and adjust it according to offset, then round
  Serial.println(data_buff[counter%200]); //print the values measured
```

Figure H.3: Code used to extract data from the MaM Sense and Arduino Uno modules

Test plan

The following plan was used during a test to get some initial information and understanding of the MaM Sense and EOG.

Steps:

1. Prepare materials (attach Arduino uno to MaM Sense, attach electrodes to the MaM sense, Start Arduino IDE and open the created code, place camera)
2. Get informed consent from the participant for the execution of the test
3. Place electrodes on the face (Red electrode on the left side of the left eye, black electrode on the right side of the right eye, reference electrode on the forehead)
4. Guide the wires out of the visual field of the test person
5. Attach the Arduino Uno board to the computer
6. Attach the battery to the MaM Sense board
7. Start recording
8. Ask the person to look at the black dot in front of them, instruct them to follow the tasks given
9. Start screen recording
10. Start Arduino measurement while saying it out loud to be able to synchronise the recordings
11. Ask the following of the test person
    (a) Keep looking at the black dot in the middle unless asked otherwise
    (b) Look at the first red dot (on the right) *wait five seconds*
    (c) Look at the black dot *wait five seconds*
    (d) Look at the first green dot (on the left) *wait five seconds*
    (e) Look at the black dot *wait five seconds*
    (f) Look at the second red dot (on the right) *wait five seconds*
    (g) Look at the black dot *wait five seconds*
    (h) Look at the second green dot (on the left) *wait five seconds*
    (i) Look at the black dot *wait five seconds*
    (j) Quickly look back and forth to the second red dot (on the right)
    (k) Quickly look back and forth to the second green dot (on the left)

(l) Take approximately five seconds to get your focus to the second red dot (on the right) and five seconds to go back

(m) Take approximately five seconds to get your focus to the second green dot (on the left) and five seconds to go back

(n) Blink quickly *wait five seconds*

(o) Look at the black dot normally

12. Stop the Arduino recording
13. Stop the screen recording
14. Stop the video recording
15. Tell the test person they can look wherever they want again
16. Unplug the battery
17. Unplug the Arduino board
18. Detach the electrodes (if necessary, use a damp cloth to detach the adhesive more easily)

J

Calculations deformation and stress

The following calculations were done to show the difference in force needed to push an electrode, an additional layer of material and an electrode between a snap-ring and the skin. Figure J.1 shows all used variables which are listed below. The situation is based on the compression of the electrode and its attached materials portrayed in Figure 6.18 in Chapter 6.

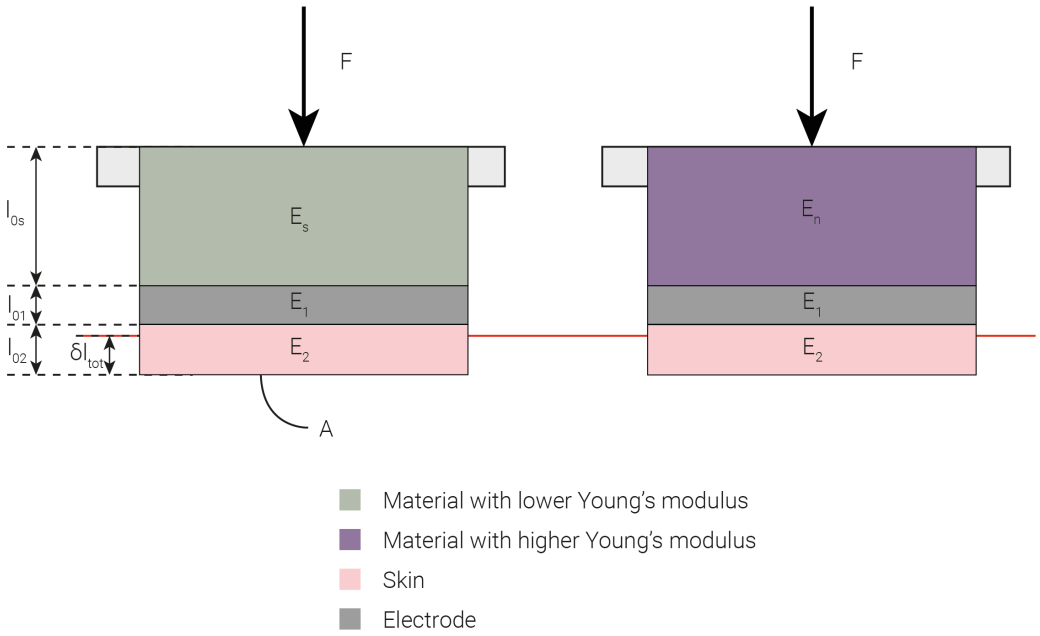


Figure J.1: Variables used to compare the use of two materials with different Young's moduli for the material that pushes the electrode through the snap-ring onto the skin

F - Force used to push the layers below the edge of the snap-ring

E_s - Young's Modulus of a material with a Young's modulus lower than E2

E_n - Young's Modulus of a material with a Young's modulus higher than E1

E_1 - Young's Modulus of the electrode material

E_2 - Young's Modulus of the skin

l_{0s} - Height of the layer of material before compression

l_{01} - Height of the electrode layer before compression

l_{02} - Height of the skin

δl_{tot} - Total difference in height of all layers of material after compression (This value is also equal to the difference between h1 and h2 in Figure 6.18 in Chapter 6.)

A - Surface area of the top plane of the module that is compressed, it is assumed that this area is equal throughout the module and therefore also the same area as the bottom plane of the skin

Equations J.1 J.2 and J.3 are standard formulas for respectively Young's modulus, strain and stress.

$$E = \frac{\sigma}{\epsilon} \qquad \epsilon = \frac{\sigma}{E} \tag{J.1}$$

$$\epsilon = \frac{\delta l}{l_0} \tag{J.2}$$

$$\sigma = \frac{F}{A} \tag{J.3}$$

Combining the equations leads to the resulting equation J.4.

$$\frac{\delta l}{l_0} = \frac{F/A}{E} \qquad \frac{\delta l}{l_0} = \frac{F}{AE} \qquad \delta l = \frac{F l_0}{AE} \tag{J.4}$$

When applying the deformation formula to a situation with three materials, equation J.5 is true, which, when filled in with the resulting formula of equation J.4, leads to equation J.6.

$$\delta l_{tot} = \delta l_1 + \delta l_2 + \delta l_3 \tag{J.5}$$

$$\delta l_{tot} = \frac{F l_{01}}{AE_1} + \frac{F l_{02}}{AE_2} + \frac{F l_{03}}{AE_3}$$
$$\delta l_{tot} = \frac{(F l_{01} AE_2 AE_3) + (F l_{02} AE_1 AE_3) + (F l_{03} AE_1 AE_2)}{AE_1 * AE_2 * AE_3}$$
$$\delta l_{tot} = \frac{(F l_{01} E_2 E_3) + (F l_{02} E_1 E_3) + (F l_{03} E_1 E_2)}{AE_1 E_2 E_3} \tag{J.6}$$
$$\delta l_{tot} = \frac{F((l_{01} E_2 E_3) + (l_{02} E_1 E_3) + (l_{03} E_1 E_2))}{AE_1 E_2 E_3}$$
$$F = \frac{\delta l_{tot} * AE_1 E_2 E_3}{(l_{01} E_2 E_3) + (l_{02} E_1 E_3) + (l_{03} E_1 E_2)}$$

Comparing two situations in which E_3 is different in both cases, equation J.7 will show what the influence on the force in both those cases will be compared to each other.

$$\frac{F_1}{F_2} = \frac{\delta l_{tot} * AE_1E_2E_s}{(l_{01}E_2E_s) + (l_{02}E_1E_s) + (l_{0_s}E_1E_2)} \Big/ \frac{\delta l_{tot} * AE_1E_2E_n}{(l_{01}E_2E_n) + (l_{02}E_1E_n) + (l_{0_n}E_1E_2)}$$
$$\frac{F_1}{F_2} = \frac{E_s}{(l_{01}E_2E_s) + (l_{02}E_1E_s) + (l_{0_s}E_1E_2)} \Big/ \frac{E_n}{(l_{01}E_2E_n) + (l_{02}E_1E_n) + (l_{0_n}E_1E_2)}$$
$$\frac{F_1}{F_2} = \frac{E_s}{(l_{01}E_2E_s) + (l_{02}E_1E_s) + (l_{0_s}E_1E_2)} * \frac{(l_{01}E_2E_n) + (l_{02}E_1E_n) + (l_{0_n}E_1E_2)}{E_n} \quad \text{(J.7)}$$
$$\frac{F_1}{F_2} = \frac{(l_{01}E_2E_nE_s) + (l_{02}E_1E_nE_s) + (l_{0_n}E_1E_2E_s)}{(l_{01}E_2E_sE_n) + (l_{02}E_1E_sE_n) + (l_{0_s}E_1E_2E_n)}$$

Simplifying the equation using constants leads to equation J.8.

$$l_{01}E_2E_nE_s + l_{02}E_1E_nE_s = a$$
and
$$l_{0_n}E_1E_2 = b \quad \text{(J.8)}$$
$$\frac{F_1}{F_2} = \frac{a + bE_s}{a + bE_n}$$

If it is assumed that E_s is smaller than E_n, then equation J.9 holds.

$$E_s < E_n$$
so
$$a + bE_s < a + bE_n \quad \text{(J.9)}$$
so for the equation to be true
$$F_1 < F_2$$

This calculation shows that using a material with a lower Young's modulus decreases the force needed to push the electrode and the material above it between the snap-ring and the skin.

K

Invention disclosure form questions

The following questions were derived to get a first sense of the novelty of the design for a new electrode configuration. The answers can be found below each question.

WIPO [64]:

1. What problem does the invention solve? - Do not describe the invention but instead focus on the problem found with existing technology, processes or services, or a recognized problem not adequately solved by existing technologies, processes or services.
    - The problem this invention would solve is that currently used electrodes need an adhesive or gel to conduct signals properly. Both of these can cause damage to the skin. For applications in the medical field that need electrodes, dry electrodes would therefore be better. Pressure however needs to be applied to those electrodes for the contact to still be well enough to get a good signal. This pressure again damages the skin. So a way should be found to decrease the pressure while ensuring proper contact.
2. What is the stage of development of the invention?
    - idea/concept
    - early stage
    - **proof of concept**
    - prototype
    - industry interest/use
3. Describe the invention in detail - Consider the commercial applications of the technology and how they might be applied to a product, process or service. Importantly, please describe what aspects of the inventions have been proven experimentally and what is shown by the data. Also describe what materials or prototypes have been created in relation to the invention. Attach any technical documents of Invention including (submitted or draft) manuscripts, posters, theses and grant applications.
    - The invention has been explained in Chapter 6. The part that is novel includes the electrode and a sponge-like material layer. The snap-ring is not part of the invention, since it already exists. The configuration which leads the wire through the sponge-like material to connect to the electrode is part of the invention.
4. Competitive advantage: - Describe the competitor technologies, processes or services which attempt to address the above described problem. What is the closest existing or known technology – please provide links to the related companies' products or service webpages. What are the advantages and benefits of your invention over these competitor approaches – have you experimentally compared your invention to the "gold standard" competitor technology or process?

- The closest invention that solves the described problem above are inventions that are on-skin electrodes. Chapter 2 describes these electrodes in detail and also references the competitors webpages. No actual experiments have been done to compare the invention to these inventions, but the main concept on which their solution to the problem is based is different – namely, this invention uses a layer that dampens the forces within the configuration, whereas the on-skin electrodes focus on finding new materials for the electrodes themselves that are more flexible or skin-like.

5. To what can this invention be applied? (Technical applications)
    - The invention can be used in any device that needs electrodes in contact with the skin, but poses exceptional advantage for patients that have a fragile or pressure-sensitive skin.
6. What further research will be conducted over the next 12 months to demonstrate proof of concept or further validate the invention?
    - No planned activities exist yet to develop this invention further. Informed parties such as the TU Delft and UMCU or specific informed persons might be interested in developing a plan for further development or validation.
7. Are you aware of any obligations to any sponsors e.g. disclosure of inventions/IP, final project reports, or commercial grant of rights (option/licenses)?
    - No obligations exist right now for the disclosure of this invention. A thesis report will be submitted to the registry of the TU Delft, but an embargo of my own choice will be applied. In this case, an embargo of one year seems suitable, because an application that would protect this invention could easily be applied for within that timeframe.
8. Has any software been developed?
    - The invention is solely based on hardware.
9. Please provide details of literature and patent searches - Please list publications that are closely related to your work. Please also list closely related patents and attach a list of the keywords used and results obtained.
    - Patent database Espacenet has been searched to find other related patents. Searches lead to mostly very specific applications of dry electrodes and some that are similar to the sensors of Sentec that have been described in Chapter 6. A quick search did not lead to finding any patents that use a damping material to lessen the pressure on the skin. The following search terms have been used:
        - (On-)skin electrodes
        - Dry-electrodes
        - Dampened electrodes

NWO [65]:

1. Key words - these are required to allow patent databases to be searched for similar inventions
    - See question 9 of WIPO
2. State of the art - patent search performed, search in scientific literature performed
    - See question 9 of WIPO and Chapters 2 and 6
3. List all publications (by yourself and by others) and patents on this topic known to you which may jeopardize the novelty of your invention and consequently its patenting, or which come closest to your invention. Please briefly summarize the main points of each relevant publication and patent and describe the differences with your invention.
    - See question 9 of WIPO, furthermore, some on-skin electrodes or EEG electrodes also try to reduce the damage they can cause to skin
4. For which problem has a solution been found?

- See question 1 of WIPO

5. How does the invention resolve the problem? Describe the new or improved method or product. Explain the invention and how it works
    - See Chapter 6
6. Is the invention completely new, or does it build on the current state of the art?
    - An important distinction needs to be made as to what the new part of the invention is. The new part of the invention is the use of a sponge-like material, or a material with a low Young's modulus, through which the wire that connects the electrode is placed. The part that the invention interacts with, which is the snap-ring, is not novel.