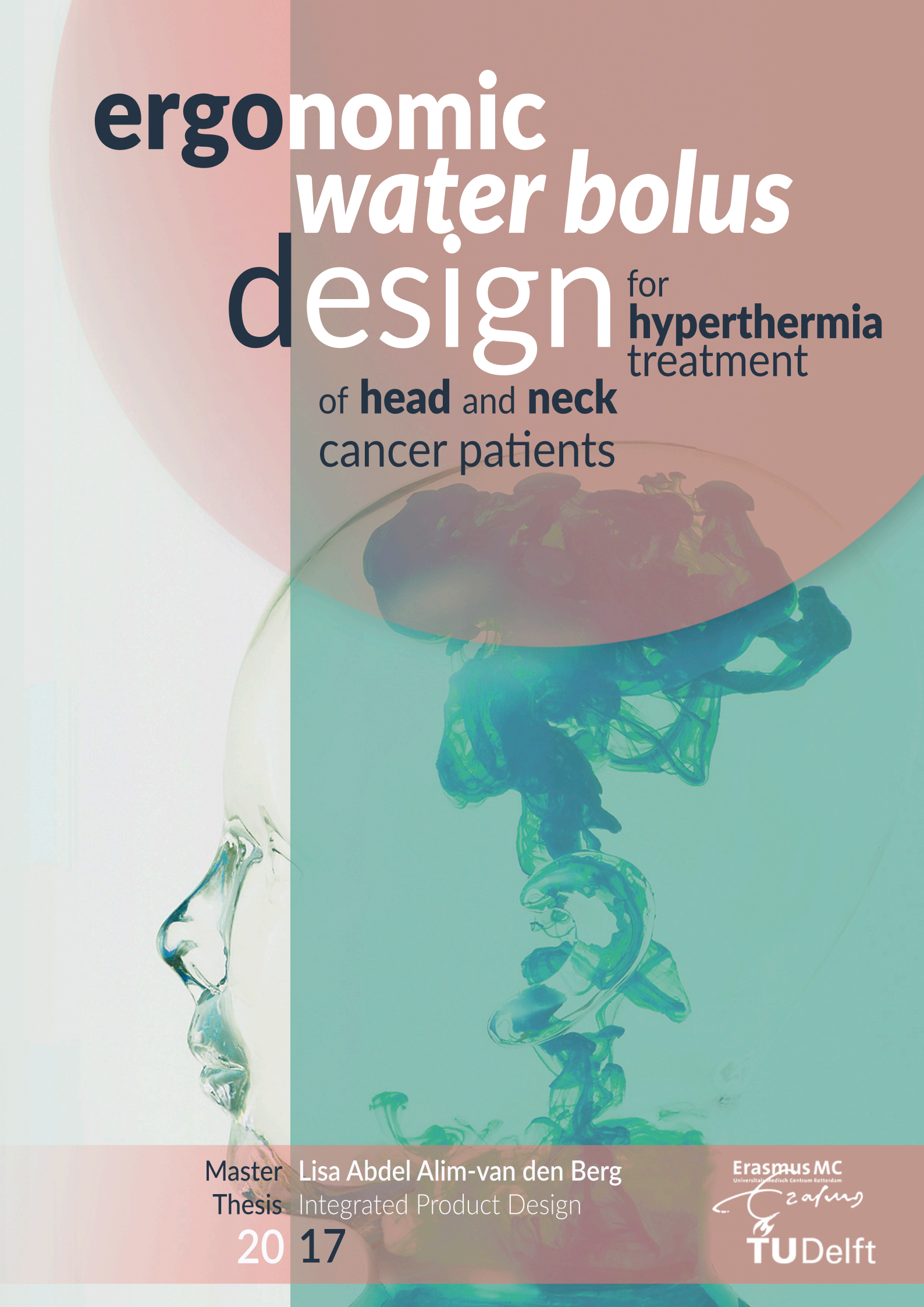
ergonomic *water bolus* design for **hyperthermia** treatment of **head** and **neck** cancer patients



Master Thesis
Lisa Abdel Alim-van den Berg
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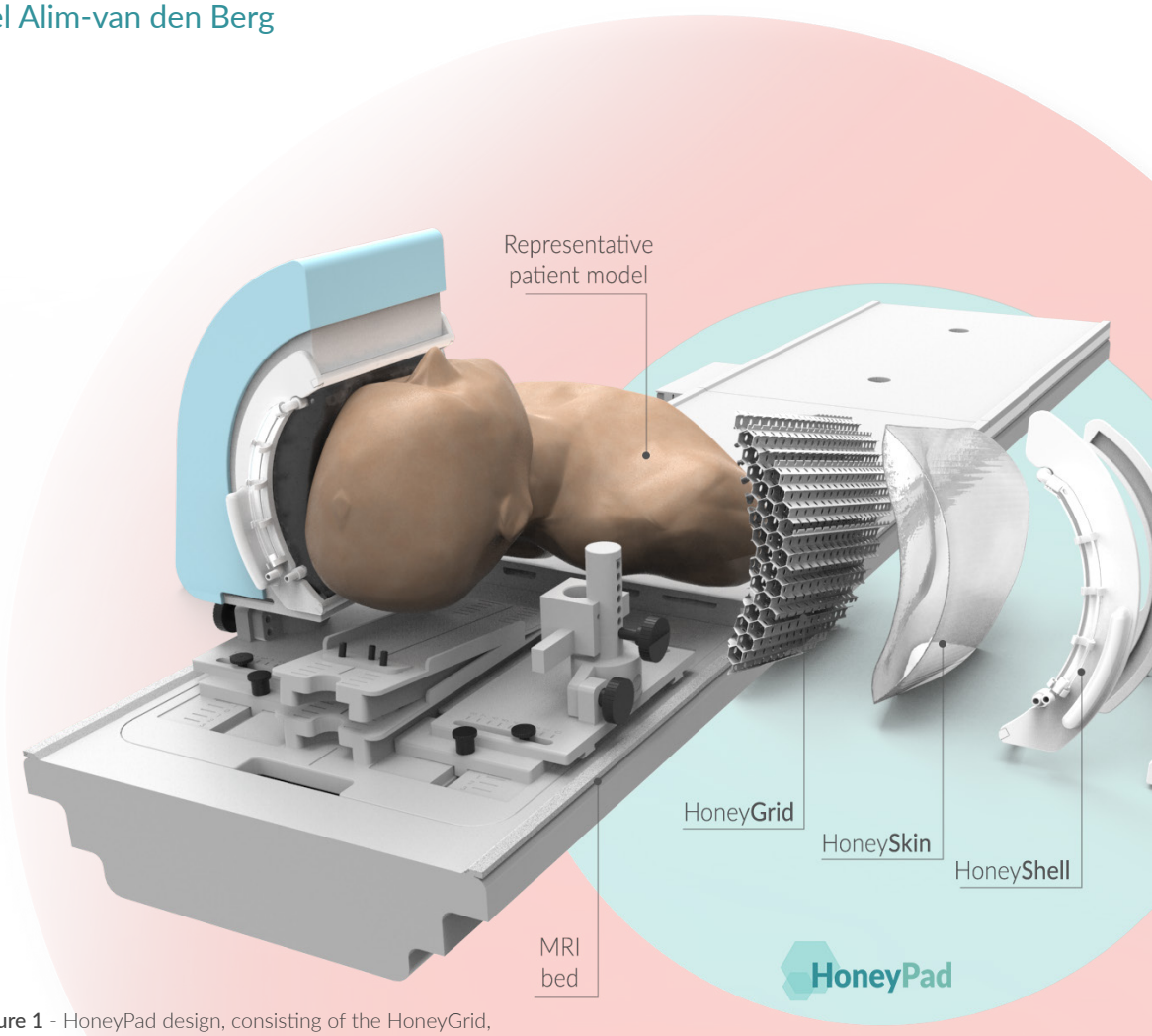

Figure 1 - HoneyPad design, consisting of the HoneyGrid, HoneySkin and HoneyShell, integrated in DHT equipment

II Executive Summary

This master thesis report focuses on the development of the HoneyPad: a redesigned water bolus for deep head and neck hyperthermia treatment that increases patient- and operator comfort. Hyperthermia is a clinical cancer treatment method that relies on the principle of selectively heating tumour tissue with temperatures between 40 - 44 °C. For most head- and neck tumours deep hyperthermia treatment (DHT) is applied, in which electromagnetic energy is emitted to tumour tissue located ≥ 4cm below the skin surface. At the Erasmus MC Cancer Institute in Rotterdam, The Netherlands, electromagnetic energy is applied from a circular shaped applicator that is placed around the patient's head or neck. A water bolus is placed between the applicator and the patient's skin to act as a cooling agent to prevent skin burns and as a transferring agent to conduct the electromagnetic energy to the internal tumour tissue.

Design Challenge

The goal of this master thesis was to redesign the water bolus that is currently applied in DHT at the Erasmus MC to increase patient- and operator comfort. For this purpose two main design challenges were addressed:

i) Design of an ergonomic fit for the water bolus
ii) Development of a method for uniform skin cooling and pressure control

To design a water bolus with an optimal fit for the head and neck of every patient, a 4D anthropometric analysis was conducted with 3D CAD models of head- and neck cancer patients that have been treated with hyperthermia at the Erasmus MC. Based on this analysis, a 4D representative patient model was created that has been used to form an anatomically shaped water bolus. Furthermore, operator comfort was addressed by optimizing the mechanism to connect the water bolus to the equipment and by increasing shape stability of the water bolus. Additionally, to address uniform skin cooling and pressure control, a series of prototypes, simulations and experiments has resulted in the design of an optimal water flow pattern and a flexible honeycomb grid.

HoneyPad

The final water bolus design, i.e. HoneyPad, consists of the HoneyGrid, HoneySkin and HoneyShell. These components are depicted in Figure 1. The HoneyGrid provides shape stability to the water bolus in the direction that is pressed during installation, whereas the sides of the grid that are in contact with the patient's skin provide flexibility. This ensures that the HoneyPad closely follows the human contours and that any pressure points are eliminated. Honeycomb shaped pipes ensure an optimal water versus bolus material ratio, which is beneficial for the transferring and cooling functions. A strategic perforation pattern in the HoneyGrid guides circulating water through the entire water bolus volume to uniformly cool the patient's skin. The HoneyGrid can be 3D-printed with flexible filament to ensure an accurate anatomical shape and minimize human labour for the manufacturing. The HoneySkin is wrapped closely around the HoneyGrid and holds the water volume of the bolus. This component is made from biocompatible materials that feel comfortable when touching the skin. The HoneyShell enhances the shape stability of the HoneyPad and forms the mechanical connection with the hyperthermia equipment. A stable shape, sliding mechanism design and handles enable an easy attachment to the DHT applicator by the operator. The HoneyPad design will be implemented into the existing DHT treatments at the Erasmus MC and will significantly improve patient- and operator comfort.

III Acknowledgement

Although a master thesis is said to be the work of an individual, it would most definitely not have been possible to achieve this results without having the great team of project coaches, colleagues, experts and my family and friends around me. Therefore I would like to take this opportunity to express my gratitude to all of the people that were in any way involved in this master thesis.

First of all I would like to thank Iemkje Ruiter, who was the Chair of the supervisory team, for sharing her knowledge on ergonomics, directing me to the right experts or literature and for providing the right feedback at the right time. Her friendly guidance helped to minimize the pressure of the project and focus on the priorities.

I also want to thank Nina Bogerd, who agreed to be the Mentor of the supervisory team, for taking extensive time to analyse my work into detail and provide me with advice on scientific writing and physiological cooling systems. Her commitment and sincere enthusiasm significantly contributed to the quality of this project.

The elaborate, constructive criticism of my company mentor, Maarten Paulides, contributed to the achievements in this master thesis as well. He encouraged me to keep improving the results and helped me to do so by sharing his expertise regarding hyperthermia and the clinical context. Thanks to him, I was offered the opportunity to contribute to the developments of hyperthermia by working on this challenging, educative project.

My appreciation also for the help I received from the staff of the Hyperthermia Unit, to get access to the equipment, to get in contact with patients and experts and to provide feedback on my ideas. Special thanks to Audrey Wijngaarde who took the time to share all the facts and skills regarding the use and manufacturing of the water bolus. Also thanks to Daniel de Jong, who gave me a lot of input based on his experience with the clinical procedures of hyperthermia. Furthermore I want to thank Ali Ameziane and Kemal Sümser who assisted me in selecting, setting up, executing and interpreting the results of clinical experiments, and for coming up with new strategies when things did not work out as planned. Thanks to Tomas Drizdal as well, who shared his expertise on the EM and MR context, provided feedback on the feasibility of ideas and pointed out directions for improvement.

Special thanks to the staff from the Instrument Makerij at the Erasmus MC and the PMB at the Industrial Design Engineering faculty as well, for advising and assisting me in the development of prototypes. I also want to express my gratitude to Tessa Essers from Applied Labs, who offered me the possibility to use the 3D-printing equipment and who shared her knowledge in this area. Furthermore, thanks to Wonsup Lee from StudioLabs who showed me different methods of performing a 3D anthropometric analysis and to alumni Stefan van Seggelen who taught me more about applying Grasshopper algorithms.

Last but not least, I want to thank my family and friends who showed sincere interest and sympathy, and who did everything they could to think along at times when I seemed to be out of solutions. They shared my stress and relief and encouraged me to achieve my goals.

IV Glossary

Applicator
The part of the hyperthermia equipment that applies the heat to the tissue. In this report often referred to as the round shell part that contains the antennas.

Chemotherapy
A clinical method to treat cancer with anti-cancer drugs.

Clinical Target Volume (CTV)
The Gross Tumour Volume plus a margin that takes into account the disease spread that cannot be fully imaged with an MRI or CT.

Dielectric Heating
The heating of an object through molecular friction in a high frequency alternating electric field consisting of electromagnetic waves.

Electromagnetic Waves
Synchronized oscillations of electric and magnetic fields that can carry energy and impart this to matter with which they interact.

Erasmus MC Cancer Institute
A cancer institute in Rotterdam that focuses on treating patients, education and research regarding cancer. The Erasmus MC Cancer Institute asked for a graduate student to be involved in the development of a water bolus for an innovative hyperthermia system.

Gross Tumour Volume (GTV)
The volume of tumour tissue as is imaged by an MRI- or CT-scan.

HoneyGrid
Honeycomb shaped flexible grid that is inserted in a water volume inside the HoneySkin. The HoneyGrid provides an ergonomic fit to the head and neck, shape stability and a uniform water flow. See Figure 1.

HoneyPad
The ergonomic redesign of the water bolus, increasing patient and operator comfort, that has been developed in this master thesis. The HoneyPad consists of the HoneyGrid, HoneySkin and HoneyShell as is visualized in Figure 1.

HoneyShell
Frame around the HoneyGrid and HoneyShell that forms shape stability and the mechanical connection to the hyperthermia equipment. See Figure 1.

HoneySkin
Watertight plastic bag that surrounds the HoneyGrid and the water and forms the contact layer between HoneyPad and patient. See Figure 1.

HYPERcollar
The first generation prototype of the innovative deep head and neck hyperthermia equipment that has been developed by the Erasmus MC Cancer Institute.

HyperCollar3D
The second generation prototype of the innovative deep head and neck hyperthermia equipment that has been developed by the Erasmus MC Cancer Institute.

Hyperthermia
A clinical method to treat cancer by exposing body tissue to high temperatures with minimal damage to normal tissue. In superficial hyperthermia treatment (SHT) tumours located ≤ 4cm under the skin are targeted. In deep hyperthermia treatment (DHT) tumour located ≥ 4cm under the skin are targeted.

Landmarks
Measurement points on the human body that are used for anthropometric analyses.

MRcollar
The third generation prototype of the innovative deep head and neck hyperthermia equipment that has been developed by the Erasmus MC Cancer Institute, which is used inside an MRI-scanner. See Figure 1.

Radiotherapy
A clinical method to treat cancer by exposing body tissue to electromagnetic radiation with minimal damage to normal tissue.

Specific Absorption Rate (SAR)
The power absorbed from the emitted electromagnetic waves per mass of tissue, which influences the thermal distribution in the tissue.

Technobis
Mechatronics company in Alkmaar, The Netherlands, that the Erasmus MC collaborates with for development of the improved HyperCollar3D and MRcollar equipment.

Water bolus
A flexible cushion between the patient and the hyperthermia equipment that acts as a skin cooling agent and as a conductor for electromagnetic waves by circulating water through. The hyperthermia equipment of the Erasmus MC consists of an inner and an outer water bolus, which is depicted in Figure 2.

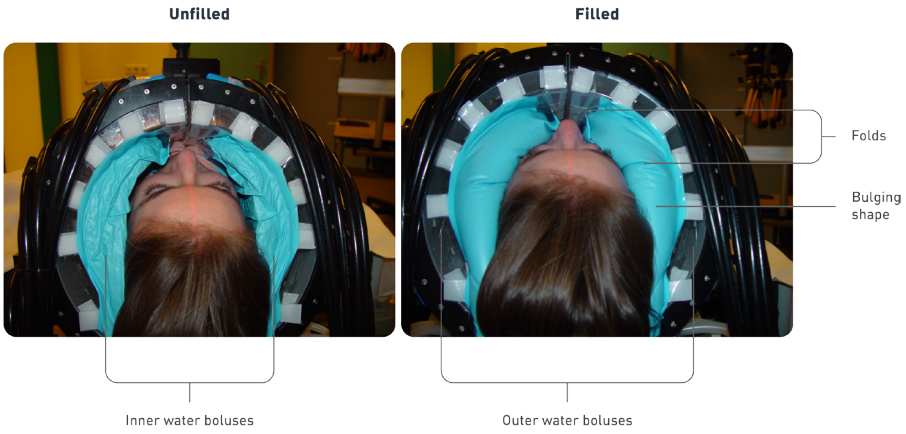

Figure 2 - Inner and outer water bolus of deep hyperthermia treatment equipment

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1 Introduction

What and Why?

The medical field of cancer treatment technologies is under constant development. Hyperthermia is one of the fields in which innovations are currently being made. This clinical cancer treatment method relies on the principle of locally heating tumour tissue. A relevant element in hyperthermia equipment is the so called water bolus, which is a flexible cushion between the equipment and the skin of the patient. By circulating water through this water bolus, the component acts as a cooling agent that prevents the skin of the patient from heating to uncomfortable and dangerous temperatures. Furthermore, the water bolus ensures that all the heating energy is conducted to the internal tissue of the patient.

This thesis focuses on the development the HoneyPad, which is an ergonomic water bolus for hyperthermia treatment of head- and neck cancer patients. The HoneyPad increases the patient and operator comfort in different aspects of the treatment. The design has been developed in collaboration with the Erasmus MC Cancer Institute in Rotterdam, who aims to use the design in deep head and neck hyperthermia treatments in their clinic. For six months I have worked at the Hyperthermia Unit of the Erasmus MC Cancer Institute as a graduate intern.

Partners

The Erasmus MC Cancer Institute focuses on treating patients, education and research related to cancer. The institute mainly consists of a large Radiology Department that has a separate Hyperthermia Unit. Apart from treating superficial tumours and deep pelvic tumours, this Hyperthermia Unit is the first institution worldwide to have developed a hyperthermia system specifically for treatment of deep head and neck tumours. The Erasmus MC asked for a graduate student to be involved in the development of a water bolus for this innovative hyperthermia system.

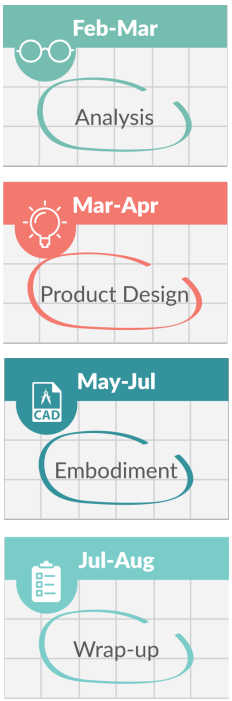
The faculty of Industrial Design Engineering of the Delft University of Technology has been involved in this thesis by coaching me throughout the design process. The involved coaches were from the departments of Applied Ergonomics and Design Engineering. Their knowledge of anthropometry, emerging materials and physiological cooling has been applied in this thesis.

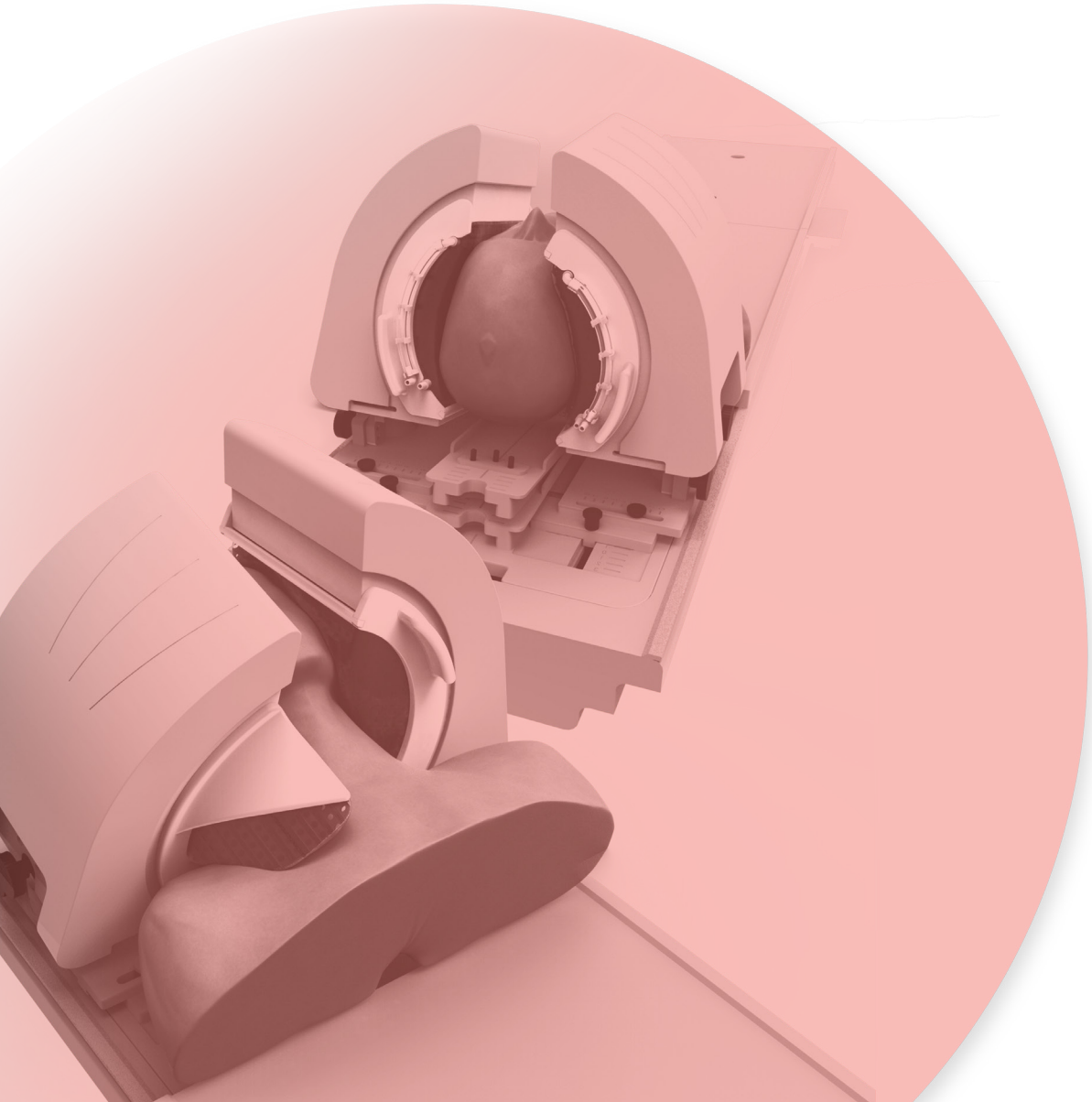
Design Brief

The Erasmus MC Cancer Institute has defined a thesis assignment for further improvement of a water bolus to be used in two different hyperthermia devices of which one will be commercialized. This redesigned water bolus has to be suitable for deep head and neck hyperthermia treatment. To ensure good contact with the skin of the patient for adequate cooling, the water bolus should ergonomically follow the patient´s contours. In addition, the water bolus should enable adequate treatment of patients with tumours in the larynx. The current equipment is unable to transfer heat to target areas in the larynx, resulting in the inability to treat these patients with hyperthermia. Furthermore, the redesign should provide optimal comfort because the effectiveness of hyperthermia is dependent on the stress that is experienced by the patient. The usability for clinicians should be taken into account as well. Important to consider in this thesis is the MRI-compatibility of the redesigned water bolus, as one of the devices is guided by MRI-imaging. The goal of the thesis is to develop a design and prototypes that can be used in clinical studies of the Erasmus MC Cancer Institute.

Approach

The six-month duration of this design project has been divided into three consecutive phases; the analysis, product design and embodiment phase. Because the priority in this thesis is the development of prototypes, a longer period of time has been dedicated to the embodiment phase compared to the analysis and product design phase. In this thesis report the results of the contextual analysis that are relevant for defining boundary conditions and design opportunities will be discussed. The design challenges that have been formulated based on the analysis outcomes form the input for idea generation and the creation of conceptual water bolus designs. One of these concepts has been selected for further detailing and prototyping to finally result in the HoneyPad design. The different insights and design steps regarding these three phases will be presented in this thesis report.





2 | Analysis

The context regarding hyperthermia treatment at the Erasmus MC Cancer Institute has been analysed to get a deep understanding of the relevant factors in this field and to discover points for improvement. In this contextual analysis, attention has been paid specifically to the usability and functionality of the water bolus, but also to the broad picture of the entire hyperthermia equipment and the treatment procedure. This is needed to identify the boundary conditions for the water bolus and to discover opportunities to make the redesigned water bolus fit seamlessly into its context. Points for improvement have been derived from the perspectives of different user groups; the patients, the clinicians, the technicians and the engineers. These points for improvement have been translated into design challenges that will be addressed by the redesign of the water bolus.

Hyperthermia

Hyperthermia is a clinical method to fight tumour cells by exposing body tissue of cancer patients to high temperatures. Research has shown (Van der Zee, 2002) that tumour cells are selectively affected when exposed to temperatures between 40 and 44 °C during hyperthermia treatment. This effect is related to a characteristic difference in the physiology of tumour tissue and healthy tissue. Tumour tissue is characterized by a reduced blood flow compared to healthy tissue, resulting in regions with a reduced oxygen content and low pH level. These characteristics allow tumour tissue to heat more easily than healthy tissue, which increases the sensitivity to hyperthermia. Healthy tissue mostly remains undamaged by a hyperthermia treatment of one hour at a temperature up to 44 °C, which makes hyperthermia suitable to locally control tumours while sparing healthy tissue.

Hyperthermia treatment causes an increased blood flow by dilating the blood vessels around the tumour, which causes oxygen carrying red blood cells to spread into the tumour. When radiotherapy is applied within one hour after hyperthermia treatment, the radiation reacts with the high levels of oxygen in the tumour, resulting in an increased potential to destroy the tumour cells. When the patient receives chemotherapy after hyperthermia treatment, the increased flow of blood to the tumour tissue can potentially guide more administered anti-cancer drugs towards the tumour (Cancer Treatment Centers of America, n.d.).

Research indicates (Van der Zee, 2002) that hyperthermia as a single treatment results in an overall increased percentage of patients whose tumour shrinks after treating. However, only a part of the tumour cells will be eliminated by exclusively applying hyperthermia. Therefore, hyperthermia is mainly used as a complementary treatment to, and sensitizer of, radiotherapy or chemotherapy, because hyperthermia enforces the effects of these conventional methods. This combination of treatments can result in a doubled response rate of the cancerous tissue and better overall patient survival rates.

Application Methods

The high temperature that is required to heat the tumour tissue of cancer patients is induced by exposing this tissue to electromagnetic waves. This dielectric heating principle is similar to the technology of a microwave. Electrically charged particles form an alternating electrical field combined with an alternating magnetic field when they are accelerated

or decelerated; resulting in an electromagnetic wave as can be seen in Figure 3. The high frequency electromagnetic field that is created by multiple electromagnetic waves can heat a dielectric object because the molecules in this object will constantly move to align with the alternating field, creating frictional interaction with the surrounding molecules which results in heat (Piyasena et al., 2003).

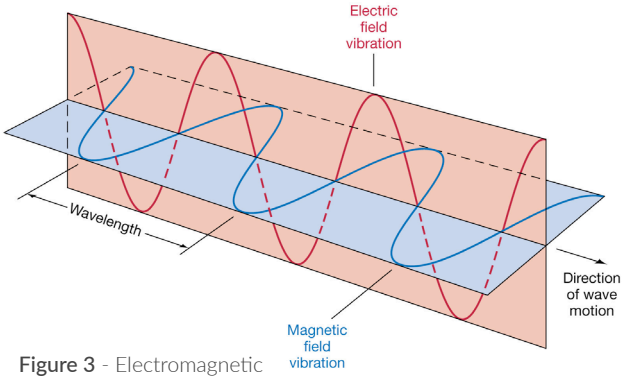


Figure 3 - Electromagnetic wave consisting of alternating electric and magnetic fields

Currently two methods exist for applying hyperthermia externally (Van der Zee, 2002). These methods include:

I) Superficial hyperthermia treatment (SHT), which is used to treat tumours located at a depth less than 4 cm under the skin (Erasmus MC Cancer Institute, n.d.);
II) Deep hyperthermia treatment (DHT), which is used to treat tumours located at a depth more than 4 cm below the skin (Erasmus MC Cancer Institute, n.d.).

In SHT, electromagnetic energy inducing the heating effect is emitted by multiple applicators that are positioned on the body surface in such a way that the entire treatment area can be reached by the waves (De Bruijne, 2011). As can be seen in Figure 4, the different applicators emit the electromagnetic waves from a single direction (Van der Zee, 2002). The treatment area that the waves should cover is defined by the location and volume of the tumour as is imaged by an MRI or CT-scan (the Gross Tumour Volume, GTV), plus a margin that takes into account the disease spread that cannot be fully imaged (the Clinical Target Volume, CTV). The CTV must be adequately treated to achieve cure. To ensure that

the electromagnetic dose is actually delivered to the CTV, a Planning Target Volume (PTV) can be used as the treatment area to allow for uncertainties in the treatment planning and delivery (Burnet et al., 2004).

A layer with circulating water, the water bolus, is placed between the applicators and the skin of the patient as a cooling agent to prevent burns from the radiated heat and as a transferring agent for the electromagnetic energy. The set-up for SHT treatments is visualized in Figure 4.

In DHT, the electromagnetic waves are radiated from different directions around the targeted tissue. The definition of the treatment area is similar as in SHT. As can be seen in Figure 5, multiple antennas are distributed radially on a circular shaped applicator which is placed around the patient (Van der Zee, 2002). The DHT equipment consists of one applicator that can be translated and rotated around the patient in limited ways and a water bolus that is placed between the applicator and the skin. In order to cool the skin and transfer the energy adequately, the water bolus should cover the same treatment area as the electromagnetic waves.

The scope of this master thesis is limited to deep hyperthermia, specifically for head and neck cancers. Therefore, the content of the following sections will focus on this technology in particular.

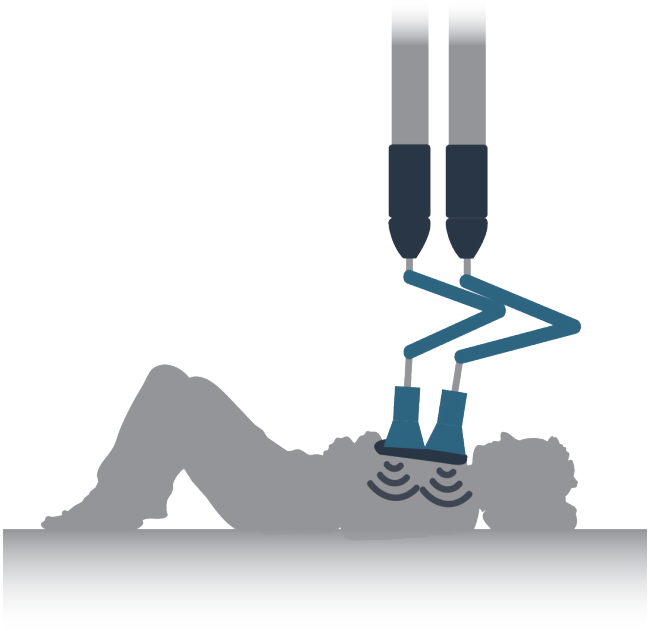


Figure 4 - Set-up for superficial hyperthermia treatment (SHT)

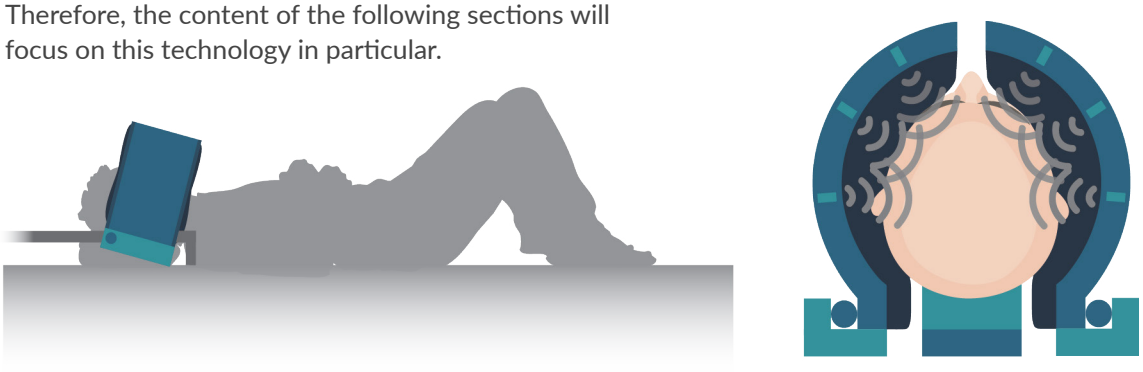


Figure 5 - Set-up for deep hyperthermia treatment (DHT)

Head and Neck Cancer

The scope of this master thesis is focusing specifically on the hyperthermia treatment of tumours located within head and neck regions. This scope is chosen because the Erasmus MC Cancer Institute, with whom has been collaborated during this thesis, is developing an innovative deep hyperthermia applicator to treat head and neck tumours. Such tumours usually start developing in the squamous cells that are located in the mucosal membranes, for example inside the nose, mouth and throat (National Cancer Institute, 2013). Tumours located within head and neck regions account for approximately 3,2% of all cancer incidences in the United States. Figure 6 shows how this percentage of head and

neck cancers is divided into the incidences of larynx, oral cavity and pharynx tumours (Jemal et al., 2010).

Approximately 48,5% of the total head and neck tumours are located in the oral cavity (Jemal et al., 2010). Tumours in the oral cavity can grow on the lips, tongue, gums, mucosal membrane of the cheeks, hard palate or under the tongue (National Cancer Institute, 2013). Whereas, the larynx tumours account for approximately 25,8% and pharynx tumours for 28,7% of the tumours located in the head and neck (Jemal et al., 2010). An overview of these head and neck cancer regions is shown in Figure 7.

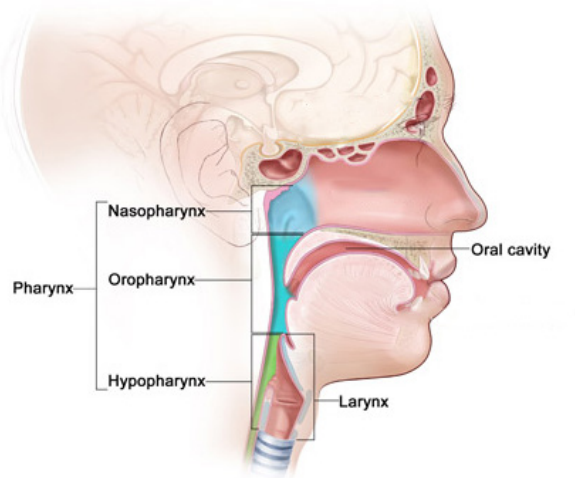


Figure 7 - Common areas of head and neck tumours

Applying hyperthermia treatment to the head and neck area is a challenging task. Namely, this region is characterized by many tissue transitions, for example transitions from bone to muscle, and large blood vessels that have a significant effect on the thermal distribution of the heat that is applied during hyperthermia. Varying absorption properties of different tissues make it difficult to direct energy of the electromagnetic waves toward the tumour because they cause an inhomogeneous distribution of the energy. The large blood vessels have the function to cool the arterial blood before it reaches the brain. This cooling function counteracts the

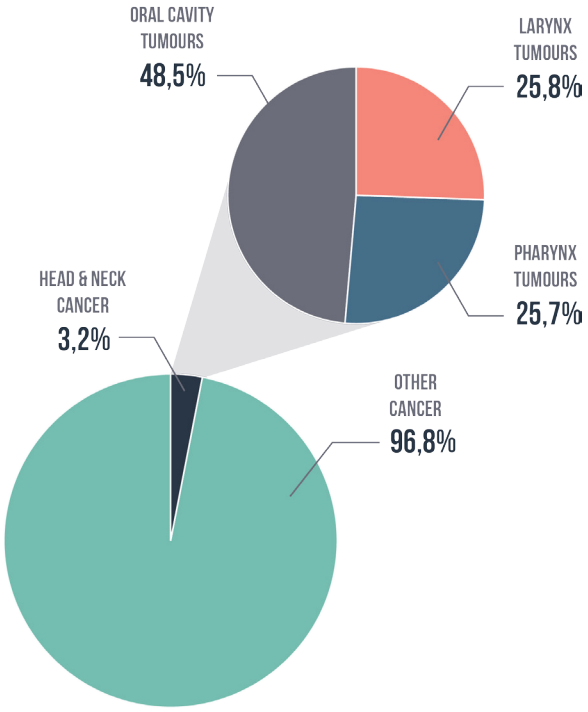


Figure 6 - Incidence of different types of head and neck cancer

dielectric heating of tissue, putting difficult demands on the applied energy dosage. To ensure precise control of heating, the temperature of the tumour tissue and the surrounding critical healthy tissue should be monitored during treatment. By accurately measuring local temperatures, it can be ensured that the tumour is exposed to the optimal treatment temperature of 40-44 °C and that the critical healthy tissues are not exposed to dangerously high temperatures. Another challenge in deep head and neck hyperthermia is the effect of body positioning differences during the treatment and over the course of different treatments (Paulides et al., 2010). Differences such as a slight rotation of the head or an alternating shoulder position can cause the electromagnetic waves to inadequately treat the CTV or even the GTV area. Due to these challenges, deep head and neck hyperthermia is currently still in a developmental stage.

Hyperthermia Equipment

Various types of equipment exist intended for treatment of superficial and deep tumours. The Hyperthermia Unit of the Erasmus MC Cancer Institute in Rotterdam is having a particular interest in developing technologies for deep hyperthermia treatments of head and neck tumours. This section is therefore focusing on the equipment that has been developed by this institute. Two generations of functional prototypes have already been developed and used in clinical treatments. The first generation was the so called HYPERcollar and the second generation was called the HyperCollar3D. A third generation, which is called the MRcollar, that improves several drawbacks from the previous generations is currently being developed.

HYPERcollar

The first generation of the hyperthermia system, the so called HYPERcollar, consists of a ring shaped applicator. The head or neck of the patient should be positioned inside the applicator's ring. Electromagnetic waves are radiated by twelve antennas that are distributed at equal over the entire circumference of the applicator's ring. The antennas are divided in two groups lined up on two separate sub-rings and each antenna is powered by a so called COAX cable. As shown in Figure 8, the HYPERcollar contains one large circular shaped water bolus.

Drawbacks of the water bolus in the HYPERcollar include a large volume in which the temperature and total water volume are difficult to control. The shape of the water bolus is unpredictable and has a non-linear behaviour, which makes it difficult to reproduce treatment set-ups and apply uniform cooling of the antennas and the patient's skin. In addition, large folds in the water bolus block the water circulation inside the bolus and cause hotspots on the skin induced by air inclusions. Furthermore, the mouth and nose are covered by the water bolus which obstructs the possibility to breathe and makes the treatment an unpleasant experience for the patient (Rijnen et al., 2015).

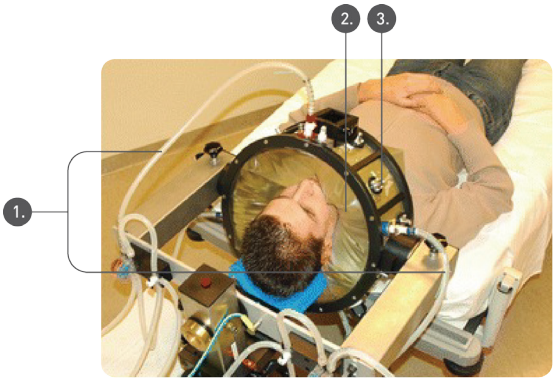


Figure 8 - HYPERcollar, the first generation of DHT equipment

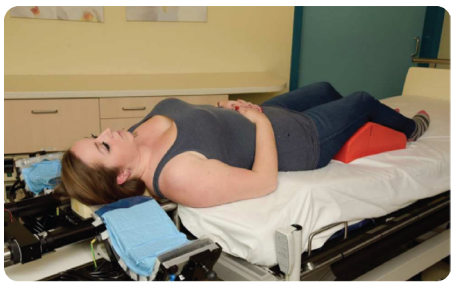


Figure 9 - HyperCollar3D applicator splitting mechanism

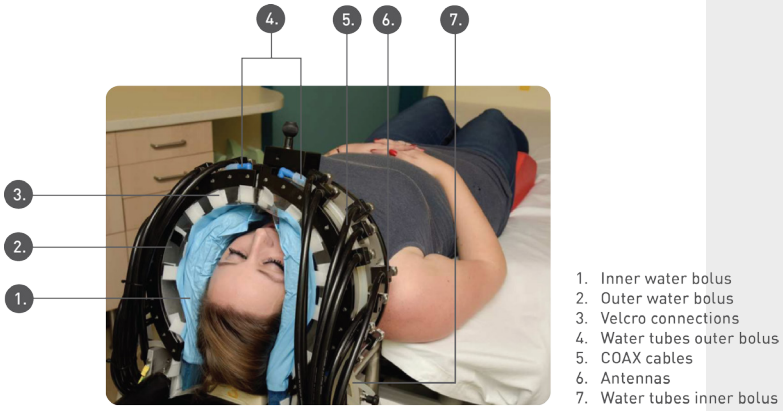


Figure 10 - HyperCollar3D, the second generation of DHT equipment

HyperCollar3D

Several improvements on the HYPERcollar have been made in the second generation, which was named HyperCollar3D. This improved equipment is currently being used in head and neck hyperthermia treatments in the clinic in Rotterdam. The system still consists of a ring shaped applicator. However, as can be seen in Figure 9, the ring can be split in half in order to make positioning of the patient easier and more comfortable. The HyperCollar3D consists of 20 antennas instead of 12. However, for hyperthermia treatment, the 12 antennas that result in the most effective way of heating the targeted tissue are selected and the others are turned off (Rijnen et al., 2015). The antennas are lined up on three rings instead of 2, again to increase local focussing of the heat on the tumour, which is intended to lead to better clinical results in the future. A neck support is added to the HYPERcollar 3D. Because the neck support blocks the antennas beneath the head and neck, these antennas have been shifted upward.

The drawbacks of the water bolus of the HYPERcollar have been improved with many adjustments in the HyperCollar3D. For example, to make the shape, water volume and temperature of the water bolus more predictable, the volume of the entire bolus has been reduced. In order to still provide enough space for both the antennas and flexibility for contact with the patient's skin, the water bolus has been split into an inner and outer part, as depicted in Figure 10.The inner- and outer water bolus have separate tubes for water flow to enable the regulation of different optimal cooling temperatures for the antennas and the skin of the patient. Furthermore, a space for the nose and mouth is included to enable comfortable breathing (Rijnen et al., 2015). More details about the functions of the water bolus will be discussed in the course of this report.

Figure 11 shows the complete treatment set-up with the HyperCollar3D into more detail. The applicator has been mounted on a table which can be adjusted to the same height as the hospital bed in which the patient is lying. The neck support is placed inside the applicator and can be adjusted in height separately. With a connector on top of the applicator the two ring halves can be opened and secured. Water tubes from the inner water boluses are guided to the bottom of the table where they are connected to a water reservoir and a pump that is meant for filling and draining. This fill/drain process is manually regulated with a button on the side of the table. Other ends of the tubes are guided to two different circulation pumps in the corner of the treatment room. Water tubes from the outer water boluses are guided to one other circulation pump in the same corner. Apart from circulating the water, these pumps also regulate the temperature of the water inside the boluses. Power cables, i.e. COAX cables, of the antennas are guided from the applicator towards the room next to the treatment room. This adjacent room contains the hardware that feeds the electromagnetic field that is generated. Via these cables, the system is also connected to a computer controlled by a technician during treatment who creates the optimal electromagnetic field.

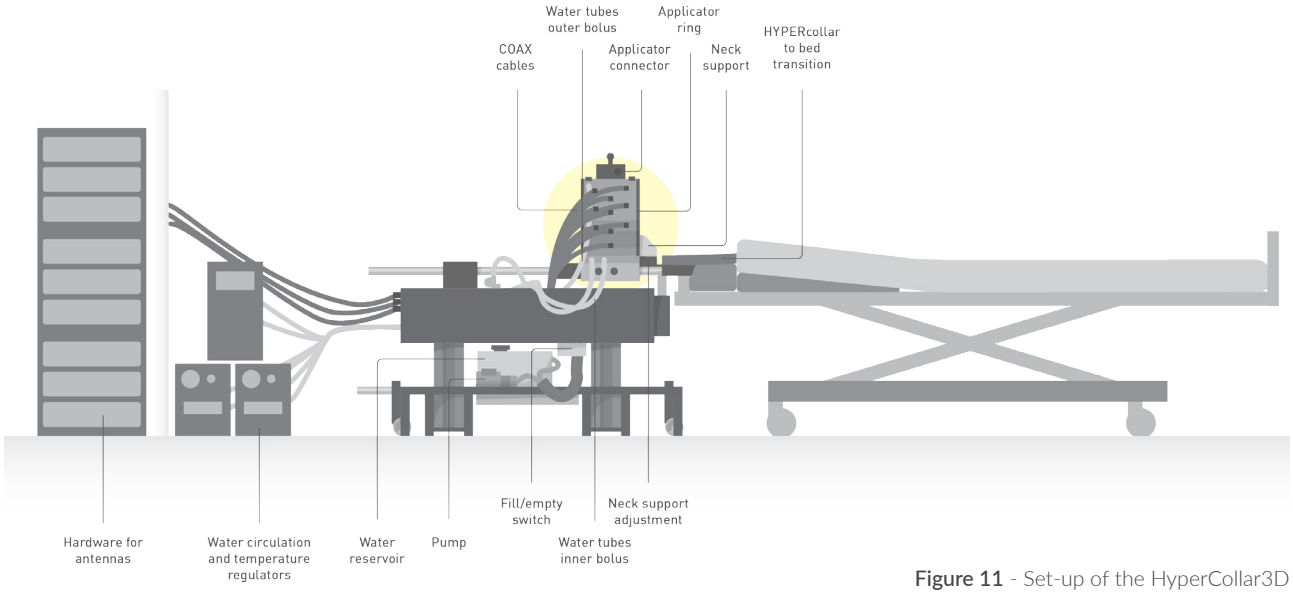


Figure 11 - Set-up of the HyperCollar3D

MRcollar

As was explained before, it is important to monitor the temperature of the patient's tissue during heating to ensure an optimal tumour treatment temperature and a safe temperature for the surrounding healthy tissue. In the HyperCollar3D system, the temperature of the tissue can be controlled by temperature sensors that are invasively placed in the tissue with the help of catheters. The location of these sensors is dependent of the tumour location and the critical tissues that have to be monitored. An example of catheter configuration can be seen in Figure 12a. The catheters cause a serious discomfort for the patient, which usually leads to the removal of the catheters after a few treatment sessions (Paulides et al., 2016). Besides the discomfort, the placement of catheters in the desired areas is often hindered by the presence of large blood vessels in the head and neck region, which is depicted in Figure 12b and 12c (Paulides et al., 2014b).

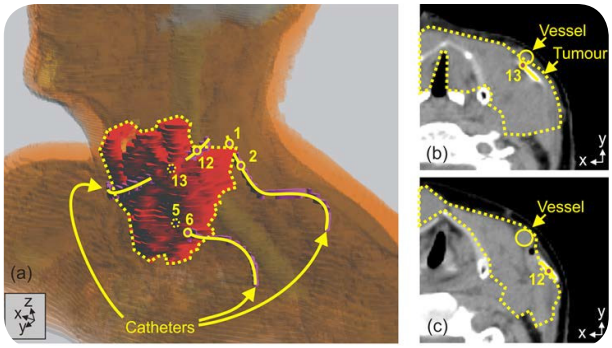


Figure 12 - (a) Catheter and thermos sensor placement in a treatment with HyperCollar3D, (b, c) hindered placement by large blood vessels.

Furthermore, it was found by Paulides et al. (2010) that swallowing and breathing of the patient severely influences the invasive temperature measurements. An improvement to obtain temperature data would be to use non-invasive thermometry techniques

instead. Research is therefore being conducted in the field of measuring temperature during hyperthermia treatment with MRI imaging. An MRI-guided hyperthermia system, called the MRcollar, is currently being developed by the Erasmus MC Cancer Institute. By placing an MRI around the MRcollar, this system is expected to monitor tissue temperatures more accurately than the first and second generations.

The MRcollar will be used inside an MRI-scanner, as Figure 13 depicts. To make the system less complex to develop, the 12 most relevant antennas from the previous 20 have been selected to be implemented in the MRcollar. The new applicator will have 6 antennas on each side, which are grouped in rows of 2 antennas. In the future the total number will be increased to 20 again for improved heat control. The applicator still consists of two half-rings that can be operated separately. In the MRcollar, these half-rings will be translated towards the patient instead of being rotated around the patient. Figure 14 shows the rotating and translating mechanisms of the HyperCollar3D and the MRcollar respectively. This adjustment might enable a smaller antenna-skin distance for an improved heating efficiency and requires less space inside the small bore of the MRI-scanner. Inner- and outer water boluses are still separated. However, only one water circulation system will be used for both water boluses together, due to the limited availability of pumps in the intended MRI-treatment room of the hospital.

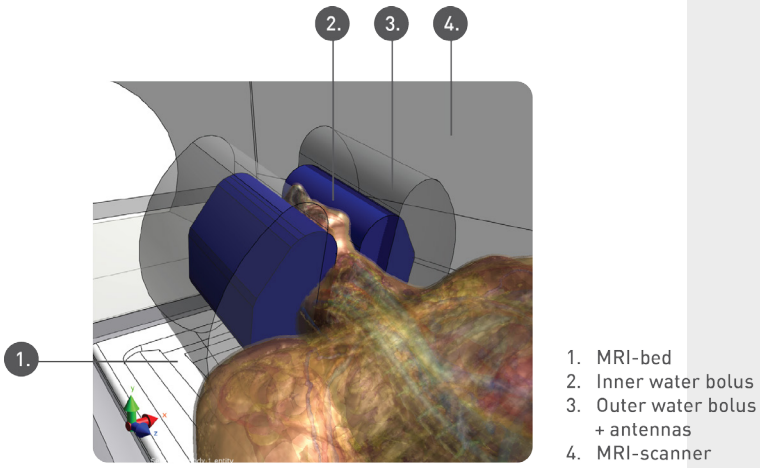


Figure 13 - MRcollar, the third generation of DHT equipment

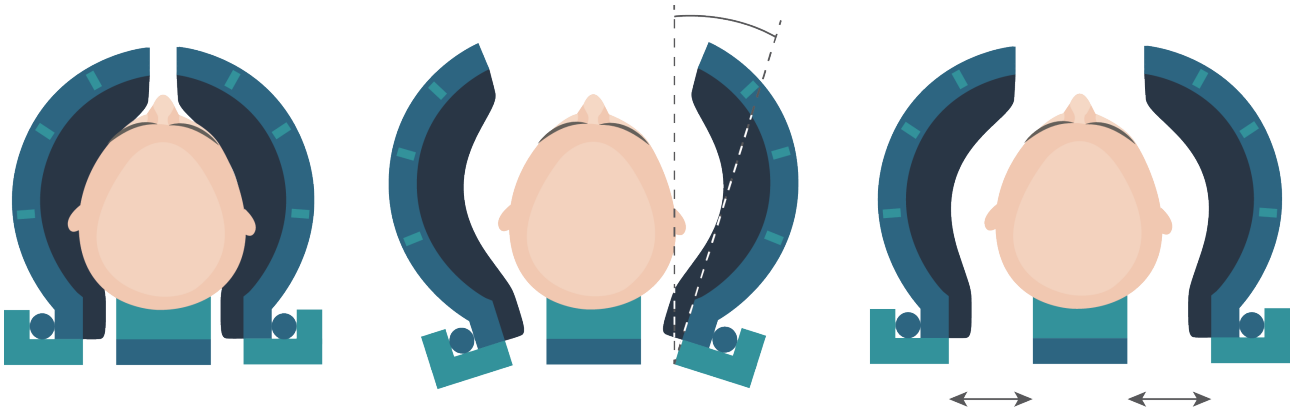


Figure 14 - Rotation and translation of applicator half-rings. (a) Closed applicator, (b) rotation in the HyperCollar3D, (c) translation in the MRcollar.

Magnetic Resonance

Designing a water bolus intended for use inside an MRI-scanner has several boundary conditions as a consequence. All materials that are used inside or near the MRI-scanner need to have non-ferromagnetic and non-conductive properties to prevent attraction to the MRI-bore and distortions of the magnetic field respectively. To prevent distortions, water flow also needs to be minimized during imaging. To understand the boundary conditions, the basic working principle of MRI-imaging is explained in Appendix A.

Because the magnetic field that is generated by the MRI-scanner is very strong, any ferromagnetic materials that come near the magnet will be attracted and drawn to the wall of the bore. If any ferromagnetic material would be used in the water bolus, this component would be drawn with a large force through the MRcollar applicator, bringing severe damage to both the hyperthermia equipment, the MRI-scanner and possibly the patient.

When a non-ferromagnetic yet still conductive material is used for the water bolus, the magnetic susceptibility of adjacent tissue of the patient will be changed. This means that the internal magnetization of the tissue will change, resulting in distortions of the entire magnetic field. For example, a conductive

material may form its own weak magnetic field which increases the local magnetic field and results in a reduction of the surrounding resonance relaxation (Bushberg and Boone, 2011).

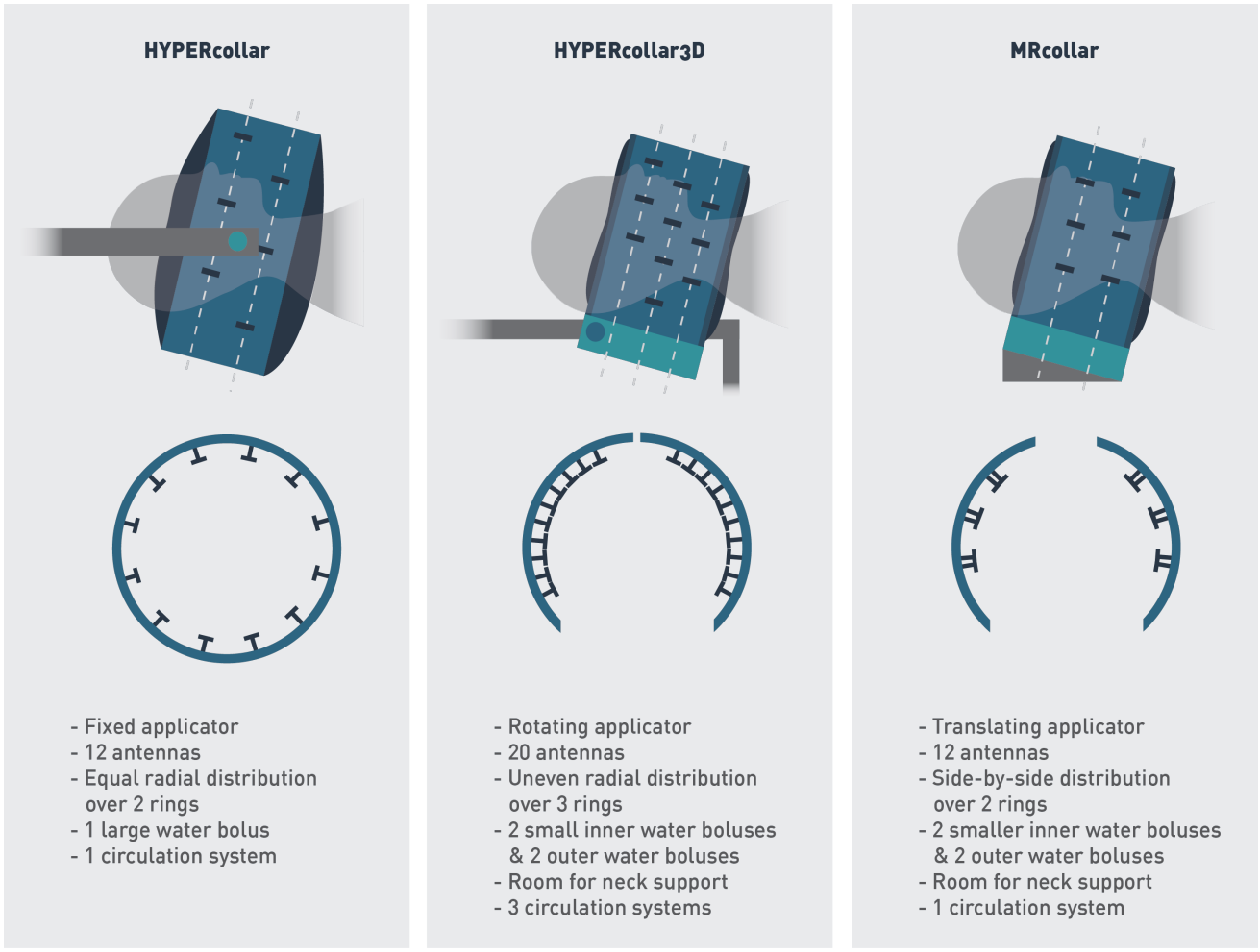
Another boundary condition for performing hyperthermia treatment inside an MRI-scanner is to constrain the flow of circulating water as much as possible. MR-thermometry is based on the same working principle as regular MR-imaging. Internal body temperatures can be measured by two different proton relaxation times or proton resonance frequency (Rieke and Butts Pauly, 2008). Because the working principle of MR-thermometry relies on the movement of hydrogen protons, moving water molecules inside the water bolus might influence the measurement results. The solution that is currently applied by the Erasmus MC Cancer Institute in case of MR-guided pelvic hyperthermia is to temporarily turn off the water circulation during thermometry measurements. The equipment that is used in this type of treatment is shown in Figure 15.

Figure 15 - MR-guided deep pelvic hyperthermia equipment

Comparison of Generations

Figure 16 depicts the different improvement steps that were made in the development from the HYPERcollar to the HyperCollar3D and lastly to the MRcollar. Further improvements for the HyperCollar3D and MRcollar are still to be defined.

Figure 16 - Comparison of the HYPERcollar, HyperCollar3D and MRcollar systems



Treatment Procedure

The treatment procedure of deep head and neck hyperthermia with the HyperCollar3D at the Erasmus MC Cancer Institute can be divided into six different phases, as can be seen in Figure 17. The steps that are performed in each phase are explained in this section. This procedure has been identified by observing different deep head and neck hyperthermia treatments, discussing with the clinical staff and conducting literature published by the Hyperthermia Unit.

Figure 17 - Phases of the head and neck hyperthermia treatment procedure at the Erasmus MC Cancer Institute

Intake

When a patient has been diagnosed with cancer, it will be defined which treatment methods are suitable. A radiotherapist will evaluate whether a patient qualifies for hyperthermia and for which type of hyperthermia. If a patient qualifies for deep head and neck hyperthermia, an intake appointment will be made. During the intake the patient will be 'test positioned', which means that the comfort and effectiveness of different patient- and equipment positions are evaluated. As Figure 18 depicts, the angle of the ring-shaped applicator is defined at 0° or 15°, where the first is mainly used for head tumours and the second for neck tumours. Furthermore, one of three available sizes of neck supports are selected. The positioning parameters of the head are defined by placing a laser light on top of the applicator that shines a bundle of light towards the ear and nose of the patient. The position of the applicator is adjusted in the x-, y- and z-direction until the laser is visible in the right spot of the patient's skin. The defined position is captured on photo with a digital camera to make sure that this position can be reproduced in following treatments.

Figure 18 - Possible angles of the head and neck applicator

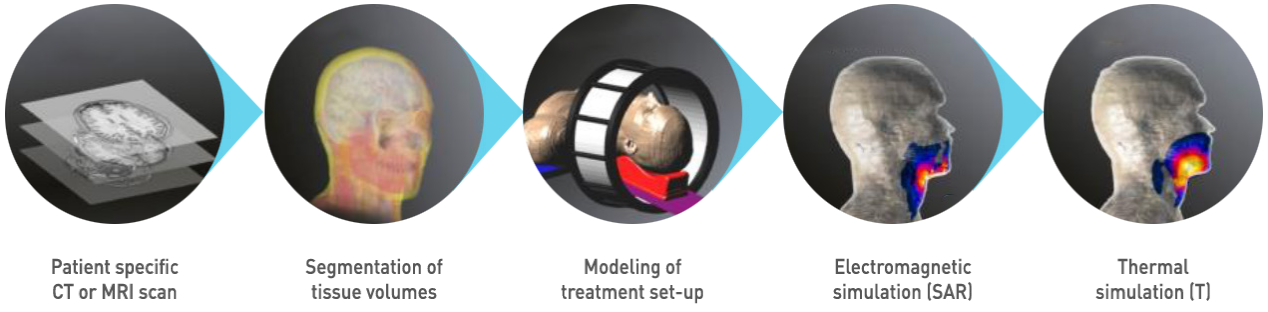


Figure 19 - Steps of hyperthermia treatment planning

Planning

The planning phase starts by making a CT-scan or MRI-scan of a specific body segment that contains the tumour to be treated, as is shown in Figure 19. In the scanner, the same neck support and the same angle as were defined in the intake phase are copied. It is important to keep the positioning parameters constant during the scan and over the course of different hyperthermia treatments to make sure that the optimal treatment parameters that are defined during planning will be similarly optimal in every treatment. The scan results in a 3D model of the patient, which contains the exterior, fat, muscle, bone, white matter, grey matter and tumour tissues (Paulides et al., 2016). These different tissue volumes are segmented, the defined positions

of patient and equipment are modelled in CAD software and a Clinical Target Volume is added to the Gross Tumour Volume. This CAD model is used to optimize the treatment parameters in a multiphysics software platform called VEDO (Paulides et al., 2016). In this software the phase and amplitude of the electromagnetic waves can be manipulated to achieve an optimal specific absorption rate and thermal distribution. The specific absorption rate (SAR) is defined as the power absorbed per mass of tissue, which influences the thermal distribution in the tissue. By simulating both the SAR and thermal distribution, an adequate energy distribution can be ensured and local energy concentrations (hotspots) can be prevented.

Preparation

After the optimal treatment parameters have been calculated, the patient can come to the clinic to receive the actual treatment. Before the patient can enter the clinic, the set-up for deep head and neck hyperthermia is made ready in the treatment room. For treatment with the HyperCollar3D, the table with the equipment attached is brought into the room and a hospital bed is positioned in front of it. The different water tubes are connected to the circulation pumps and the power cables are connected to the supply unit. The half-rings of the applicator are opened and the right neck support, the same as was used during imaging, is placed on the table. Functioning of the antennas is tested and the settings of the various planned parameters are loaded in the operating software. Sometimes, the water temperature of the inner boluses is checked by placing a fiber optical thermo sensor at the inflow, which is removed before starting the treatment. When the set-up as depicted in Figure 20 is ready, the patient is called in.

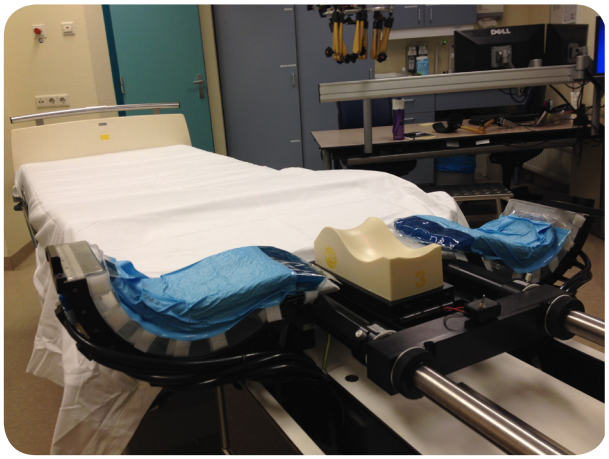


Figure 20 - Treatment preparation set-up

Installation

The clinicians support the patient to get on the bed and lay down with the head positioned on the neck support. Most of the time, the patient has to lift his upper body to reposition his head to get this position right. A clinician and technician adjust the position of the applicator in x-, y- and z-direction, matching the planned position of the made CT- or MRI-scan with the laser lights. Catheters are inserted in the planned areas, after which fiber optical thermo sensors are placed in the catheters. The half-rings of the applicator are rotated to the planned angle and are closed around the head or neck of the patient. After closing, the distance between patient and applicator is matched to the planned data by making the last changes in positioning.

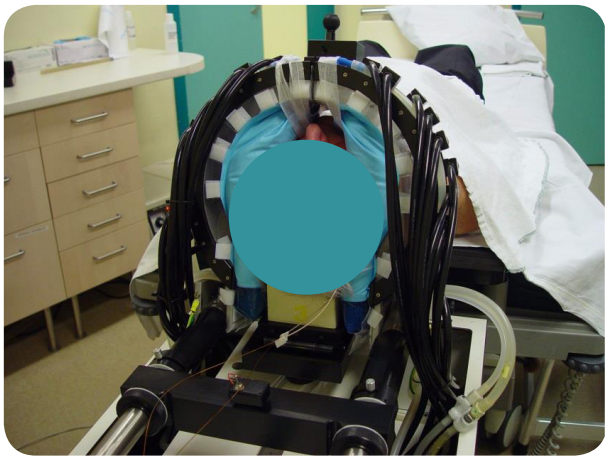


Figure 21 - Taped water bolus

Treatment

A clinician starts pushing the 'fill' button on the treatment table and holds this button until the two inner water boluses are entirely filled with demineralized water coming from the reservoir. The optimal water volume is evaluated by asking the patient how comfortable the pressure feels, by observing the skin contact and by pricking the bolus with the fingers. When it is observed that the water level reaches the patient's eyes, the filling is stopped because the foil on top of the water boluses starts to uncomfortably touch the eyes, nose and mouth. The excessive foil is therefore moved out of the way by taping it to the applicator, as Figure 21 depicts. Afterwards, the filling is continued. When the water volume is sufficient, the button is released and the circulation pumps of both the inner and outer

boluses are switched on. The outer boluses always remain filled with water and do therefore not have to be filled nor drained during treatment.

Water in the inner boluses is circulated at a temperature of 20-30 °C (Paulides, 2016), which allow the skin to be cooled sufficiently without counteracting the tissue heating principle of hyperthermia. The water surrounding the antennas in the outer boluses has a different optimal temperature of approximately 35 °C. The performance of the antennas decreases when the environment is colder or warmer than the temperature for which the antennas are designed. When the boluses are filled, the heating process is started. First, the system takes 15 minutes to warm up from 50W to 120W in small steps of 10-20W to allow the body to upregulate blood flow cooling. Subsequently, the hyperthermia treatment is applied during 60 minutes at the planned power settings. During treatment, the patient's heartrate is monitored as a stress-indicator and to foresee possible pain. The applied power, tissue temperatures, electromagnetic phase and electromagnetic amplitude are monitored as well and adapted where needed by the attending technician on the computers depicted in Figure 22. The visible data is shown in Figure 23. The measurement data is stored for patient records and future research.

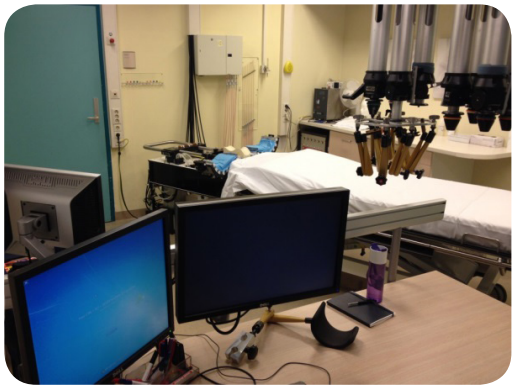
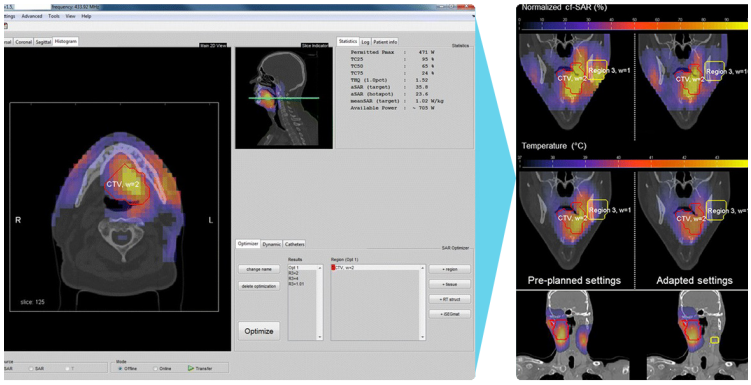


Figure 22 - Monitors in the clinic



Planned SAR and temperature distribution during treatment

Re-optimizing SAR and temperature based on temperature measurements

Figure 23 - Visible data during treatment

Wrap-up

After having lied 75 minutes in the applicator, the patient is released by opening up the two half-rings and helping the patient to get off the bed. While the patient leaves the room, the clinician and technician drain the water boluses with the same filling switch, resulting in the fluid to flow back into the reservoir where it is stored. The water tubes and power cables are disconnected and the foil that has touched the skin of the patient is cleaned with alcohol. Lastly, the equipment table, with the drained water boluses still attached, is brought out of the room. Within one hour after this hyperthermia treatment, the patient will receive radiology therapy for the most effective result. The patient will come back 5 to 6 times for hyperthermia treatment, depending on the required radiation treatment. Hyperthermia treatment will be given once or twice a week, with at least three days between each treatment. Radiation treatment will follow after every hyperthermia treatment.

MRcollar

According to a technician of the Erasmus MC the treatment procedure for the MRcollar will be quite similar to the one described for the HyperCollar3D. Only small differences will exist in the execution of the different steps, due to different mechanisms and dimensions of the MRcollar. For example, different values have to be used for the planning. Furthermore, the preparation, installation and treatment are different in terms of operating the MRcollar and setting it in the right position. Because an MRI-scanner will be added to the treatment setting, another procedure difference is that scans will be taken before and during treatment.

Water Bolus

This thesis will be focussing on a redesign of the water bolus that is currently used in the HyperCollar3D and make it applicable for both this applicator and the MRcollar applicator. Therefore, the functions and construction of this water bolus is analysed into more detail.

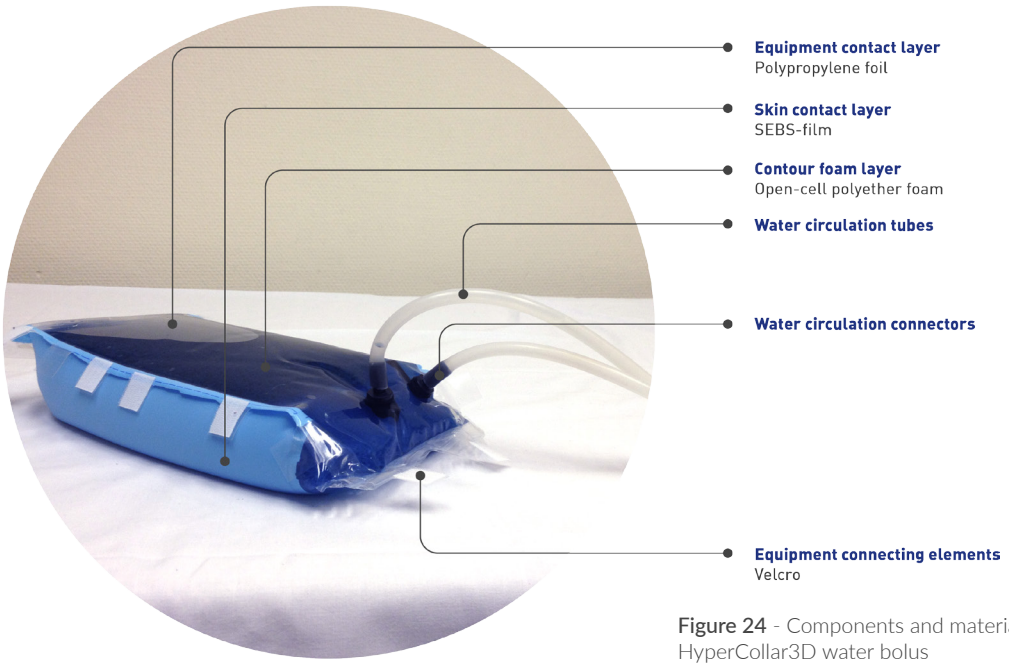


Figure 24 - Components and materials of the current HyperCollar3D water bolus

Functions

The main functions of the water bolus are cooling of the patient's skin to remove hotspots on the surface of the skin and thereby prevent skin burns, transferring electromagnetic waves from the antennas to the patient's tissue and assisting in maintaining the head of the patient in the same position during the treatment. In order to fulfil these functions, different components and materials are chosen for the current water bolus, which can be seen in Figure 24.

The relevance of the various elements of the water bolus can be explained as follows:

Circulating Water

The circulating water supports the main function of the water bolus: uniform cooling of the skin throughout the entire treatment duration. Circulation ensures that the water is constantly refreshed with water at the right temperature. The circulation also supports the removal of skin hotspots which are induced by electromagnetic field disturbing air inclusions between water bolus and skin, and the removal of air bubbles in the water. Filling the space between the antennas and the skin with water also enables a maximum energy transfer because water matches the patient's dielectric properties. If air would be included between the antennas and skin instead, energy would get lost in the different dielectric properties of the various matters. Air bubbles or inclusions create a similar effect. The water in the outer bolus is also meant to maximize the energy transfer. Surrounding the antennas with water also enables the use of smaller antennas. This helps to keep the entire system compact and to position the antennas closer to the tissue, which minimizes reflection by the matter in between.

Equipment contact layer

Polypropylene foil was selected for the equipment contact layer because it can resist the inner water pressure due to its relative stiffness (Roskam, 2010). The material remains its stiffness when manufactured in a foil of less than 1mm thick, which ensures a minimized effects on the transfer of electromagnetic waves.

Skin contact layer

Because polypropylene was uncomfortable in contact with the skin, another material was selected for the skin contact layer. SEBS-film is a

foil with rubber-like properties, a high elasticity and combination of common polymers (Roskam, 2010). These properties make the foil comfortable when in touch with the skin. The currently used SEBS-film has a thickness of 0,4mm, meant to provide a balance between strength and elasticity (Roskam, 2010). However, this thickness turns out to be vulnerable to piercing and thus leakage.

Contour foam layer

The foam insert was an improvement on the fully water-filled bolus from the HYPERcollar. Inserting foam resulted in more shape stability and less unpredictable folds (Roskam, 2010). The selected open-cell polyether foam has a minimal filling percentage, allowing most of the available volume to be filled with water and minimizing deviations from the average dielectric constant caused by various materials. Furthermore, the large cells in the foam enable a non-turbulent water flow. A disadvantage of this foil is that it needs to be cut manually and that particles can come loose which block the circulation system.

Equipment connecting elements

Velcro straps have been selected as a means to connect the water bolus to the applicator. The rationale behind this decision is mainly that it was quick to implement and a small investment. Drawbacks of the Velcro are that the straps loosen over time, that the straps are vulnerable to tearing and that alignment of the water bolus takes quite some effort. Furthermore, contact between the bolus and applicator is insufficient which causes air inclusions as is shown in Figure 25.

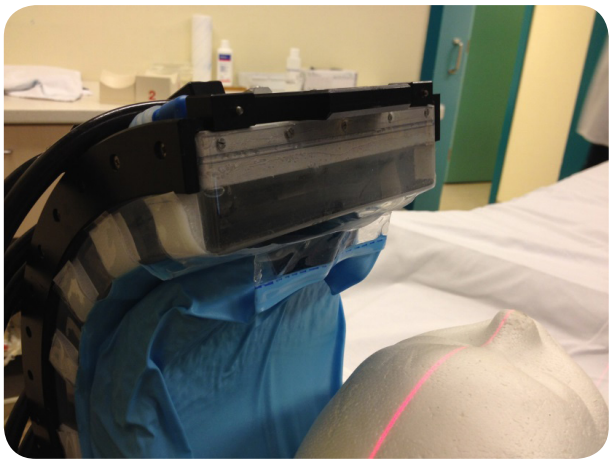


Figure 25 - Air inclusion at the top of the water bolus due to insufficient contact between bolus and applicator

Manufacturing Process

The water boluses are manufactured manually by a clinical technician of the Erasmus MC. The foam and plastic foils are cut at the required size and a building plate is used to accurately sketch the cutting and folding edges on the sheets of foil. Holes for the inlet and outlet are punched in the foil, after which the foil is sealed water tight at the edges while leaving one side open. Tube connectors that are manufactured by the in-house facility of the Erasmus MC are screwed through the holes in the foil before inserting the foam and sealing the last edge. Finally, Velcro is attached to the flaps on the sides and the water bolus is checked for leaks. If any leaks are found at the edges, this can be solved by re-sealing them. However, often leaks occur elsewhere in the foil due to the use of an inconvenient desk-top sealing device. If this is the case, the water bolus is disposed and the production process is repeated. Depending on the type of water bolus, manufacturing takes approximately human labour 1-4 hours.

Circulation System

Via a circulation system, the inner water boluses are connected to the outer water boluses and several pumping systems. To understand the boundary conditions of this circulation system, the working principles are analysed into more detail.

Figure 26 shows the water flow in the water boluses of the HyperCollar3D. It can be seen that water from the system (coming from either the reservoir or the circulation pump) flows in parallel into the two inner water boluses through connectors at the bottom. The water flows from the bottom to the top of the bolus, where it enters a tube placed in the centre of the bolus. This tube is connected to the outflow of the system and transfers the water back to the circulation pump or the reservoir.

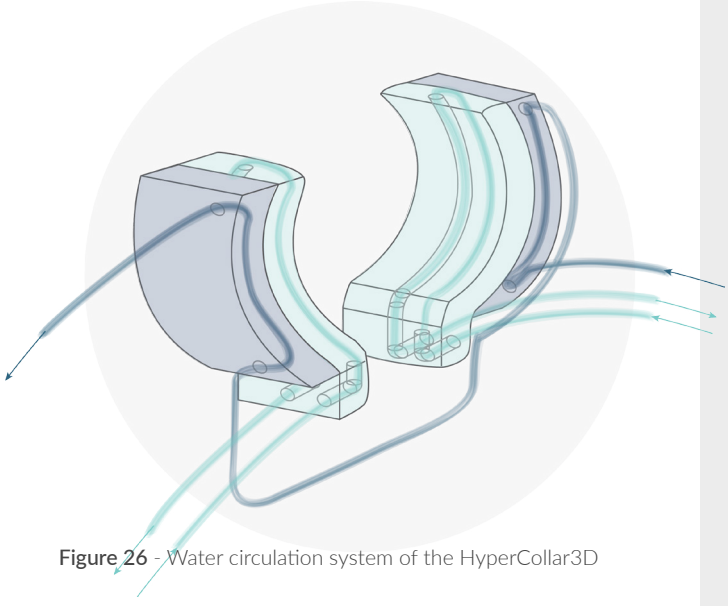
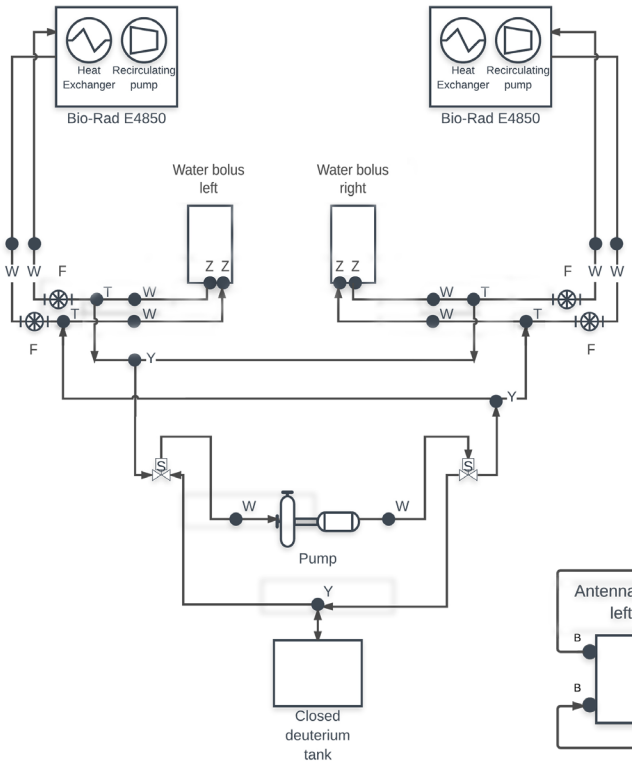


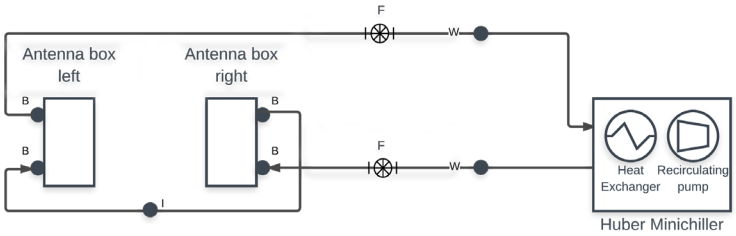
Figure 26 - Water circulation system of the HyperCollar3D

An inflow at the bottom and outflow at the top ensure that any air entrapped in the system forms as little air bubbles as possible during filling. The outer water bolus has a similar flow direction, which is connected to a separate system.

Figure 27 and Figure 28 depict the flow systems of the inner water boluses and outer water boluses of the HyperCollar3D into more detail respectively. These diagrams have been constructed based on observation of the system and discussing with an instrument maker at the Erasmus MC.

Contrary to the HyperCollar3D, the MRcollar will only have one pumping system at its disposal. This available system is indicated in Figure 29 by a grey area. A parallel water flow has therefore been designed. The inner boluses will be filled first and the outer boluses will follow when the inner boluses are full. When in the future more pumping systems will be available, the tubes between the inner and outer boluses can be disconnected with coupling W to connect them to different pumps. This system enables both filling and draining from the bottom of the boluses, which is an improvement on the flow system of the HyperCollar3D. This MRcollar flow diagram has been designed by discussing with the engineers of the Erasmus MC and their partner Technobis, Alkmaar, The Netherlands.



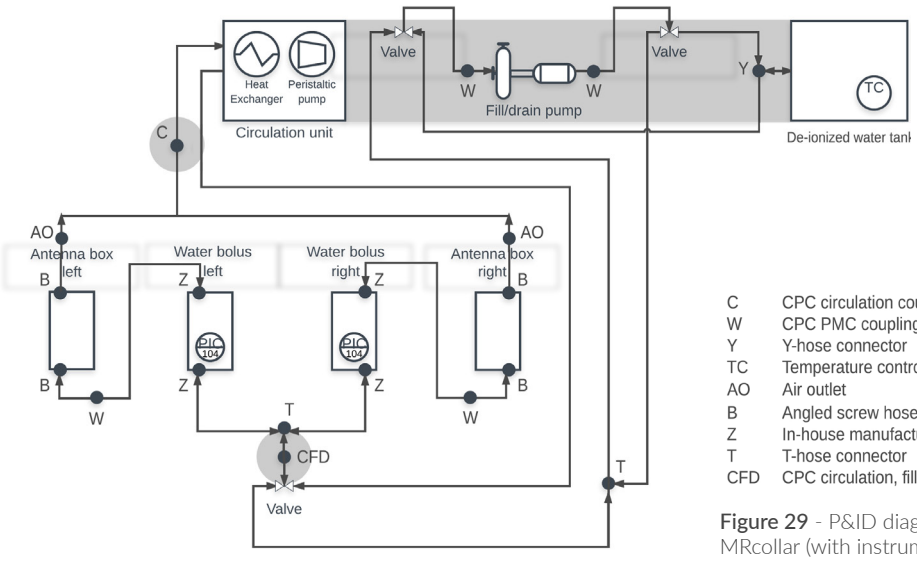


Z	In-house manufactured POM/Delrin connector
W	CPC PMC coupling body + insert
F	Burkle flow indicator
T	Norma TS8 T-hose connector
Y	Norma YS8 Y-hose connector

Figure 27 - P&ID diagram of the inner water boluses of the HyperCollar3D system (with instrumentation names)

F	Burkle flow indicator
W	CPC PMC coupling body + insert
B	Angled screw hose connector
I	Straight hose connector

Figure 28 - P&ID diagram of the outer water boluses of the HyperCollar3D system (with instrumentation names)



C	CPC circulation coupling body + insert (tbd)
W	CPC PMC coupling body + insert
Y	Y-hose connector
TC	Temperature controller
AO	Air outlet
B	Angled screw hose connector
Z	In-house manufactured POM/Delrin connector
T	T-hose connector
CFD	CPC circulation, fill and drain coupling body + insert (tbd)

Figure 29 - P&ID diagram of the water flow system of the MRcollar (with instrumentation names)

User Groups

Before designing any improvements for the water bolus or hyperthermia system, it is important to define the main user groups, their relation to the system and their opinion about the system. The hyperthermia equipment, including the water bolus, is mainly handled by three user groups. These user groups include

I) The patients, who undergo the treatment
II) The clinicians and technicians, who plan, carry out and supervise the treatment
III) The engineers, who develop and improve the treatment equipment

For the first two user groups, comfort and operating handing should be kept optimal on all instances. The third user group is mainly concerned with the technical performance of the system. Observations of treatments and interviews with the first two user groups have been conducted to get a grasp of the possible points of improvement in their context. The perspectives of the engineers were obtained by daily team discussions, as I have been a part of this team as a graduation intern.

Patient's Perspective

The aspects of discomfort that patients encounter when being treated with the HyperCollar3D were analysed. Because the equipment is still in the development phase, only one patient was being treated with the HyperCollar3D during analysis phase of this thesis. Conclusions about the patients' perspective were therefore derived from an interview with one patient who had undergone several hyperthermia treatments. The specific questions that have been asked in this interview are presented in Appendix B. The validity of the conclusions from this interview for other patients that have been treated in the past was evaluated by discussing it with a clinician and technician, who have worked closely together with many patients. To get a better grasp of the patient's experience, several treatments with the HyperCollar3D were observed and the drawn conclusions were evaluated by testing the comfort of the device by myself as well. Conclusions regarding the patient's comfort during treatment are shown in Figure 30.

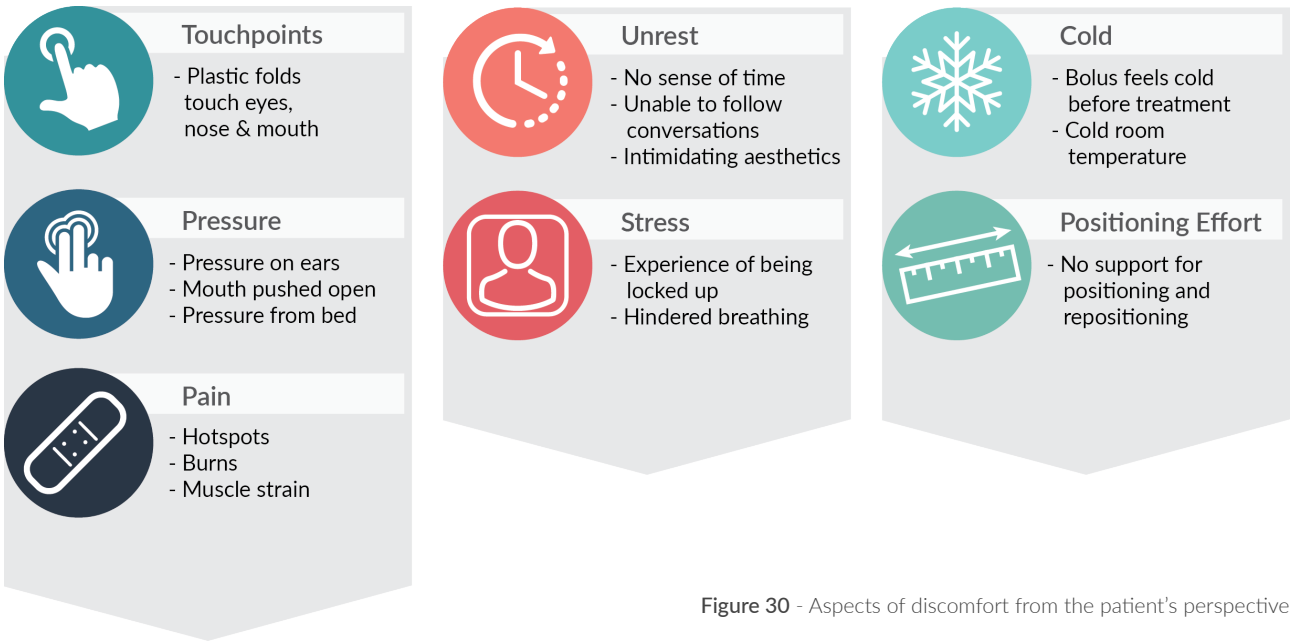


Figure 30 - Aspects of discomfort from the patient's perspective

Clinician's and Technician's Perspective

The perspective of clinicians and technicians regarding the comfort of operating the HyperCollar3D was analysed. Both a clinician and technician for head- and neck hyperthermia, who plan, carry out and supervise the treatments, were interviewed. Because only a small amount of patients is currently being treated with the HyperCollar3D, these two experts form the main staff capacity during treatments and therefore have most knowledge of the advantages and disadvantages of the current equipment. Questions were asked about the functionality, usability and comfort control of the system and water bolus specifically. The exact questions that have been asked in these interviews are presented in Appendix C. Apart from interviews, conclusions have also been derived from observations of the operating activities of the clinicians and technicians during several treatments. Because the interaction that these user groups have with the equipment is quite similar, the outcomes are grouped together. The discovered opportunities for improvement from the clinician's and technician's perspective are shown in Figure 31.

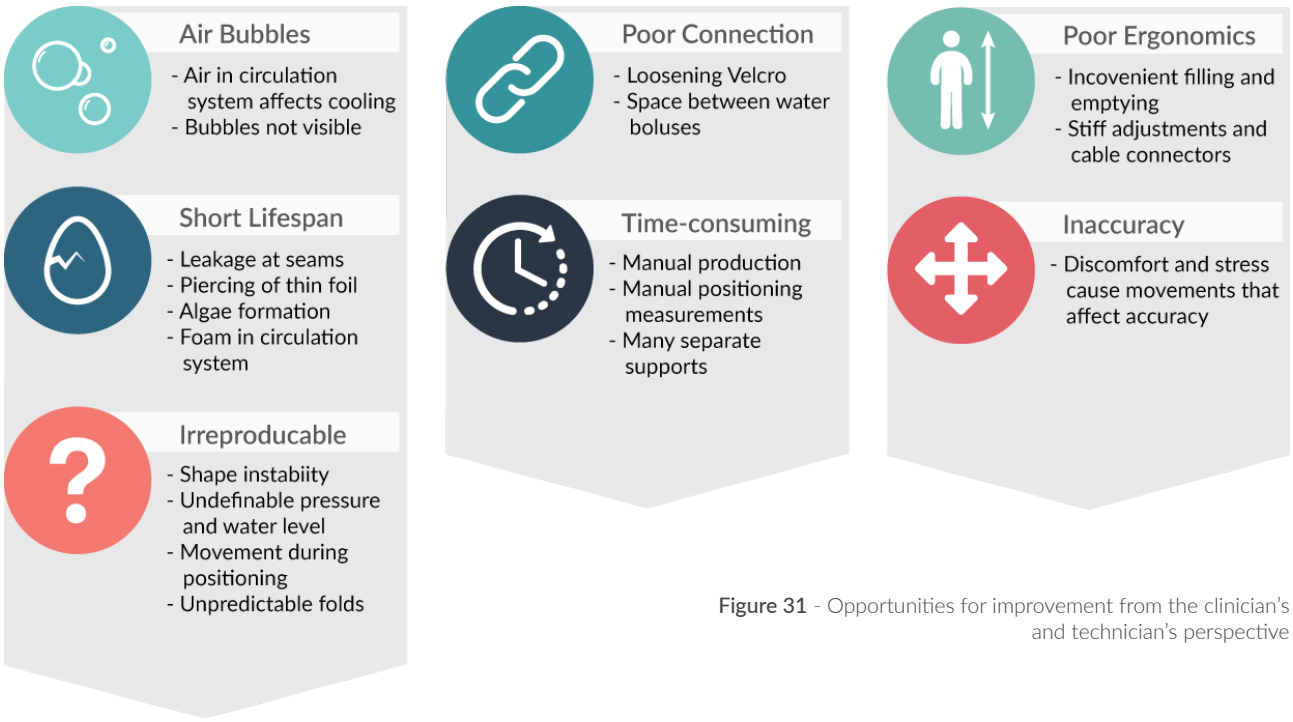


Figure 31 - Opportunities for improvement from the clinician's and technician's perspective

Engineer's Perspective

The engineers who design and optimize the hyperthermia equipment have more technical and ambitious aims for the next generation of the equipment, the MRcollar, and for the commercialized version of the HyperCollar3D. Because I have been a part of this team during the timeframe of this thesis, the opportunities from the engineers' point of view are identified by having several discussions together.

The main problem according to the engineers is the inability to treat patients with larynx tumours. With both the HYPERcollar and HyperCollar3D it is difficult or even impossible to reach tumours in the larynx region. As can be seen in Figure 32, the HyperCollar3D applicator hampers the shoulders of the patient. Even when the applicator is rotated 15° and the water bolus is bulging out a bit, larynx regions cannot be reached adequately. As a result, patients with tumours in the lower neck are treated with an added water bolus component as Figure 33 depicts, or cannot be treated at all.

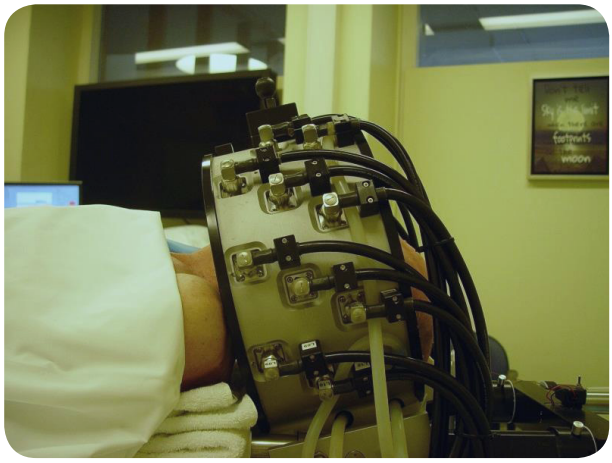


Figure 32 - Applicator hampering shoulders

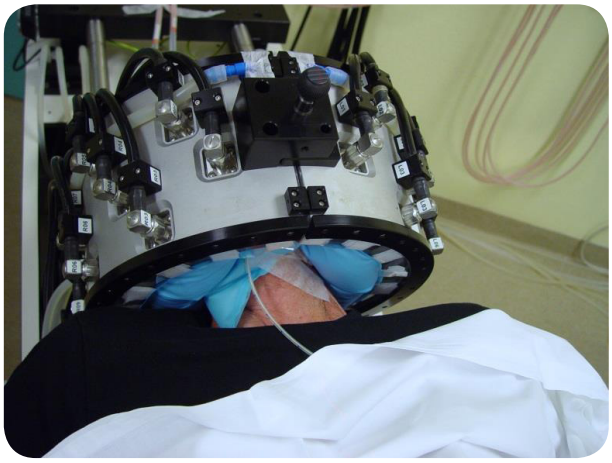


Figure 33 - Added water bolus component

The HYPERcollar, i.e. first generation applicator, could reach lower neck tumours slightly better because part of the unstable water bolus could be pulled out of the applicator. This is depicted in Figure 34. However, even with this applicator, larynx patients were left untreated. Other challenges according to the engineers are depicted in Figure 35.

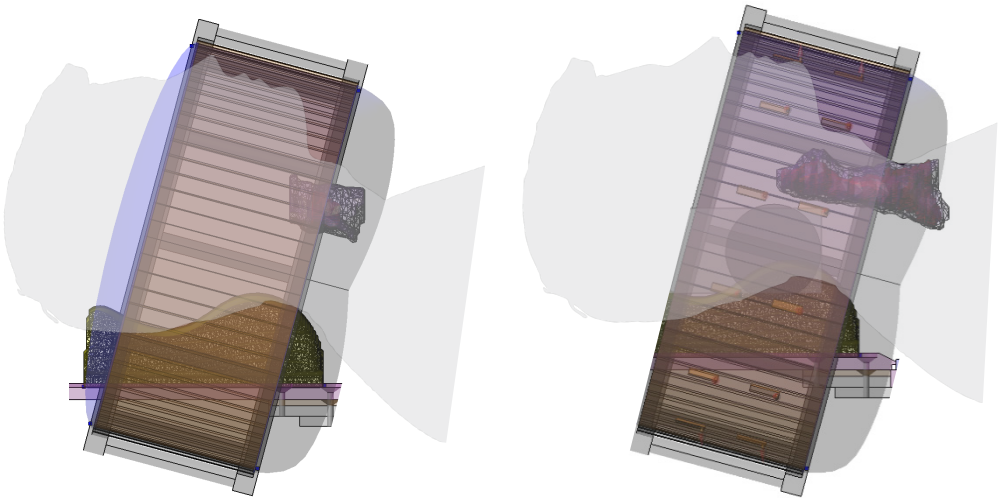
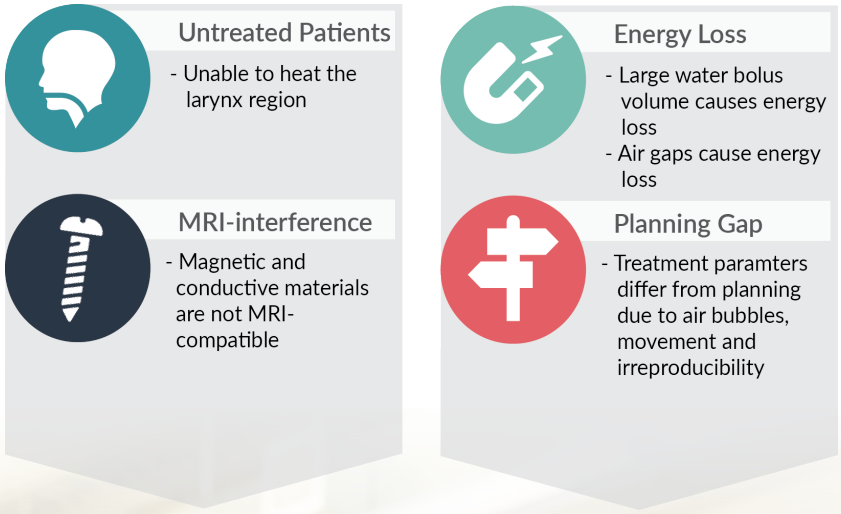


Figure 34 - Lower neck and larynx tumour coverage with the HYPERcollar, i.e. first generation

Figure 35 - Aims for improvement from the engineer's perspective



Design Challenges

The opportunities for improvement of the water bolus and the hyperthermia equipment that have been identified in the different analyses of this chapter are used to formulate several design challenges that will be addressed in this graduation project. The analysis results are translated in a problem definition which is then split into two focus points which are ranked by priority. Most time will be spent on addressing the first priority, which is the 'fit'. Less yet still significant attention will be paid to the second priority 'cool&press'. The focus points are translated into different design challenges for which lists of requirements have been set-up. Finally, the approach to address the defined design challenges is explained.

Problem Definition

The problem definition regarding the performance and ergonomics of the hyperthermia system has been divided into two different focus points. As it can be seen in Figure 36, the primary focus is to design an ergonomically shaped water bolus that not only fits all head and neck cancer patients but also has a good fit with the hyperthermia system. The secondary focus is the design of uniform distribution of cooling and pressure within the water bolus.

Figure 36 - Primary and secondary focus of the design goal

Fit

The point of focus that has a primary priority in this project is the development of a water bolus that fits.

I) Larynx Fit

The main focus of the present project is to design an ergonomic water bolus that fits every patient with head and neck cancer, including patients with cancer located at larynx. Because the current water bolus design cannot reach the larynx region, about 26 % of the total head and neck cancer patients is not submitted to the hyperthermia treatment. When the water bolus is extended toward the larynx region, it will be possible to transfer electromagnetic waves to the larynx. With this improvement, larynx cancer patients can be offered the possibility of hyperthermia treatment. The requirements to achieve the mentioned improvement are presented in Figure 37.

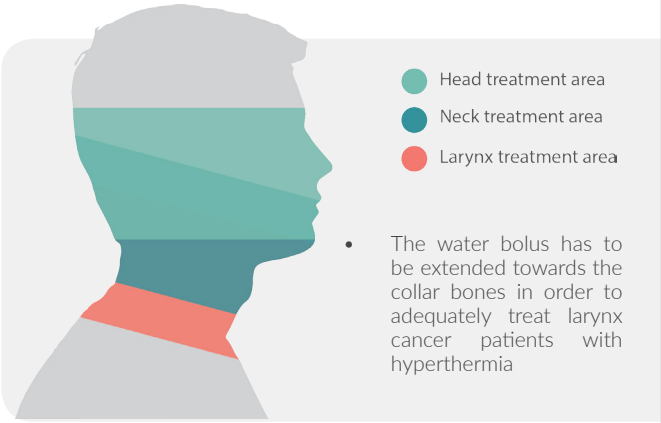


Figure 37 - Requirements for a larynx fit

II) Ergonomic Fit

The contour of the head and neck of the patient should be followed closely in order to enable an ergonomic fit. A close fit without air gaps will increase the comfort for the patient and both the efficiency and effectiveness of the treatment. The requirements for this purpose are presented in Figure 38.

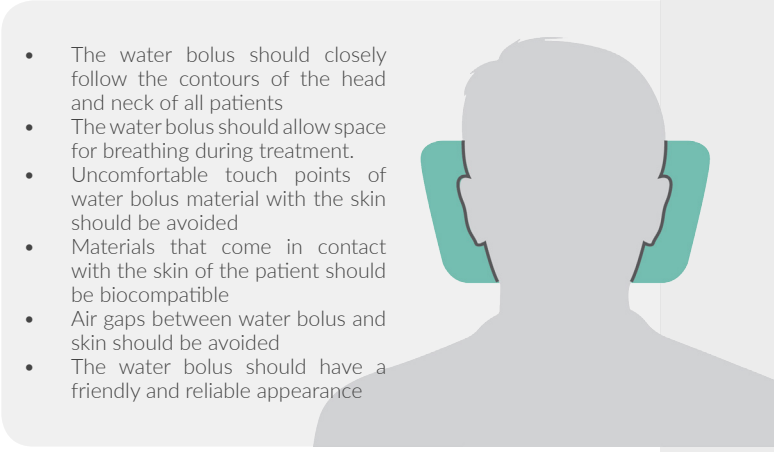
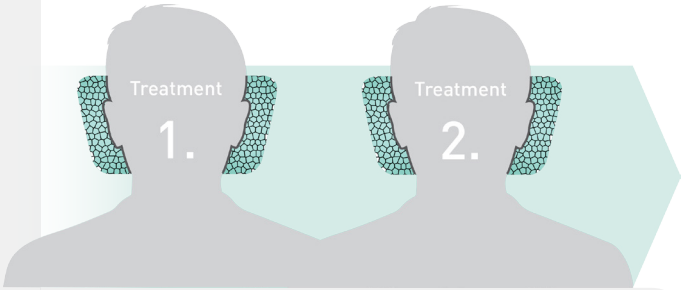
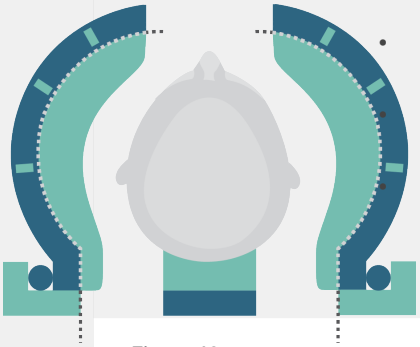


Figure 38 - Requirements for an ergonomic fit



- The shape and set-up of the water bolus should be predictable and reproducible in follow-up treatments
- The thickness of the water bolus should be minimized

Figure 39 - Requirements for a reproducible fit

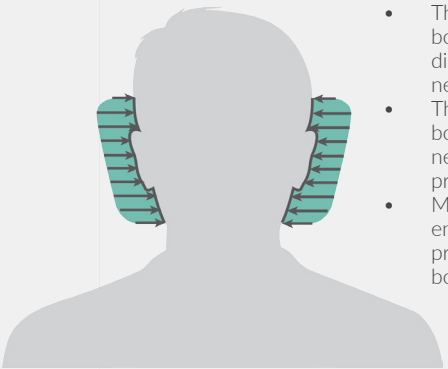


- The water bolus should have a stable and long-term, yet interchangeable, connection to the hyperthermia system
- The water bolus should fit inside the applicator of the HyperCollar3D and MRcollar It should require little time and effort to connect/ disconnect the water bolus Air inclusions between the water bolus and the hyperthermia system should be avoided

Figure 40 - Requirements for a stable fit

- The water bolus should provide uniform cooling of the skin in the head and neck region
- The water bolus should be filled with a fluid for an optimal conduction of electromagnetic waves
- The presence of air bubbles should be made visible from outside of the water bolus
- The water bolus should enable air release during filling

Figure 41 - Requirements for uniform cooling



- The pressure of the water bolus should be equally distributed over head and neck
- The pressure of the water bolus on the head and neck should be regulated to prevent discomfort
- Materials should be strong enough to resist the water pressure inside the water bolus

Figure 42 - Requirements for pressure control

III) Reproducible Fit

For both the treatment efficiency and effectiveness, it is of great importance that the water bolus has a reproducible fit. This means that it should be possible to reproduce every variable of the water bolus such as shape, temperature and position through different hyperthermia treatments over the entire treatment. Predictability and reproducibility make it possible to adequately plan the thermal dosage and settings of the antennas in simulation software and to apply the exact same parameters in the clinical treatments for optimal targeting of the tumour. The requirements for this purpose are shown in Figure 39.

IV) Stable Fit

Apart from a good fit between water bolus and the patient, a good fit between water bolus and the surrounding hyperthermia system are also part of the main focus in this thesis. The most relevant aspect to establish good fit is to design a stable connection between water bolus and applicator. A stable connection will prevent any movement or loosening of the set up, and air gaps that affect the treatment quality. The requirements for this purpose are shown in Figure 40.

Cool & Press

The point of focus that has a secondary priority in this project is the development of uniform cooling and pressure mechanisms.

V) Uniform Cooling

Uniform cooling is relevant for the comfort of the patient, as varying temperatures in different tissue areas can cause dizziness and hotspots on the skin. Furthermore, keeping the cooling variables constant enables a predictable and reproducible treatment set-up. In the current hyperthermia system, the temperature of the water outflow is monitored by the circulation equipment, but this differs from the temperature inside the water bolus. The requirements for pressure control are shown in Figure 41.

VI) Pressure Control

A uniform distribution of pressure is also relevant for the comfort of the patient, the predictability and the reproducibility. To further increase pressure reproducibility, a system to monitor and control the pressure is required as well. The requirements for pressure control are shown in Figure 42.

Approach

For an adequate development of a water bolus that fits ergonomically and enables uniform cooling and pressure control, a thorough action plan is required. As can be seen in Figure 43, a step-by-step approach has been set-up to develop the HoneyPad, starting from the design challenges.

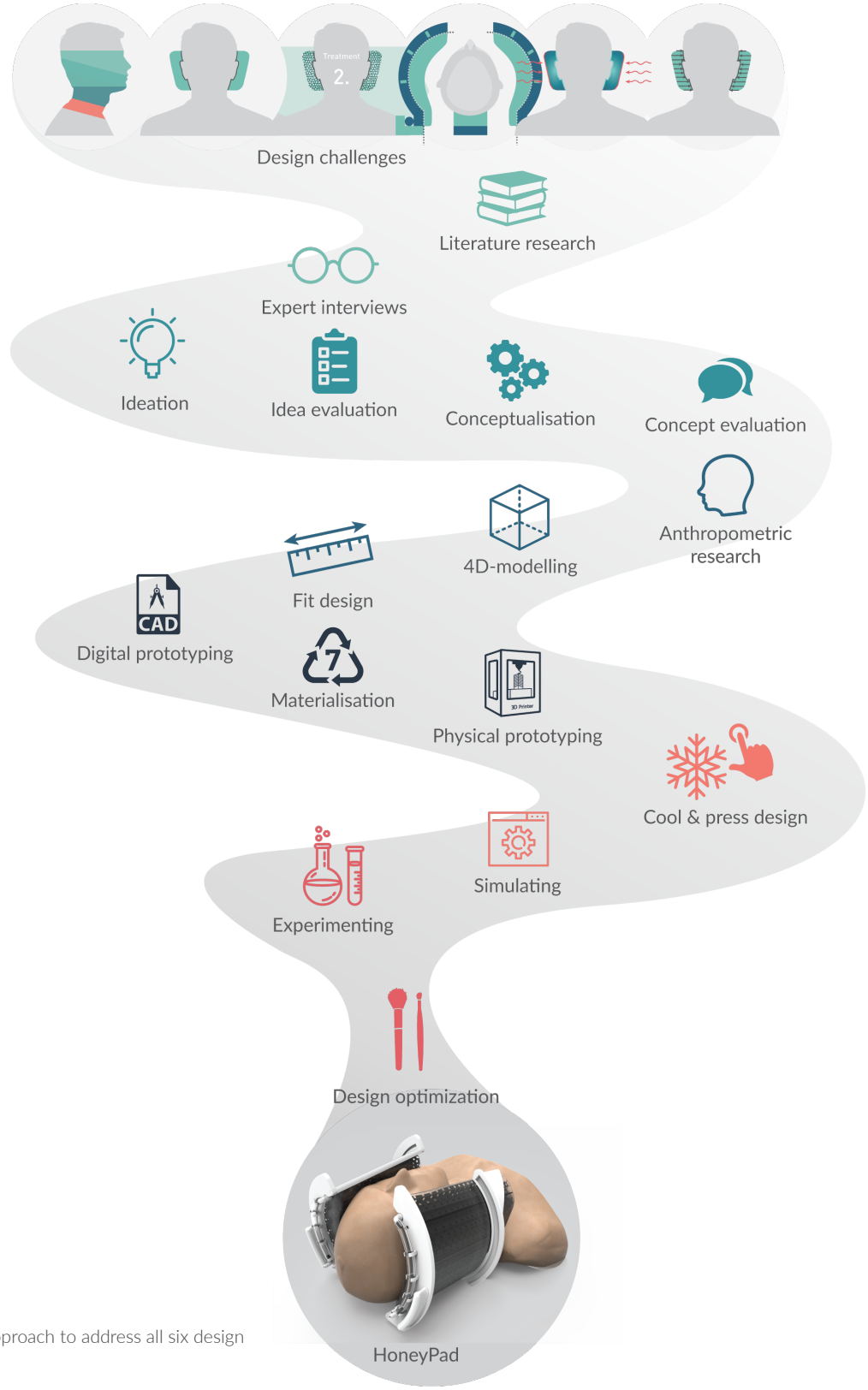
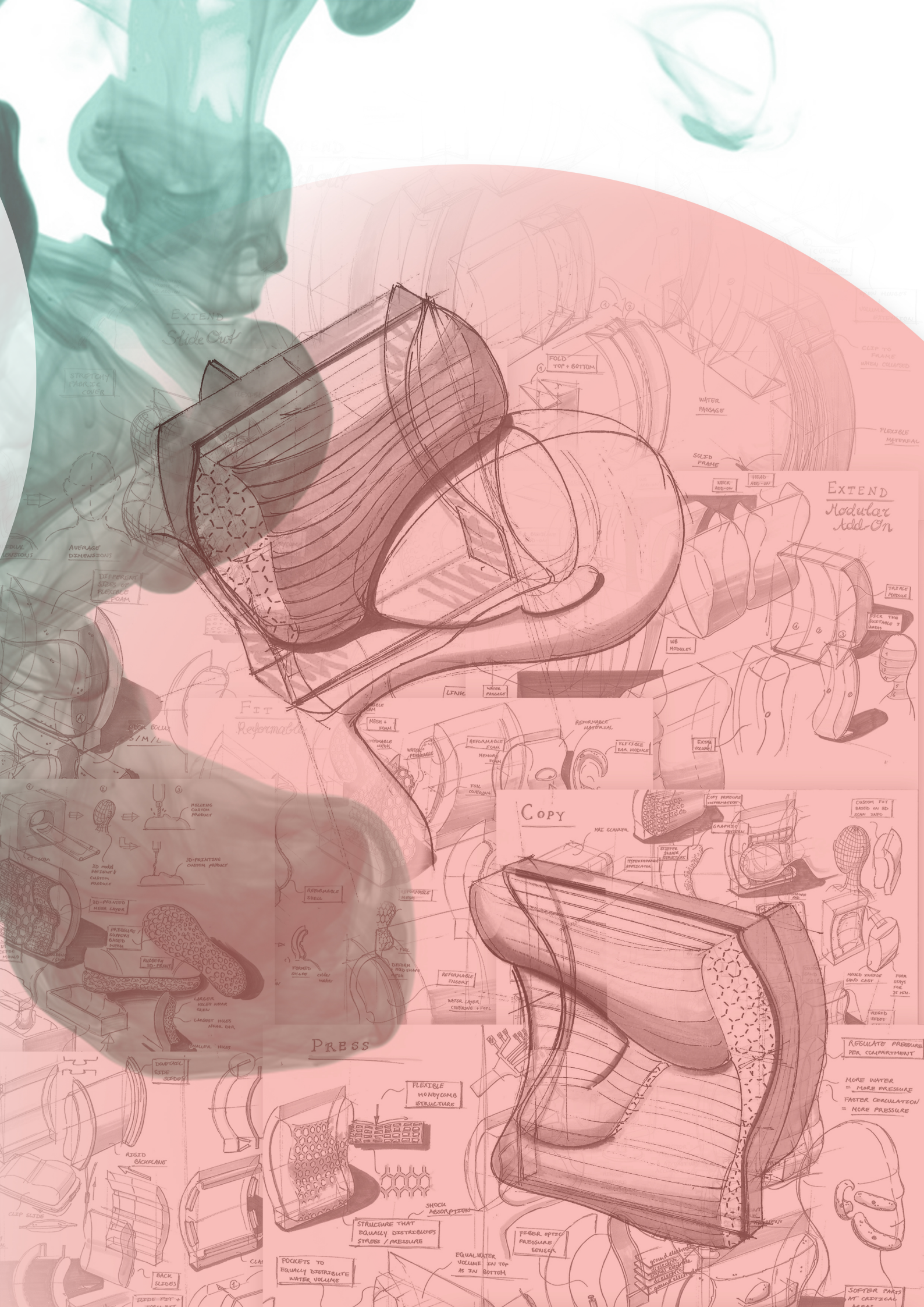


Figure 43 - Approach to address all six design challenges

3 Product Design

The design challenges that have been defined in the previous chapter form the starting point of the product design phase. Each sub-challenge has been transformed into a 'how to' question, for which as many solutions as possible were sought in a brainstorm session. Thereafter, the generated ideas have been categorized based on similar themes and the most interesting categories have been selected from each design challenge. The selected categories formed the input for an ideation session, in which different water bolus designs were drawn. The results were evaluated together with the Erasmus project coach, clinicians and technicians. Based on their feedback, a morphological chart was set-up in which the preferred designs were combined into three different concepts. The choice between these three concepts was discussed with the project coaches, resulting in a fourth concept that combined all the preferred features from the former concepts. This process will be explained in this chapter.


EXTEND
Slide Out
STRETCHY FABRIC COVER
FOLD TOP + BOTTOM
WATER PASSAGE
FLEXIBLE MATERIAL
SOLID FRAME
AVERAGE DIMENSIONS
DIFFERENT SIZES OF FLEXIBLE FOAM
EXTEND
Modular Add-On
NECK ADD-ON
HEAD ADD-ON
TABLE MODULE
WB MODULES
EXTRA VOLUME
FIT
Reformable
MESH + FOAM
REFORMABLE FOAM
MEMORY FOAM
REFORMABLE MATERIAL
FLEXIBLE BAR MODULE
FOIL COVERING
COPY
MRI SCANNER
COPY PRESSURE INFORMATION
GRAPHIC EDITION
CUSTOM FIT BASED ON 3D SCAN DATA
STIFFER SHAPED STRUCTURE
DIFFERENTIATED APPLICATION
MELLING CUSTOM PRODUCT
3D-PRINTING CUSTOM PRODUCT
3D model PAINTING & CUSTOM PRODUCT
3D-PRINTED MESH LAYER
PRESSURE SENSORS BASED MESH
RUBBERY 3D-PRINT
LARGER HOLES NEAR KNEE
LARGEST HOLES NEAR EAR
SMALLER HOLES
REFORMABLE SHELL
REFORMABLE MESH
FOIL
FORMED SHAPE
cold water
DEFORM PRINTED SHAPE MESH
REFORMABLE TABRIC
WATER LAYER COVERING + FOIL
MOULD KNEEPAD AND CAST
FOAM STAYS FOR 72 HRS
RIGID SIDES
PRESS
DOVETAIL SIDE SLIDERS
RIGID BACKPLANE
CLIP SLIDE
BACK SLIDERS
SIDE PET + FOAM PET
FLEXIBLE HONEYCOMB STRUCTURE
SHOCK ABSORPTION
STRUCTURE THAT EQUALLY DISTRIBUTES STRESS / PRESSURE
POCKETS TO EQUALLY DISTRIBUTE WATER VOLUME
EQUAL WATER VOLUME ON TOP AS ON BOTTOM
FIBER OPTIC PRESSURE SENSOR
REGULATE PRESSURE PER COMPARTMENT
MORE WATER = MORE PRESSURE
FASTER CIRCULATION = MORE PRESSURE
SOFTER PARTS AT CRITICAL AREAS

Ideation

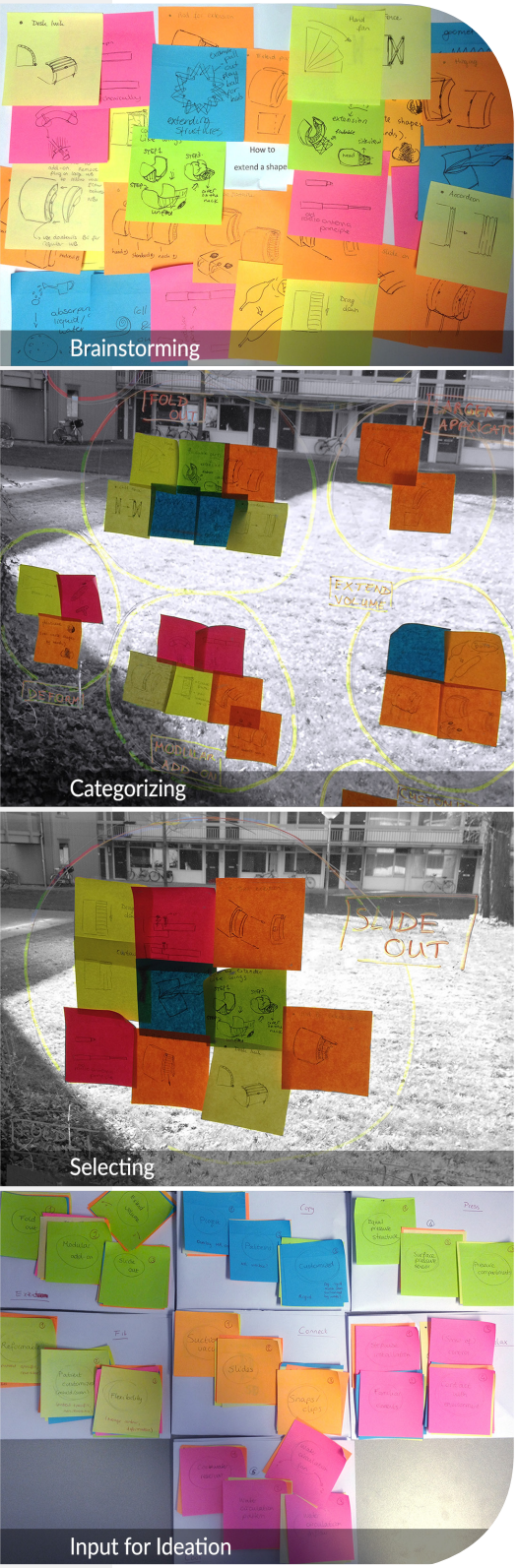


Figure 44 - Process of brainstorming, categorizing and selecting ideas to form the input for ideation

The formulated sub-design challenges were translated into the following 'how to' questions:

- How to extend a shape?
- How to ergonomically fit the head and neck?
- How to reproduce a shape over time?
- How to connect two rounded parts?
- How to uniformly cool the skin?
- How to control pressure applied on the skin?

A group of Industrial Design Engineering master students was invited to participate in a brainstorm session to generate solutions for these questions. Each question was written on a sheet of A3 paper and post-its and drawing materials were provided. The students got a brief explanation of the project but did not get to know the details. The benefit of inviting people that do not have a clear idea of the design context is that more 'out of the box' ideas will come up. These are the ideas that are not realistic in the eyes of the expert that knows all the contextual constraints, but are likely to lead to potential innovative solutions when worked out properly. Each student received a question sheet and got 3 minutes to generate ideas for this 'how to'. Afterwards, the question sheets were exchanged and another 3 minutes were given. This went on until every student had brainstormed for every question. Next, another brainstorm round with the same rules was held. Yet this time the students had to pull two cards with random words on them. This process was supposed to inspire the students to think of solutions from a new perspective. One of the sheets that resulted from the brainstorm session is depicted in Figure 44.

As Figure 44 depicts, all ideas that resulted from the brainstorm session were categorized based on theme. For example, extensions with a rail movement or a pull-out movement were categorized as 'slide out', whereas exchangeable variants or mountable parts were categorized as 'modular add-on'. For each of the six 'how to' questions the three most potential categories were selected, based on common sense. For each of the selected categories an ideation sheet was drawn. All the ideation sketch sheets that have been made are presented in Figure 45. These ideation sheets were used to discuss the varying ideas with clinical staff and the project coach of the Erasmus MC Cancer Institute.

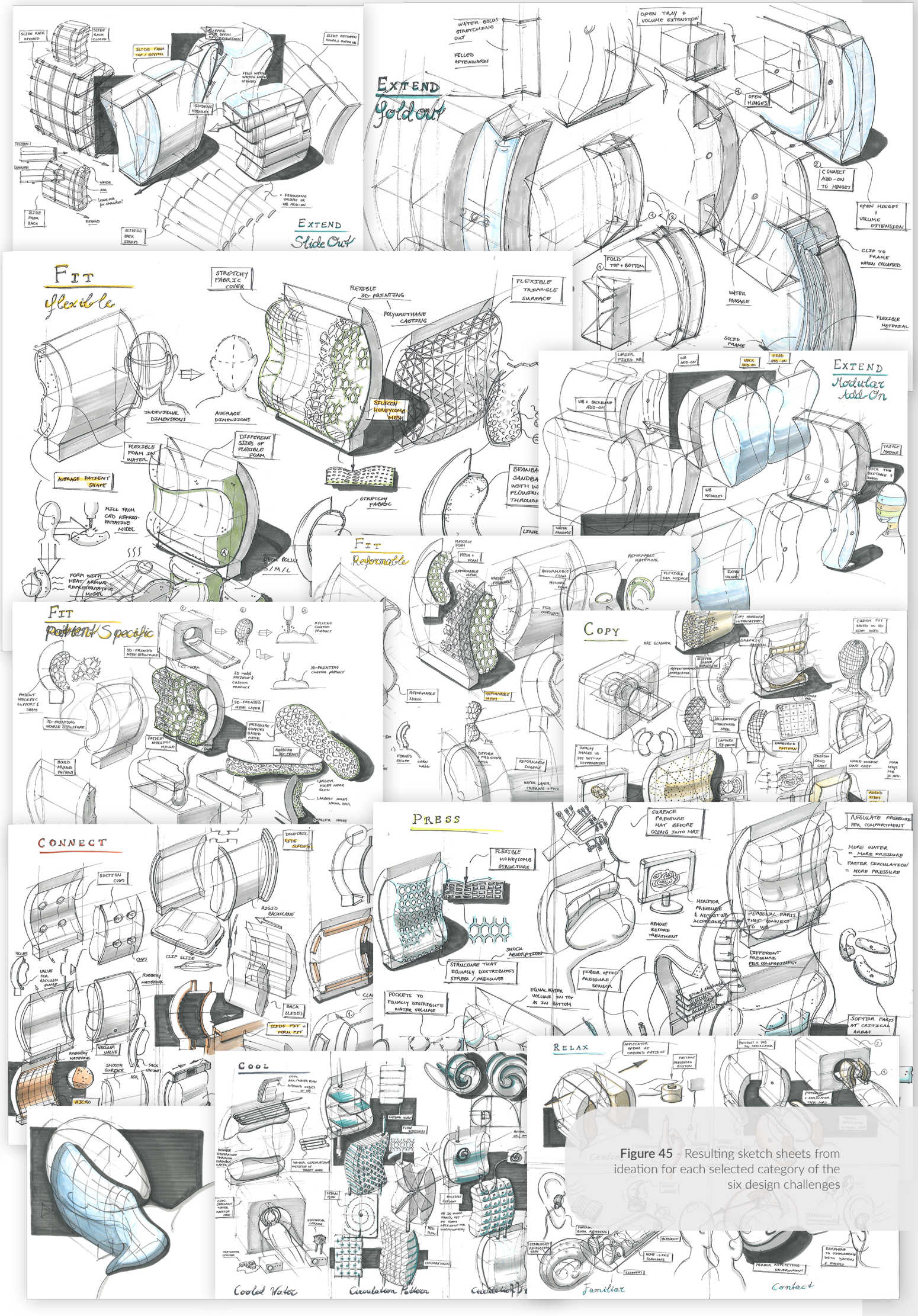


Figure 45 - Resulting sketch sheets from ideation for each selected category of the six design challenges

Evaluation

Three technicians, two clinicians and the project coach of the Erasmus MC Cancer Institute were invited to share their opinions on the various ideation sketches. They were specifically asked which ideas they found feasible or interesting and which solutions were more problematic. The results of this group evaluation can be found in Appendix D. Figure 46 depicts the ideation process and the ideas that have been selected based on the group feedback. The selected solutions were developed into three different concepts by combining the ideas that would be most functional together. These combinations are shown in Figure 46 with different line connections. A fourth concept was added later on and the combinations of this concept are indicated in the figure with coloured surfaces.

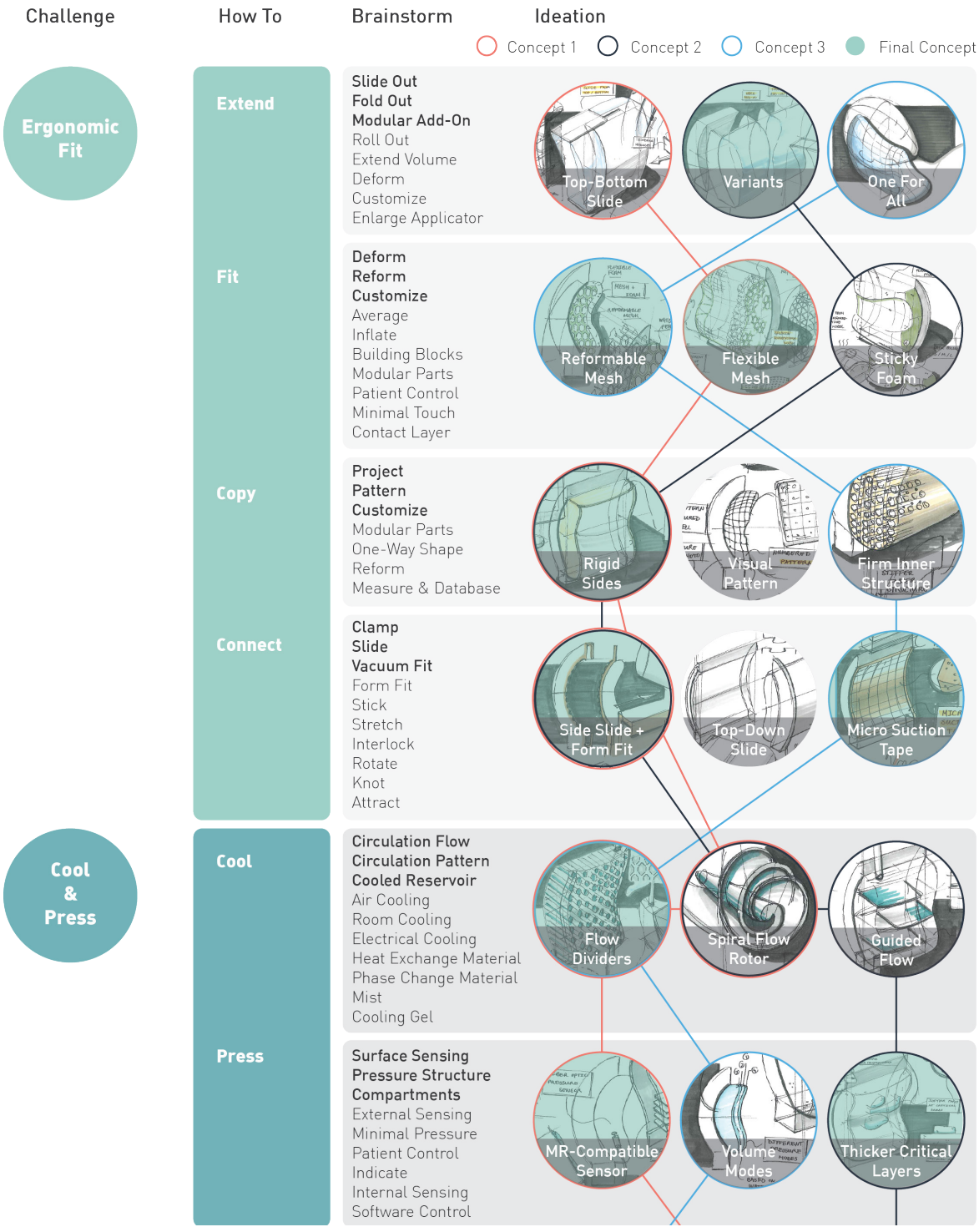


Figure 46 - Ideation and conceptualisation process

Conceptualisation

The following pages present the different concepts that have been developed: the FlexiCollar, the ModuCollar and the MorphoCollar. Each of these concepts is developed by combining the preferred solutions for the different sub-challenges as resulted from the group evaluation.

Concept 1: FlexiCollar

The first concept, which was called the 'FlexiCollar', is presented in Figure 47. This concept makes use of a slide-out on top of the water bolus to form an extension to reach the treatment area for larynx tumours. When the slide is pushed in, the water bolus can be used to fit the head, whereas the same water bolus can be used to fit the neck when the slide is pushed out. An ergonomic fit is established by inserting a flexible honeycomb shaped structure inside the bolus. This structure is able to closely form around the skin contours of the patient and is able to provide more shape stability than the former used foam inserts. A company called Supracor has developed a flexible honeycomb material that has been proven to provide uniform load distribution and extraordinary comfort, which is depicted in Figure 48 (Supracor, 2015). This Stimulite material can release pressure by distributing it away from high pressure spots, resulting in an experience of a similar pressure throughout the entire cushion. The honeycomb cells conform to body shape and can distribute pressure over a wider area than conventional foams. Additionally, the honeycomb cells flex and compress with movements which stimulates the blood circulation. In Stimulite, the honeycombs are positioned perpendicular to the human anatomy to improve stabilization of the body position. A similar material can be used in this concept.

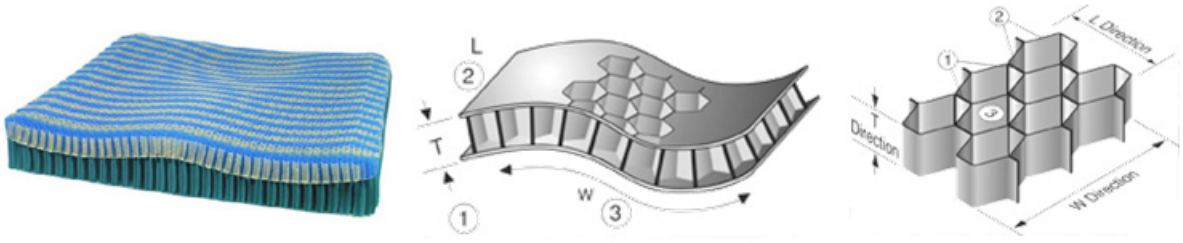


Figure 48 - Flexible honeycomb material from Supracor

The shape stability of this concept is enforced by rigid shells on the side of the bolus, which prevent unpredictable shapes that bulge out on the sides and ensure a similar shape over different treatments. The water bolus can be connected to the applicator by means of a form-fitted slide. Each slide is located in between groups of antennas to prevent blockage of the electromagnetic waves. The bolus is slid in from the side of the applicator and is held in place by a flap that sticks to a strip of micro suction tape on the side of the applicator. Micro suction tape consists of a flexible surface filled with thousands of microscopic air pockets that create partial vacuums between the tape and the target surface. The micro suction tape AirStick developed by Sewell can be used repeatedly without losing its holding power. A strip of 18*10 cm of this tape can hold a water bolus of 3kg (Sewell Direct, n.d.). A product application of micro suction tape is depicted in Figure 49.

Figure 49 - Phone stand using micro suction tape

Apart from comfort, the honeycomb structure also acts as a guidance for the water flow inside the water bolus. The water will be guided from the inflow towards the outflow through a structured path of hexagonal shaped pipes. This pattern restricts the space of movement for water molecules and might therefore minimize the influence on the MR-thermometry. Another benefit of the honeycombs is that this structure has a high strength-to-weight ratio (AskNature, 2015). As the name already implies, the honeycomb structure is inspired by the way bees build their beehive to provide enough strength yet as much space as possible for their honey. The hexagonal architecture eliminates unnecessary material which enables a small filling percentage of structure material and a large filling percentage of water inside the water bolus. This ensures a limited influence of material on the electromagnetic waves. As stated before, the honeycomb structure already ensures an equal distribution of the applied pressure. To be able to measure the pressure applied on the patient's skin, an MR-compatible fiber optic pressure sensor can be inserted inside the water bolus. Based on the measured pressure, the water volume inside the bolus can be increased or decreased. Such a pressure sensor can be provided by Opsens (n.d.).

Concept 2: ModuCollar

'ModuCollar', the second concept is shown in Figure 50. Instead of moving larynx extensions this concept makes use of a modular system. The concept has one bolus to be used for head hyperthermia treatments, and another bolus to be used in neck treatments. The neck bolus has a triangular extension that can reach the larynx area. In this concept, the foam from the former equipment generations is used to establish an ergonomic fit. To further improve this fit, average head and neck contours are cut from the foam. A sticky silicone layer is applied to the outer surface of the bolus to ensure optimal contact between bolus and skin. Skin-safe, reusable and removable adhesives are manufactured by for example BASF, who has developed Oppanol for this purpose (BASF, 2013). This isobutene homopolymer based self-adhesive material is applicable for medical uses like ostomy bags and plasters. Figure 51 depicts ostomy bags with self-adhesive Oppanol patches and the flexible structure of the material. The 'cold flow' characteristic of Oppanol as depicted in Figure 52, makes this material suitable to follow the uneven structure of the skin without air inclusions.

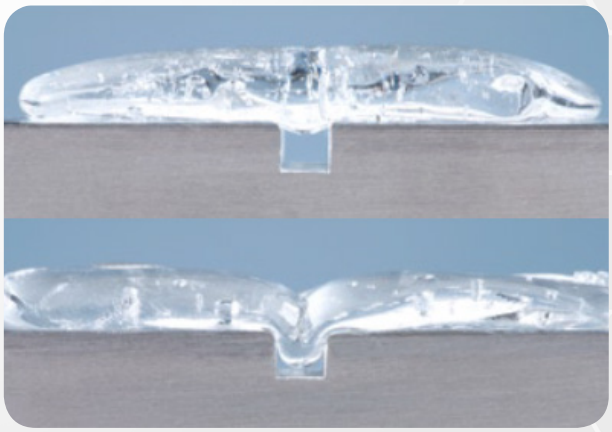
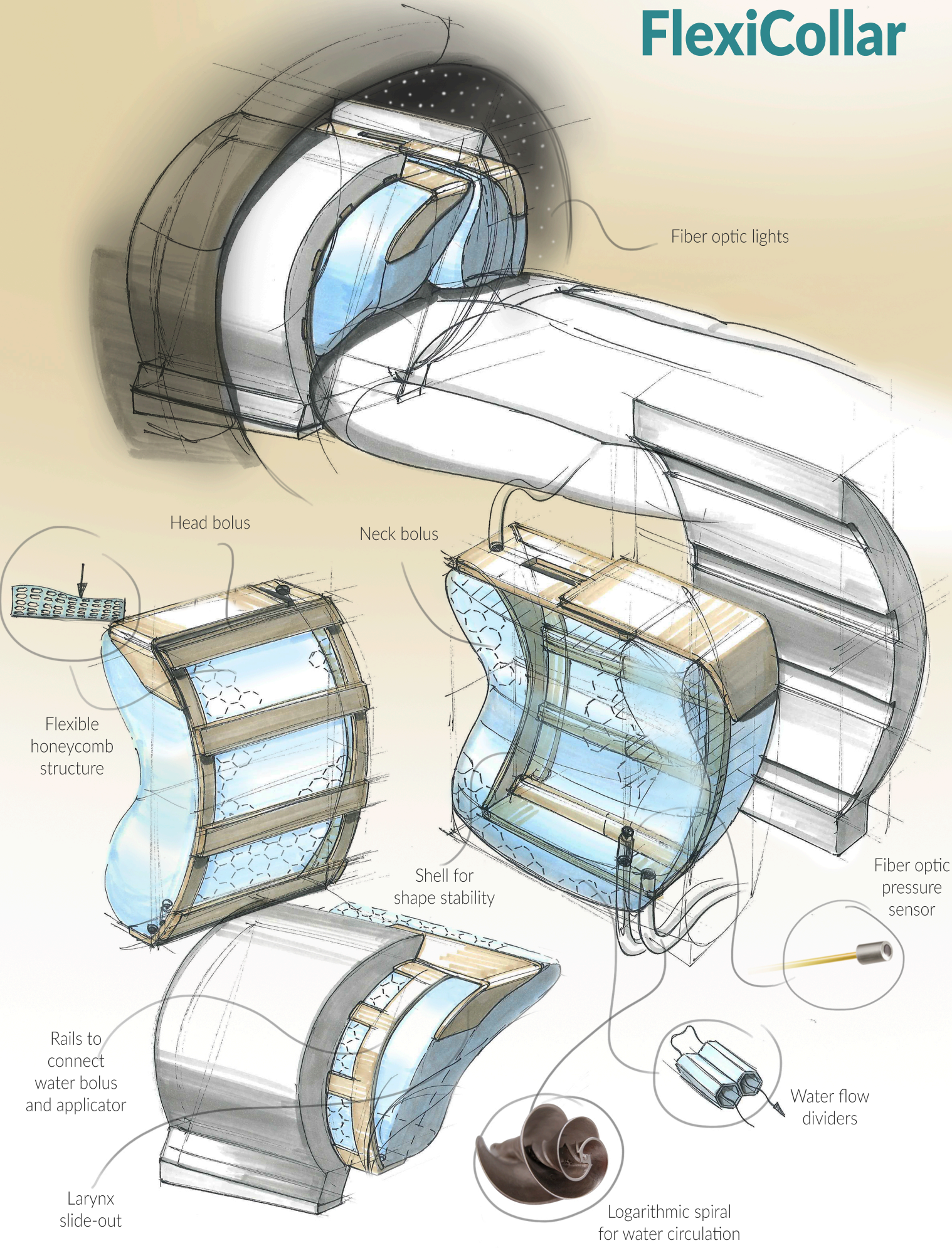


Figure 52 - Structure of Oppanol adhesive

Figure 51 - Applications of Oppanol adhesive

Figure 47 - Concept 1

Concept 1
FlexiCollar



Shape stability and reproducibility in this concept are achieved by a rigid shell on the sides of the water bolus. A similar connecting mechanism as the FlexiCollar is used: a sideways slide with a micro suction tape placeholder.

Uniform cooling is achieved by placing flow guiders inside the foam. Several cuts on the left and right side of the foam are made, in which separation layers are placed. As Figure 53 depicts, similar flow guidance is used in the water bolus for superficial hyperthermia treatment at the Erasmus MC Cancer Institute. This guidance system ensures that the water will circulate throughout the entire bolus, including the edges.

To ensure a laminar flow that disturbs patient comfort and MR-thermometry as little as possible, a logarithmic spiral rotor can be included in the circulation pump of the treatment room. The rotor depicted in Figure 54 has been designed by PAX Water Technologies (AskNature, 2016). This logarithmic spiral is inspired by the recurrent patterns in nature of vertical flows and can efficiently move fluids and manage turbulence.

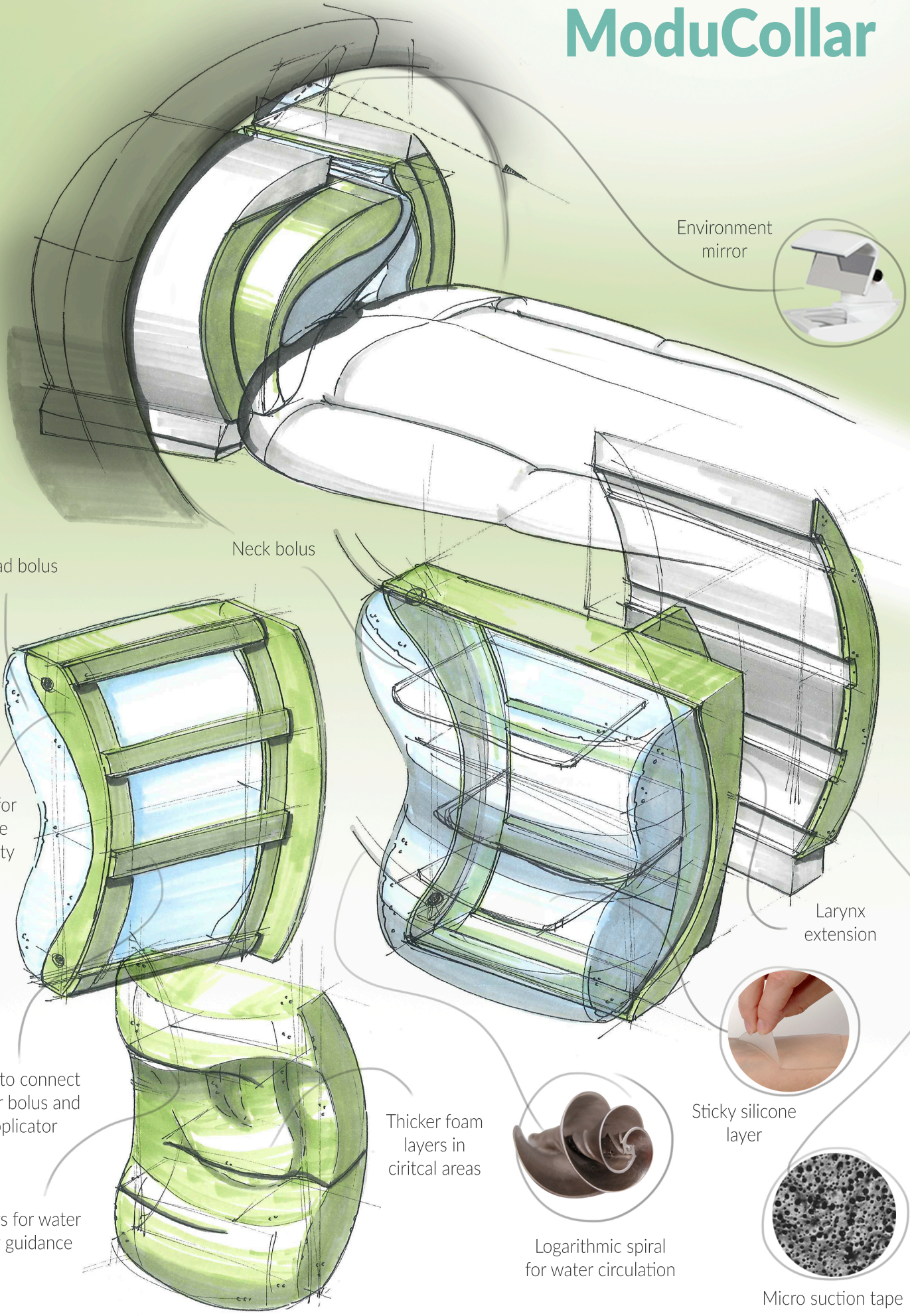
Figure 53 - Flow guidance in superficial hyperthermia treatment

An equal pressure distribution is addressed by adding extra thick or soft layers of foam in the pressure sensitive anatomy parts. This ensures that water bolus contact with for example the sensitive ears feels as comfortable as with the less sensitive cheeks.

Figure 54 - PAX Water Mixer by PAX Water Technologies

Figure 50 - Concept 2

Concept 2
ModuCollar



Concept 3: MorphoCollar

The third concept, which was called the 'MorphoCollar' is depicted in Figure 55. This concept covers all the possible treatments areas of both the head and neck with a single shape. The end near the head is straight, while the end near the larynx is slanted to adequately reach this area. This water bolus harness is made from a rigid, reformable material instead of a flexible material. The benefit of this feature is that the water bolus can copy the exact shape of every patient and lock the position of the patient to prevent motion. For a comfortable touch to the skin, a thin layer of foam can be placed over the rigid structure. When heating the rigid material, the water bolus can be formed around the head or neck and when it is cooled down, the material holds its shape. The created shape can now be used in the following treatments of the same patient to ensure optimal reproducibility and shape stability. After the patient finished the treatment trajectory, the water bolus can be reheated and reformed around a new patient. Heating and shape freezing can be done by letting hot and cold water flow through the bolus. Figure 56 depicts bracing systems from Exos that use a similar (re-)thermoforming technique (Exos, n.d.). The braces can be heated and moulded directly on the skin. After freezing the shape, the material can be reheated and reshaped.

Figure 56 - (Re-)Thermoformable braces from Exos

In radiology, this thermoforming phenomenon is also well known. During radiotherapy masks that are placed over the head of the patient are used to prevent movement during treatment and to reproduce the body position. As I observed in the moulding room of the Erasmus MC, this mask is made before the start of the treatment trajectory by immersing a polymer sheet into a water bath of 60-70°C, where it becomes soft and stretchable. The sheet is then moulded over the head of the patient. Because the cooling process is slow when only exposing the material to room temperature air, the process is accelerated by placing ice packs over the mould. According to the mould maker of the Erasmus MC, the masks could be reused up to 8 times. However, due to hygienic reasons and insecurities about quality after reuse, the mould room only forms the material once. Figure 57 shows an example of a radiology mask from the company Orfit.

By a micro suction tape connection, the MorphoCollar can be attached to the equipment very quickly, ensuring easy operability by the clinicians. The micro suction tape layer covers the applicator surface facing the water bolus. Areas near the antennas are left uncovered to prevent blockage of electromagnetic signals. The back of the water bolus is covered with a smooth surfaced frame that can stick to the suction tape.

The reformable structure is built up out of honeycomb shaped pipes, similar to the FlexiCollar. Again this is intended to have a small filling percentage of structure material and a large filling percentage of water that transfers the electromagnetic waves. Uniform cooling of the skin is achieved by guiding the water flow through the honeycomb pipes, enabling the flow to reach all edges of the water bolus. The pressure of the water bolus on the skin is controlled by monitoring the water volume used to fill the bolus. Indicative volume lines are visibly added to the water tank. Clinicians can read the used volume of water, note this and use the same water volume in following treatments of the same patient.

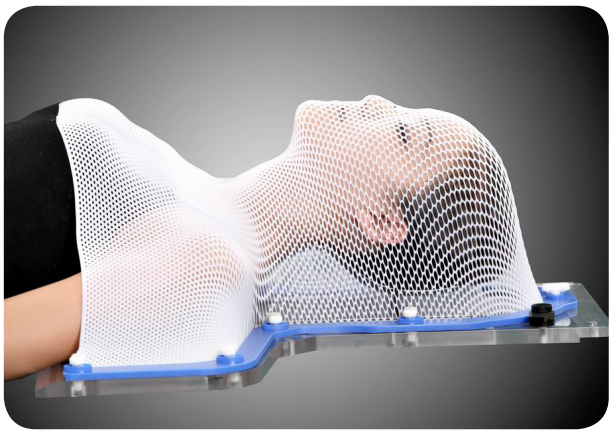
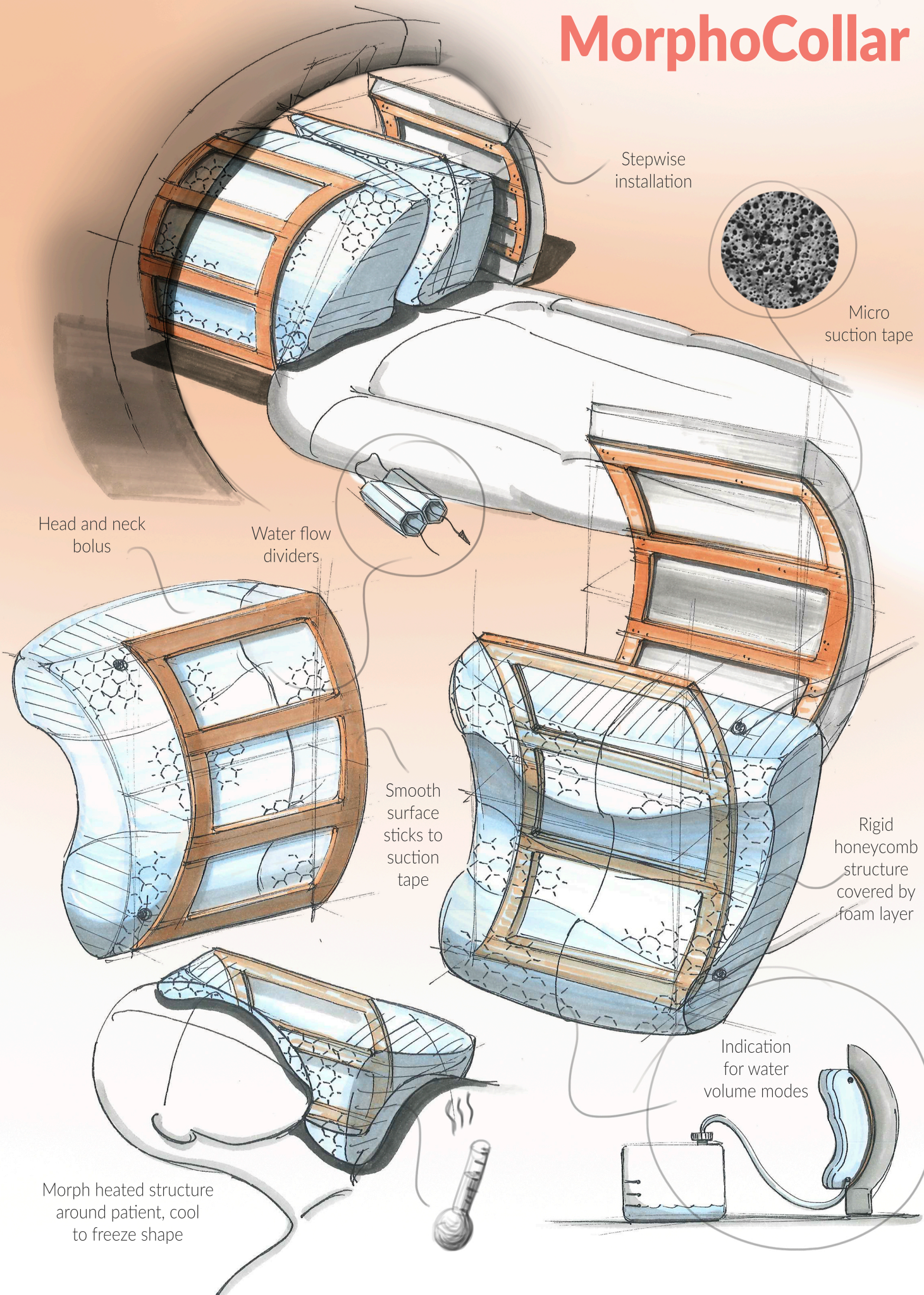


Figure 57 - Radiology mask by Orfit

Figure 55 - Concept 3

Concept 3
MorphoCollar



Concept Choice

The concept with the greatest potential to solve all six design challenges and to be feasible in the timeframe of this thesis had to be selected. To make a choice that would be feasible from both the student's, the Erasmus' and the industrial designer's perspective, the pros and cons of each concept were discussed together with the project coaches. The conclusion from this discussion was to create another concept that combines the feasible solutions and eliminates insecure, high risk ideas from all three concepts. This is needed to make sure a working prototype can be made in the timespan of this thesis. Innovative, high risk ideas like the thermoformable material do therefore not form the main solution of the final concept. However, to enable testing of such innovative techniques, this solution can still be tested by incorporating it to a lesser extent in the concept. A new combination of solutions was made with help of the morphological chart. The choices for the final concept have already been shown in Figure 46.

Concept 4: CombiCollar

The fourth concept, i.e. CombiCollar, was mainly formed from the features of concept ModuCollar. The foam has been replaced by the flexible and partly reformable structures from concept FlexiCollar and concept MorphoCollar respectively. The rationale behind the selected solutions as shown in Figure 58 will be explained.

To reach tumours in the larynx area, the solution of modular variants was chosen for the final concept. Developing one bolus for head treatments and another bolus for neck treatments ensures that only the required skin area of the patient is covered. This prevents that the patient feels locked up inside a water bolus from head to larynx. Eliminating sliding elements from the bolus, as were used in concept FlexiCollar, minimizes the risk of material tearing and resulting leakage of the bolus.

A flexible honeycomb structure was chosen to ensure an optimal ergonomic fit. The honeycomb structure will feel soft to the skin and can closely follow the anatomy. The homogeneous structure of the honeycombs will have a more predictable behaviour than the inhomogeneous foam that is originally used in the hyperthermia equipment, which is a benefit for the digital treatment planning. The honeycomb cushions will have anatomical shapes with average head and neck dimensions. Thermoformable material posed high risks on the installation procedure and the quality of reformed material. However, a customized fit would be optimal in making good skin contact. Therefore, materials that can be slightly reformed when exposed to heat can be used in the honeycomb cushion and larynx extension of the CombiCollar. Reforming in this case can only be used to make minor shape corrections.

Shape stability and reproducibility are obtained by adding a firm shell around the water bolus or by making the outer surface of the bolus thicker on the sides. This support material will be needed on the top, bottom, left and right side of the bolus. The material on the back of the bolus needs to be thin in order to disturb the electromagnetic signals from the antennas as little as possible.

As connecting mechanism the same solution as concepts FlexiCollar and ModuCollar has been selected. The sliding technique enables a more defined placement than the micro suction tape surface from concept MorphoCollar, while the ease of operating is expected to be comparable. A micro suction tape placeholder is added again to prevent sideward movement of the bolus.

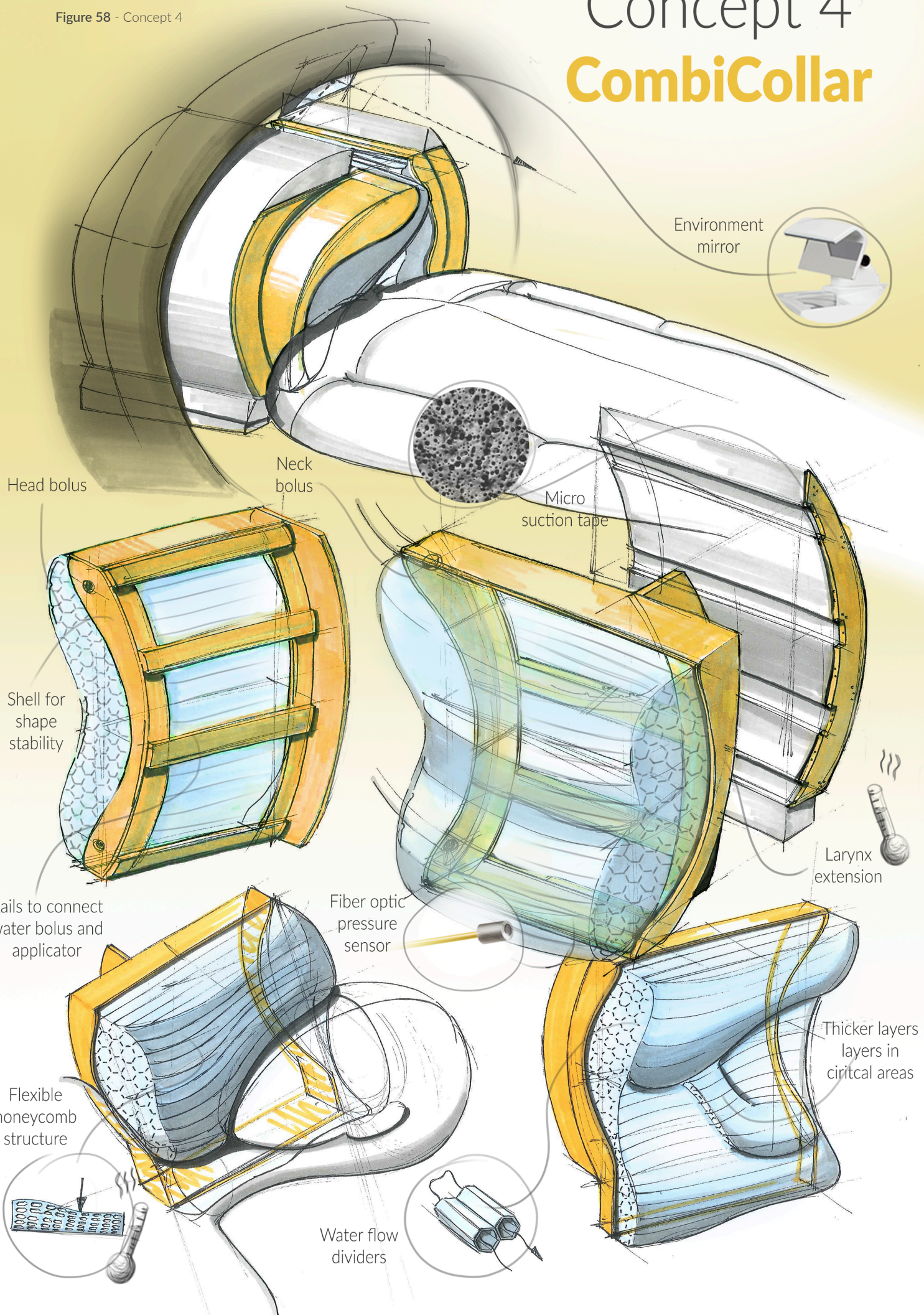
The uniform cooling principle of concepts FlexiCollar and MorphoCollar are applied to the final concept. The hexagonal pipes of the honeycomb cushion form guidance for the water flow to enable uniform cooling throughout the entire bolus. The orientation of the pipes has been rotated compared to the previous concepts to enable water flow parallel to the head or neck instead of perpendicular, which ensures more uniform cooling.

The honeycomb cushion already equally distributes the pressure applied on it. To further improve the comfort of pressure applied on the skin, the honeycombs surrounding sensitive anatomic parts can have an increased flexibility. This solution does not address the lack of indicators regarding high or low pressure applied on the skin of the patient. A fibre optic pressure sensor is therefore added to one of the water boluses as well. This solution is more accurate and requires less operation steps than the manual water volume indicators from concept MorphoCollar.

The CombiCollar is the final concept of this thesis, which will be further detailed into the final HoneyPad design by conducting more research and experiments.

Concept 4
CombiCollar

Figure 58 - Concept 4



4 Fit

The different aspects of concept ‘CombiCollar’ will be further developed into the final design of the HoneyPad in the following chapters. First the ergonomic fit of the water bolus is optimized, which includes the fit between the bolus and the patient as well as the fit between the bolus and the equipment. An ergonomic fit between water bolus and patient is designed by analysing anthropometrics of the head and neck of cancer patients and by using these results to develop a shape that closely follows the human contours. In this anthropometric analysis, extra attention is paid to the anthropometrics in the larynx region to ensure an ergonomically designed larynx extension. Furthermore, reproducibility of the ergonomic fit will be addressed by detailing the honeycomb structure and side panels that generate shape stability. An ergonomic fit between water bolus and equipment is designed by optimizing the sliding- and place-holding mechanism to increase operator comfort.

This chapter will discuss the different optimization steps, material selections and prototyping methods. Multiple iterations are made in prototyping before deciding on the final implementation method of each water bolus part.

Head and Neck Anthropometrics

Analysing the anthropometrics of heads and necks of patients is relevant to define suitable dimensions for the water bolus. The water bolus that is currently used in treatment with the HyperCollar3D has a straight, rectangular shape that is not suitable for accurately following human contours. The ergonomic fit of this water bolus relies completely on the flexibility of the materials. However, due to bending and stretching of the geometric shape, folds are formed on the surface of the bolus which results in air inclusions. This phenomenon can be minimized by designing a water bolus that is shaped to fit the human contours. For this purpose, the anthropometrics of 3D CAD models of head and neck cancer patients are thoroughly analysed and translated into a dedicated water bolus shape. This section will describe the relevant anthropometric data that will be used to develop a 4D representative patient model.

Patient Specific Data

Because the anthropometrics of cancer patients can vary from the healthy population, the anatomical data of cancer patients specifically has to be analysed. Apart from differences in internal physiological processes caused by cancerous tissues, the external anatomy of cancer patients differs significantly from the healthy population as well. Cancer patients suffer from a progressive fat loss and muscle loss over the course of their illness (Wendelsdorf, 2013). A study of Gros et al. (2016) presents clear evidence that the effects of head and neck cancers combined with the effects from radiotherapy result in external volume shrinkage of the neck. The anatomical variations are caused by overall weight loss and local tumour shrinkage. Figure 59 shows an example of these anatomical variations of the neck during the first week of radiotherapy treatment. The anatomical differences between cancer patients and the healthy population stress the importance of using patient specific anthropometric data for the water bolus design. For this purpose, a database with 3D CAD models from head and neck cancer patients has been obtained from the Erasmus MC Cancer Institute.

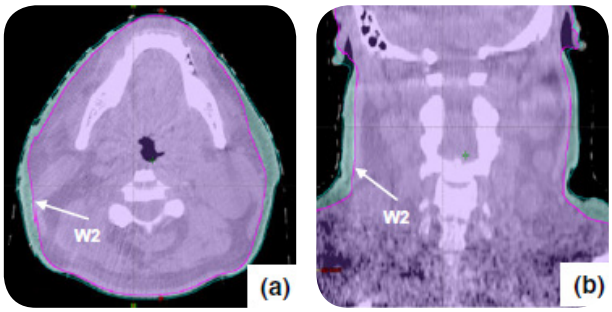


Figure 59 - Anatomical variations of the neck in the first week of radiotherapy treatment

1st Dimension: Sizes

First, the one-dimensional measurements that are relevant for the shape and fit of the water bolus are defined based on the contact points between the skin of the patient and the current water bolus design. These measurements include different lengths, widths and depths of the head and neck.

As can be seen in Figure 60, the current water bolus makes contact with the side of the face during hyperthermia treatment of the head. The space over the eyes, nose and mouth is left open to enable comfortable breathing. However, the material of the water bolus is still touching these parts of the face in an uncomfortable way. The top of the water bolus follows the face contour from the eyebrows down to the chin. In the length, the water bolus runs from the cheeks over the ears towards the sides of the head. The protrusion of the ear in relation to the rest of the face is one of the reasons that patients experience pressure in this area during the treatment.

As can be seen in Figure 60, the water bolus makes contact with the sides of the neck and chin during treatment of the neck. The middle part of the throat is left untouched for breathing purposes. For the redesign of the water bolus, it is important that the head and neck contours in the mentioned contact areas are accurately followed.

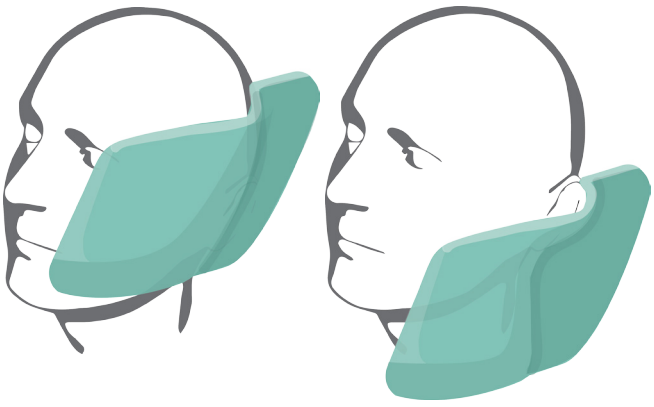
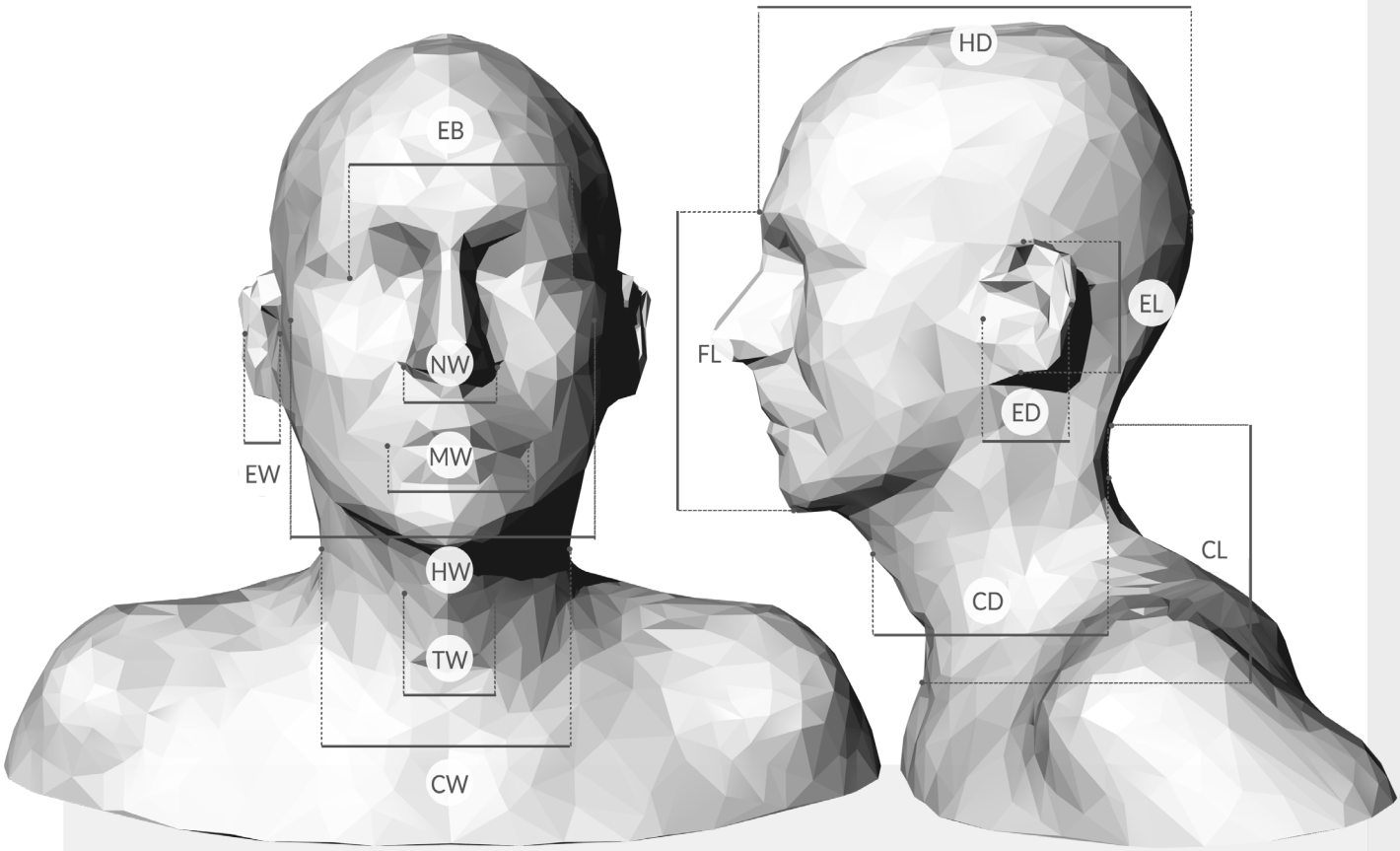


Figure 60 - Water bolus skin contact for head (left) and neck (right) DHT

The selected relevant sizes are shown in Figure 61. The Eye Base, Nose Width, Mouth Width and Throat Width are required to identify the borders of the water bolus shape. The water bolus may not exceed these borders in order to allow comfortable breathing and to prevent uncomfortable touchpoints. Dimensions of the Collar Width, Collar Length, Collar Depth, Head Width, Face Length and Head Depth are relevant to get a grasp of the overall required dimensions of the water bolus. The various dimensions of the ear will be analysed in order to design a solution to overcome experienced discomfort in this area.

These selected sizes will be analysed in different patients, using the CT-scanned 3D models that were obtained from the Erasmus MC Cancer Institute. One-dimensional measurements will differ per individual and are dependent of the age, gender and race of the individual as well. Trends and averages should be therefore looked for when defining the dimensions of the water bolus based on this analysis. This will be analysed by defining two so called 'landmarks' for each of the selected dimensions. The use of landmarks is further explained in the next section.



EB	Eye Base	HD	Head Depth
NW	Nose Width	FL	Face Length
MW	Mouth Width	EL	Ear Length
EW	Ear Width	ED	Ear Depth
HW	Head Width	CD	Collar Depth
TW	Throat Width	CL	Collar Length
CW	Collar Width		

Figure 61 - Selected measurements to analyse in different patients

2nd Dimension: Proportions

One-dimensional measurements alone are not enough to accurately describe the head and neck anatomy of cancer patients. When combining measurements into two-dimensional data, differences in proportion can be found between individuals. A study of Zhuang et al. (2013) indicates that proportions of the head are dependent of the gender and race of individuals. Where age is shown to influence the proportions to a lesser extent. As can be seen in Figure 62, the study of Zhuang et al. (2013) analysed several common proportional variations of the head, such as the head length in relation to the head width, and compares different percentiles of these data.

Variations in proportions will also be present in the sample of cancer patients that will be analysed in this report. The diversification between individuals therefore has to be taken into account in the analysis. This will be done by combining multiple measurements as were defined in the previous section. Combinations of multiple measurements in the same analysis are established by translating these measurements into three-dimensional coordinates, which are called landmarks. Relevant landmarks are indicated in each patient separately, after which all landmarks of all patients are overlapped and compared. This process is further explained in section '4D Anthropometric Modelling'.

The relevant landmarks for the defined measurements and accompanying proportions are shown in Figure 63. The landmarks that are indicated in green are standardized, because they are commonly used in ergonomic studies. These landmarks have been derived from studies of Blackwell et al. (2002), Robinette et al. (2002) and Lee et al. (2013). Landmarks that are coloured pink were developed specifically for this project and are therefore an addition to the existing database. A postdoc from the faculty of Industrial Design Engineering, who is specialized in 3D anthropometry, advised that the development of new landmarks requires an elaborate description of its anatomical position. This is required to ensure consistency in the placement of the landmark in different individuals. The landmark descriptions can be found in Appendix E.

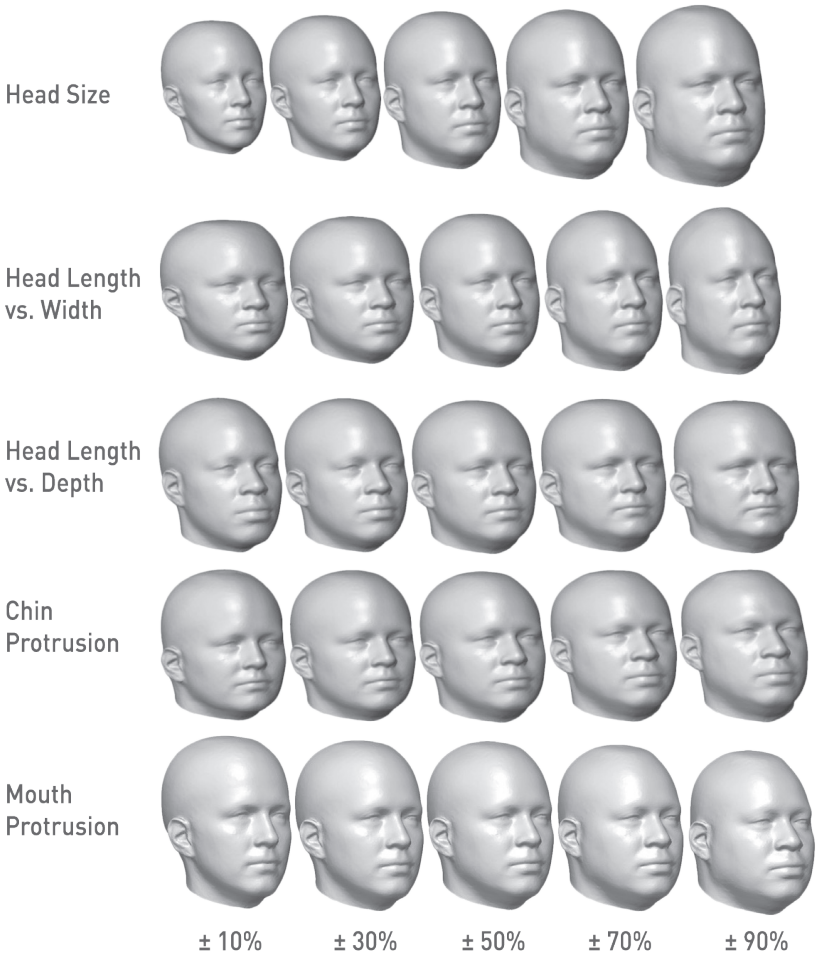
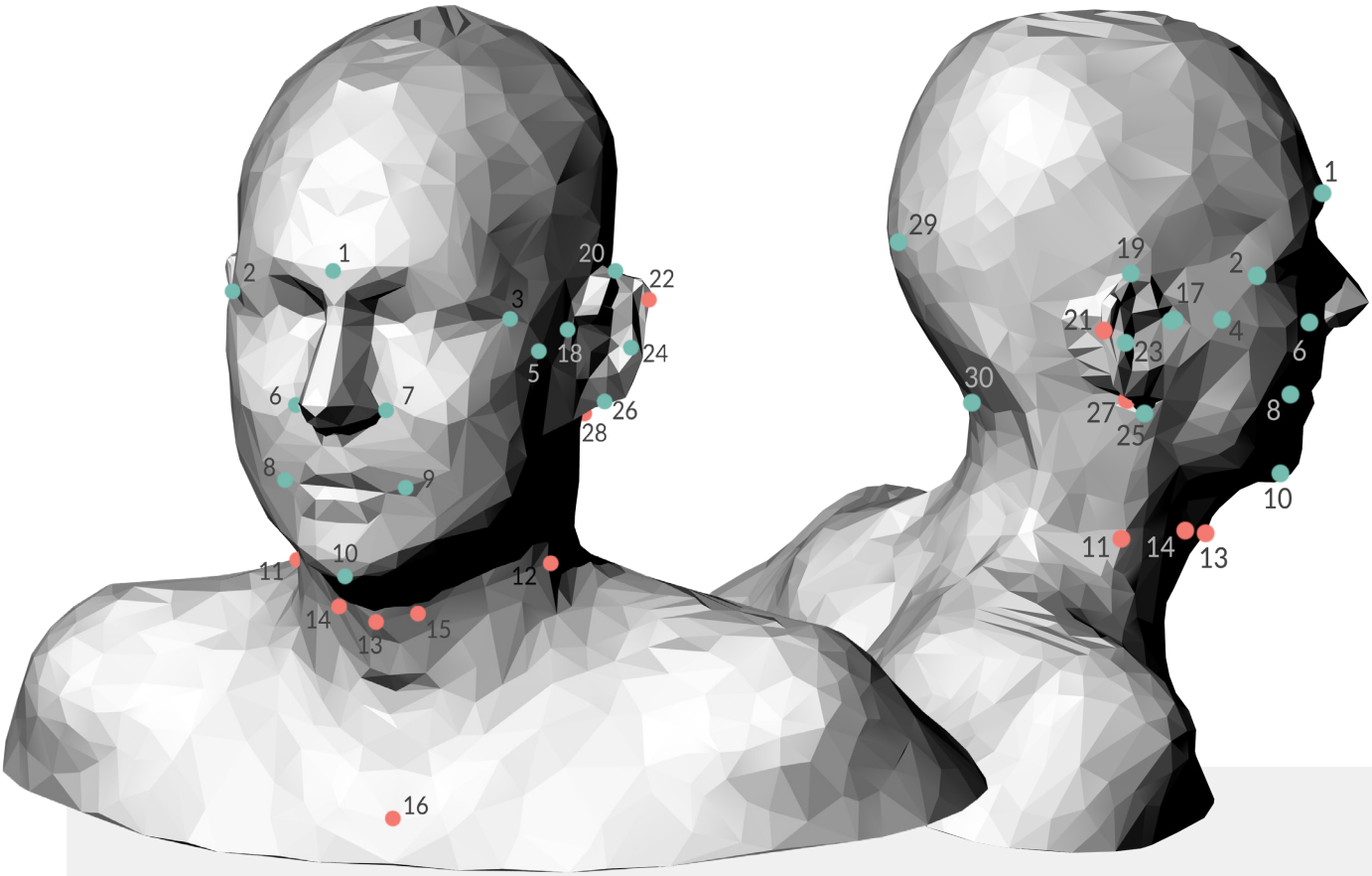


Figure 62 - Different proportions of combined male and female heads of U.S. civilians (Zhuang et al., 2013)



1	Glabella	11	Neck Extremity Right	21	Exterior Auricle Right
2	Ectocanthus Right	12	Neck Extremity Left	22	Exterior Auricle Left
3	Ectocanthus Left	13	Os Thyreoid	23	Posterior Auricle Right
4	Zygion Right	14	Os Thyreoid Right	24	Posterior Auricle Left
5	Zygion Left	15	Os Thyreoid Left	25	Inferior Auricle Right
6	Nasalala Right	16	Jugulum	26	Inferior Auricle Left
7	Nasalala Left	17	Tragion Right	27	Auricular Sulcus Right
8	Cheilion Right	18	Tragion Left	28	Auricular Sulcus Left
9	Cheilion Left	19	Superior Auricle Right	29	Occiput
10	Menton	20	Superior Auricle Left	30	Inion

Figure 63 - Landmarks of relevant measurements and proportions

3rd Dimension: Shapes

When adding a third dimension to the previously discussed measurements, the shape of the human head and neck can be described. As can be seen in Figure 64 and Figure 65, shape diversification of the head and neck is significantly influenced by race. Figure 64 shows that the curve which describes the side of the face varies for example between Asian and Caucasian races. In Figure 65, racial curvature diversifications of the back of the human head are depicted. The last example does not only show differences in intercontinental races, but also in international races.

It is possible to analyse shape variations by drawing surface curves onto the human CAD models between two or more landmarks. However, the CAD models have relatively large mesh facets which make these curvatures inaccurate. Furthermore, this anthropometric analysis is intended to find dimensions for the design of a flexible product. The flexibility of the water bolus is able to morph into the right shape, as long as it has measurements, proportions and a basic human shape that fit the entire sample of patients.

To obtain a basic human shape in the water bolus, one of the CAD models with relatively average dimensions is selected from the sample of models, as Figure 66 depicts. This selected model contains a basic human shape, which will be morphed to dimensions that fit the entire sample. With this

method, a basic human shape can still be taken into account in the design of the water bolus. The development of this representative model is further explained in section 'Representative Patient Model'.

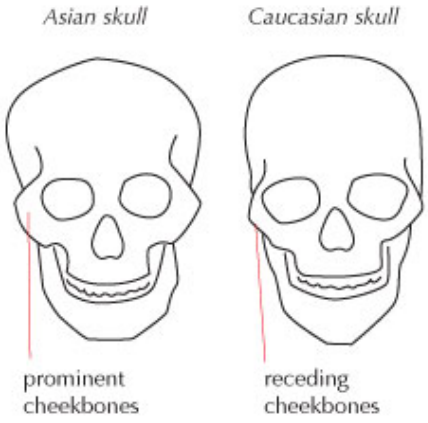


Figure 64 - Shape diversifications of the human skull (Medlej, 2014)

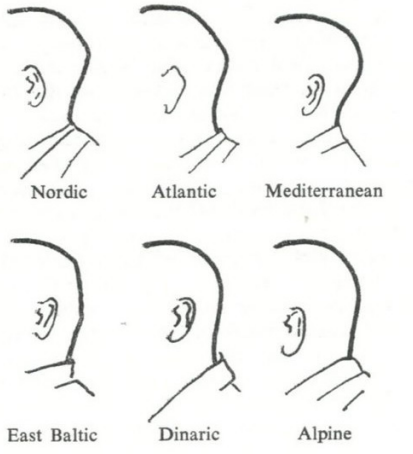


Figure 65 - Shape diversifications of the human head according to race (Gayre, 1972)

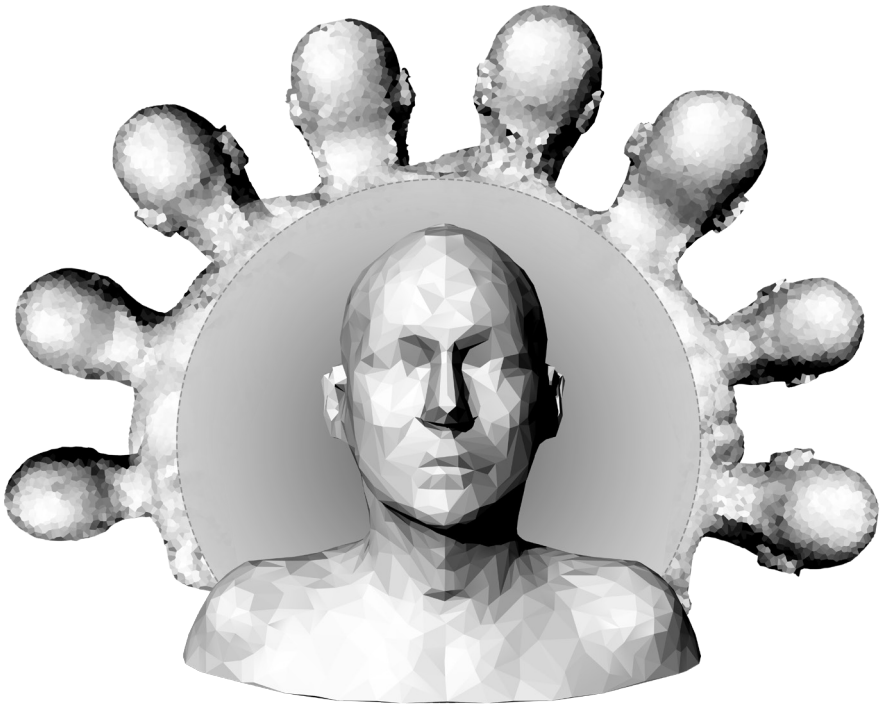


Figure 66 - Selection of a CAD model that represents the shape of the entire sample

4th Dimension: Anatomical Properties

With three dimensions, the exterior of every head and neck cancer patient can completely be described. However, as was stated previously, the anatomy of the head and neck contains many unique transitions between bone, muscle and vessel tissue. These varying tissues react in different ways to the impacts of pressure and cooling of the water bolus and to the heating of the electromagnetic waves. These characteristics can be defined by a 4th dimension: the anatomical properties.

The tissues that are sensitive to pressure and temperature and therefore require attention in the water bolus design, have been discussed with a clinical technician of the Erasmus MC Cancer Institute hyperthermia unit. According to this expert, the eyes are not a target area for heating. Combining

this insight with the fact that the current water bolus causes uncomfortable touchpoints around the eyes, it is clear that any contact in this area should be avoided. The ears form another area of attention. Patients often experience heat around their ears because the water bolus cannot make adequate contact with the skin in this irregular area. As the ears are protruding from the face and flattened by the water bolus, a large pressure on the ears is being experienced by patients as well. Because the ear canal is always filled with air, this area is also heated to uncomfortable temperatures during treatment. The close proximity of the vestibular system makes the relevance of the ear area even greater. When the temperature around the vestibular system varies from other areas in the head and neck, the patient will experience dizziness. Furthermore, the technician indicated that often large energy accumulations are noticed around the chewing muscle. Cooling this area with the water bolus is therefore of great importance. Regarding pressure, the chewing muscle is also a relevant area. Patients have indicated that their mouth is being pushed open as a result of a large water bolus pressure, which is considered uncomfortable.

An overview of the areas of attention as indicated by the expert is given in Figure 67. Based on the insights from the technician, the landmark 'Musculus Masseter' was added to the anthropometric analysis. As the ear and eye areas were already covered with landmarks, there is no need to add extra landmarks here.

A study of Barros et al. (2014) shows that pressure is considered uncomfortable in skin regions where the proportion of soft tissue compared to rigid tissue is lower. The thickness of soft tissue, which is composed of skin, fat and muscle tissue, is responsible for a variation in the resistance to pressure applied to the skin. In the head and neck areas, the cheekbones and jawbones are the main regions with small proportions of soft tissue. Figure 68 depicts these relevant anatomical areas. Therefore, the landmarks 'Cheekbone' and 'Gonion' were added to the anthropometric analysis, where Gonion stands for a standardized landmark on the jawline.

Other areas of attention regarding the pressure of the water bolus are the large vessels in the head and neck. During hyperthermia treatment the patient is exposed to pressure of the water bolus for 75 minutes. This continuous pressure is likely to lead to an experience of discomfort in the regions that contain large vessels. Looking at the anatomy of the head and neck, it is found that the carotid arteries are the main vessels that are covered by the water bolus, as can be seen in Figure 69. Because pressure in these areas should be applied carefully, the landmark 'Carotid' has been added to the anthropometric analysis.

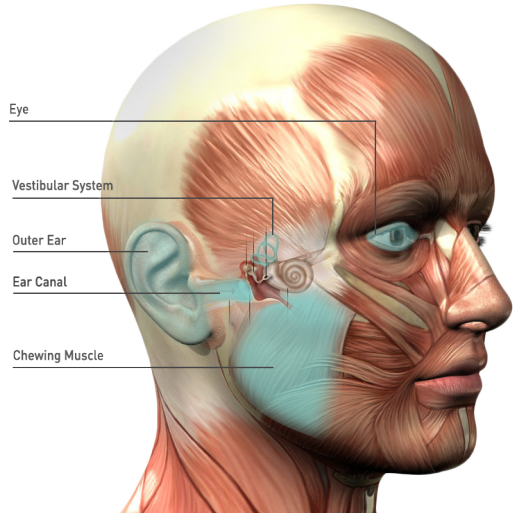


Figure 67 - Areas of attention regarding pressure and temperature according to a clinical technician in hyperthermia

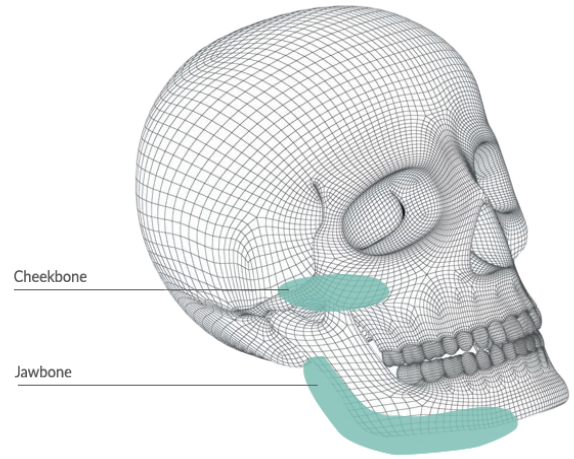


Figure 68 - Anatomical areas with small proportions of soft tissue

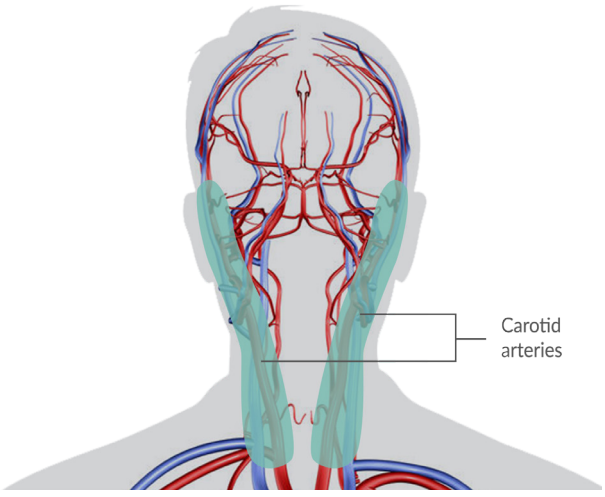


Figure 69 - Areas of attention regarding pressure on large vessels

The analysis of relevant anatomical data in the fourth dimension has led to several new landmarks. These additional landmarks are shown in Figure 70. 'Gonion' is a standardized landmark that can directly be found on the human CAD models. The other landmarks 'Cheekbone', 'Musculus Masseter' and 'Carotid' are harder to be found, or represent a curvature instead of a point. For this purpose, surface curves have been drawn over the entire contour of the cheekbones, chewing muscles and arteries by connecting landmarks that were already indicated. The middle points of these curves are used as landmarks in the anthropometric study.

31	Gonion Right
32	Gonion Left
33`	Cheekbone Right
34	Cheekbone Left
35	Musculus Masseter Right
36	Musculus Masseter Left
37	Carotid Right
38	Carotid Left

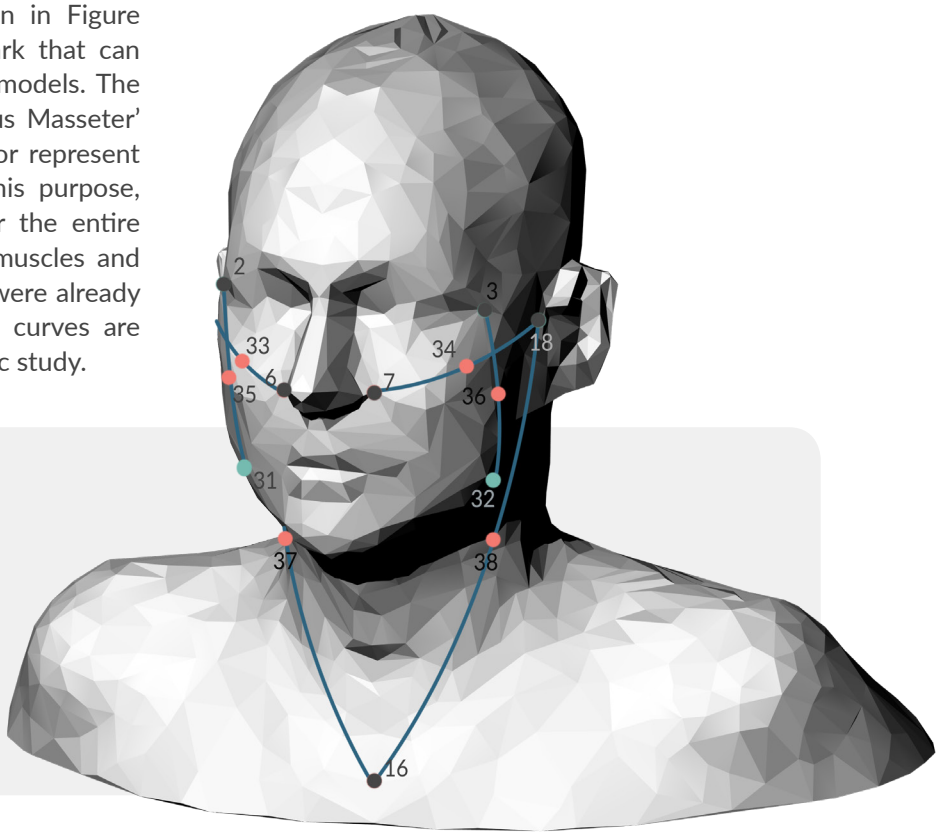


Figure 70 - Anatomical landmarks to analyse in different patients

Larynx Dimensions

The 38 different landmarks that have been selected and explained in section 'Step 1 – Head and Neck Anthropometrics', serve as a means to improve the shape of the current water bolus design. Additional to improving this shape, an extension to reach the larynx region has to be designed as well. To identify the landmarks that are relevant for this extension, the dimensions and positions of neck- and larynx tumours are analysed.

Figure 71 depicts three individuals that have tumours with large dimensions and a position in the lower neck. These examples are used as a reference for the dimensions of the required larynx extension for the water bolus. It can be concluded that these tumours can be covered with an extension that reaches onto the pit in between the collar bones; the so called jugulum. When the extension follows the path of the collar bones, tumours on the side of the neck can be reached as well. The current design of the HyperCollar3D is able to reach until the shoulders of the patient, as is shown in Figure 72. A larynx extension therefore needs to start at the top of the shoulders and go towards the jugulum via the collar bones.

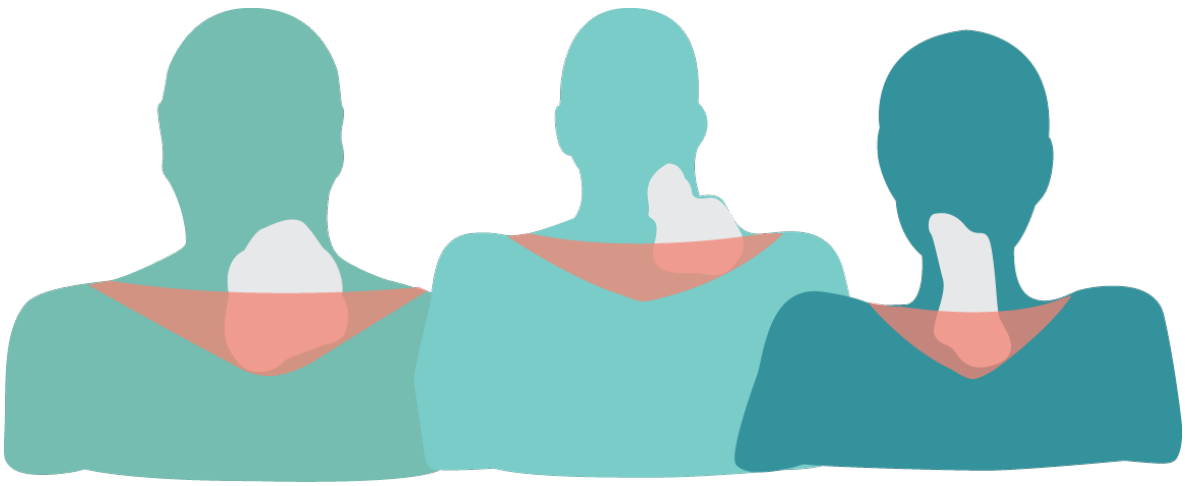


Figure 71 - Examples of larynx tumours (grey) and the area to be covered by the water bolus extension (pink)

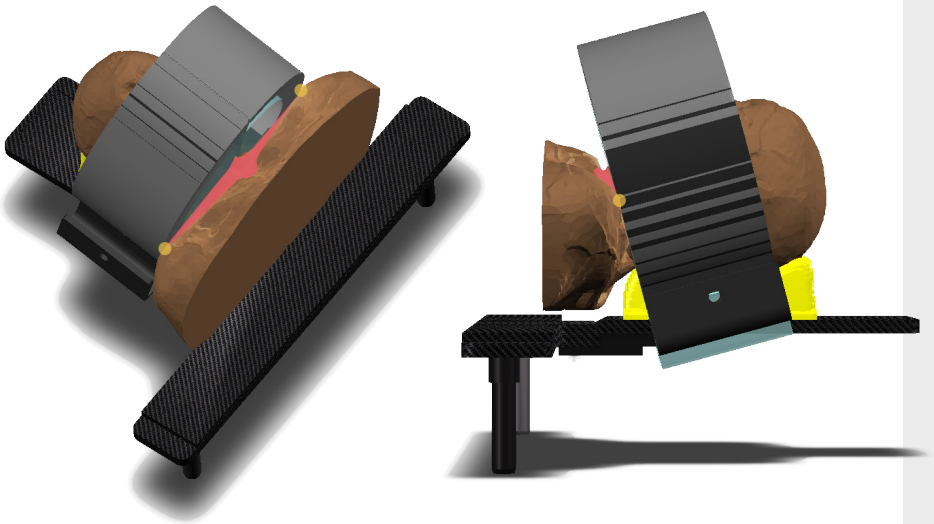
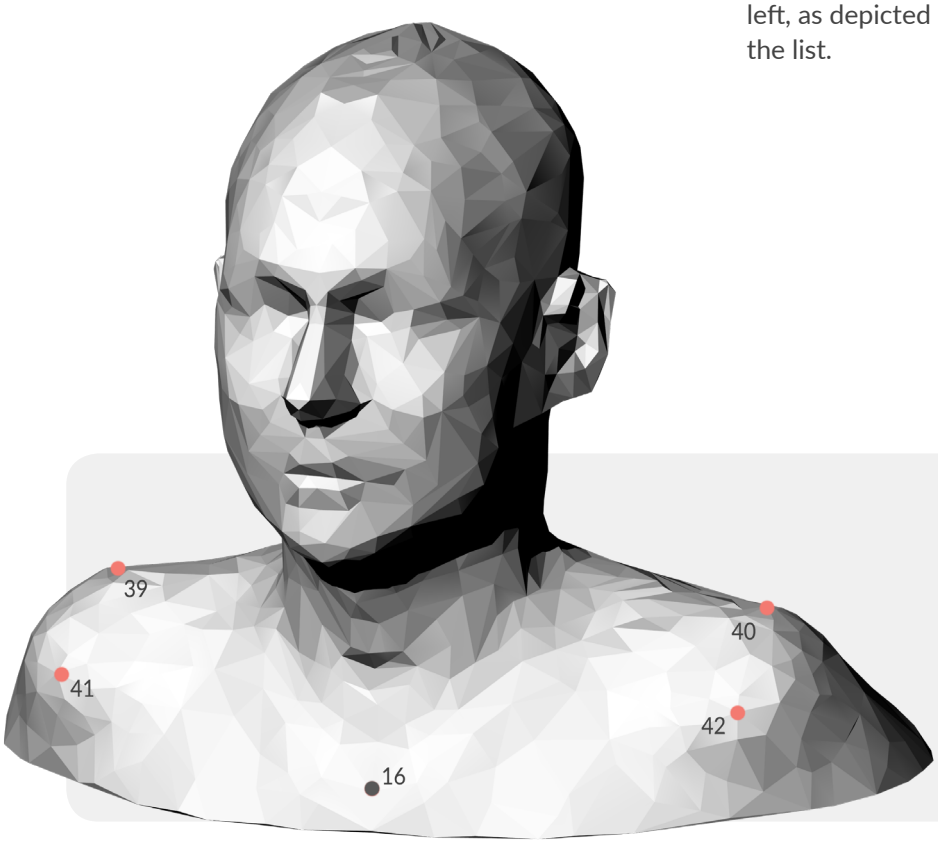


Figure 72 - Touchpoint of the HyperCollar3D with the shoulders (yellow dots) and required larynx extension of the water bolus (pink)

It can be concluded that relevant landmarks for the larynx extension of the water bolus are the 'Shoulder Superior' on the right and the left. These new landmarks are depicted in Figure 73. The landmark 'Jugulum' was already added to the list, and is of great importance for the extension.

Apart from the flexible water bolus, the rigid applicator also needs to be extended in order to support the water bolus. This applicator extension needs to start at the 'Shoulder Superior' and end at the height of the 'Jugulum'. Because this extension is rigid, it should be shaped around the shoulder of the patient and leave enough space for the shoulder height. The landmarks 'Shoulder Anterior' right and left, as depicted in Figure 73, are therefore added to the list.



31	Gonion Right
32	Gonion Left
33`	Cheekbone Right
34	Cheekbone Left
35	Musculus Masseter Right
36	Musculus Masseter Left
37	Carotid Right
38	Carotid Left

Figure 73 - Relevant landmarks for a larynx extension of water bolus and applicator

4D Anthropometric Modelling

An anthropometric analysis has been conducted based on the 42 different landmarks that were defined in the previous two steps. All of the landmarks were added to a database of 3D CAD models of head and neck cancer patients and their coordinates were compared by an algorithm afterwards. Averages, standard deviations, minimum values and maximum values were calculated by the algorithm and the variant that would results in a universal fit was selected for each of the landmarks. The results from this analysis have been used to create a representative patient model that will be used to define the shape of the water bolus. Dimensions of the applicator extension are defined based on the results of the algorithm as well.

Database

A database of 45 3D CAD models from head and neck cancer patients was provided by the Erasmus MC Cancer Institute. These models were derived from CT-scans that have been made from patients who were treated with deep head and neck hyperthermia. This group is therefore representative for the target users in this project.

To evaluate whether the database has a sufficient spread in large, medium and small individuals, the head width of the patients was compared to head widths in the online anthropometric database DINED (n.d.). The head width was chosen for this comparison because it is measured from bone to bone (zygion to zygion) and will therefore not be affected as much by effects from cancer as the neck dimensions. Figure 74 depicts the head widths of percentiles 90 (large), 50 (average) and 10 (small) as defined by DINED for a healthy population of males and females within the age range of 20-60+.

Three patients with a large, medium and small head width were selected manually from the database of human CAD models. The patients represent a population of 20-75 years old with 25% women and 75% men which are mainly Caucasian. Their head widths are depicted in Figure 75. When comparing these results to the DINED database, it can be concluded that large, medium and small individuals are present in the sample of CAD models. The sample has a sufficient spread and can therefore be used in the anthropometric analysis.

Several models from the CAD database were eliminated due to the following reasons:

- 8 models missed the top of the head or the chest
- 3 models had a lifted or rotated head
- 2 models had lifted or unevenly positioned shoulders
- 1 model had an opened mouth
- 1 model contained motion artefacts

These models could not be used in the analysis because they could not be aligned with the other models, would result in a faulty interpretation of dimensions or would lead to inaccurate results. After eliminating the unusable models, 30 models were left for the anthropometric analysis.

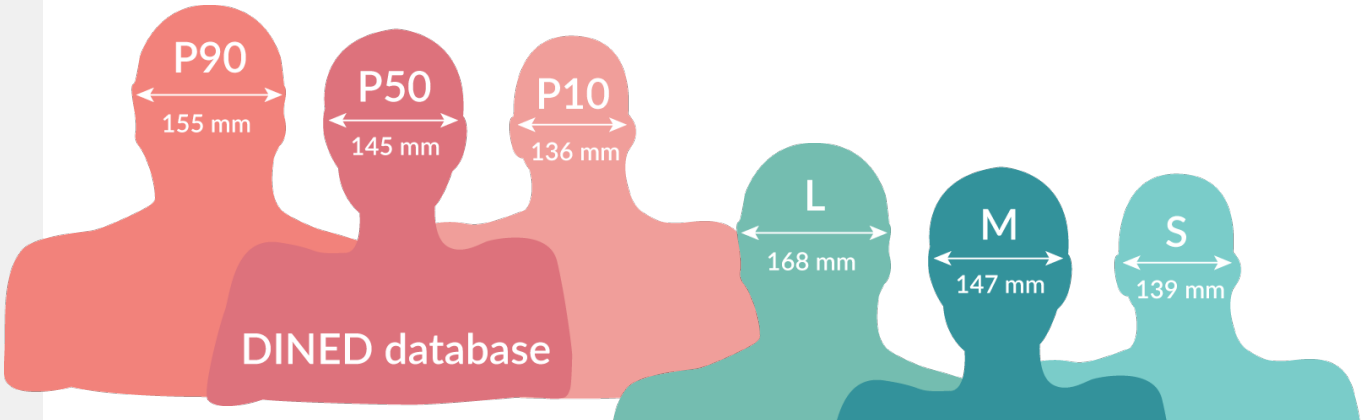


Figure 74 - Large, medium and small head widths according to the DINED database

Figure 75 - Large, medium and small head widths from the database of human CAD models

Landmarking

All 42 landmarks were indicated manually on each of the 30 CAD models by using the open source software 'GOM Inspect'. After all models were provided with landmarks, they were rotated into similar positions by aligning the Occiput with the origin of the coordinate system, the Glabella with the Z-axis (seen from side-view) and the nose tip with the Z-axis (seen from top-view). The alignment is an essential step because the patients were scanned in slightly different positions and have to be rotated to similar positions in order to compare their dimensions. The coordinates of the landmarks were exported to Microsoft Excel, in which the lists with coordinates per patient were rearranged into lists with coordinates per landmark. The steps of this process are visualized in Figure 76. The resulting 42 lists with landmark coordinates were linked to Grasshopper; an algorithm editing software that is a plug-in of the 3D-modeling software Rhinoceros. In Grasshopper multiple algorithms were generated to define the optimal dimensions for a universal fit of the water bolus and applicator extension.

Ergonomic Algorithms

An overview of the algorithms that were generated in Grasshopper is given in Figure 77. For every landmark the average of the coordinates from all patients is calculated. Furthermore, the standard deviation of the X-, Y- and Z-coordinate are calculated and for some of the landmarks the minimum and maximum X-, Y- and Z-values are included in the algorithm as well. The algorithms are subdivided into the groups 'Larynx Extension', 'Face Borders', 'Symmetrical Landmarks', 'Single Landmarks' and 'Ear Landmarks', of which the first two make use of various values and the last three make only use of averages. The different steps of the algorithm and the choice for these variations will be explained in this section.

Functions for a Universal Fit

Before the analysis of the landmark coordinates can start, a code that can read Excel files has to be generated in Grasshopper. A plug-in called 'ExcelReadWrite' was used for this purpose. Figure 78 presents the code that has been generated to read out the coordinate lists. When all 42 lists of all 30 patients are read out, the spread of the coordinates can be visualized on a 3D CAD model as is depicted in Figure 79.

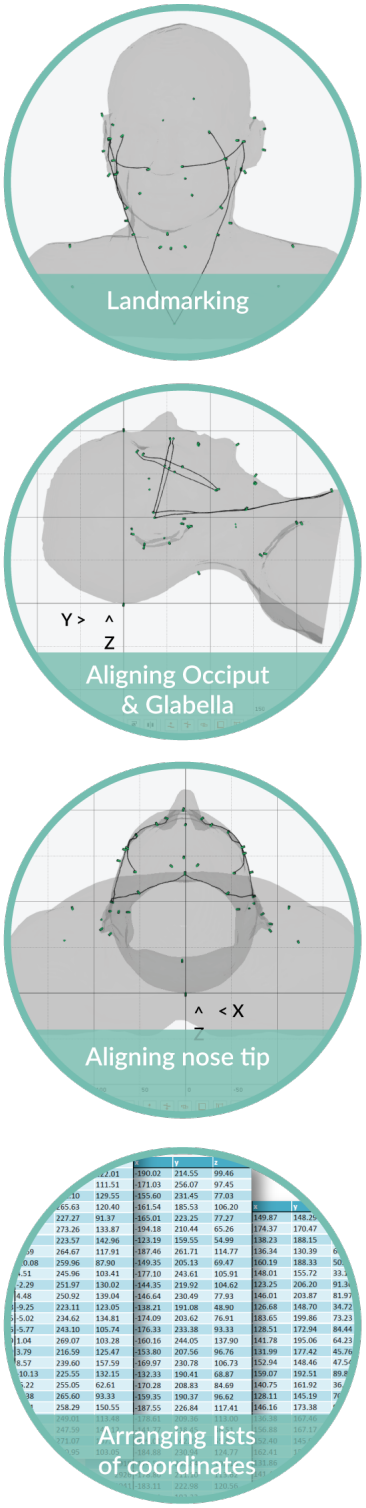


Figure 76 - Subsequent steps of obtaining data from landmarks

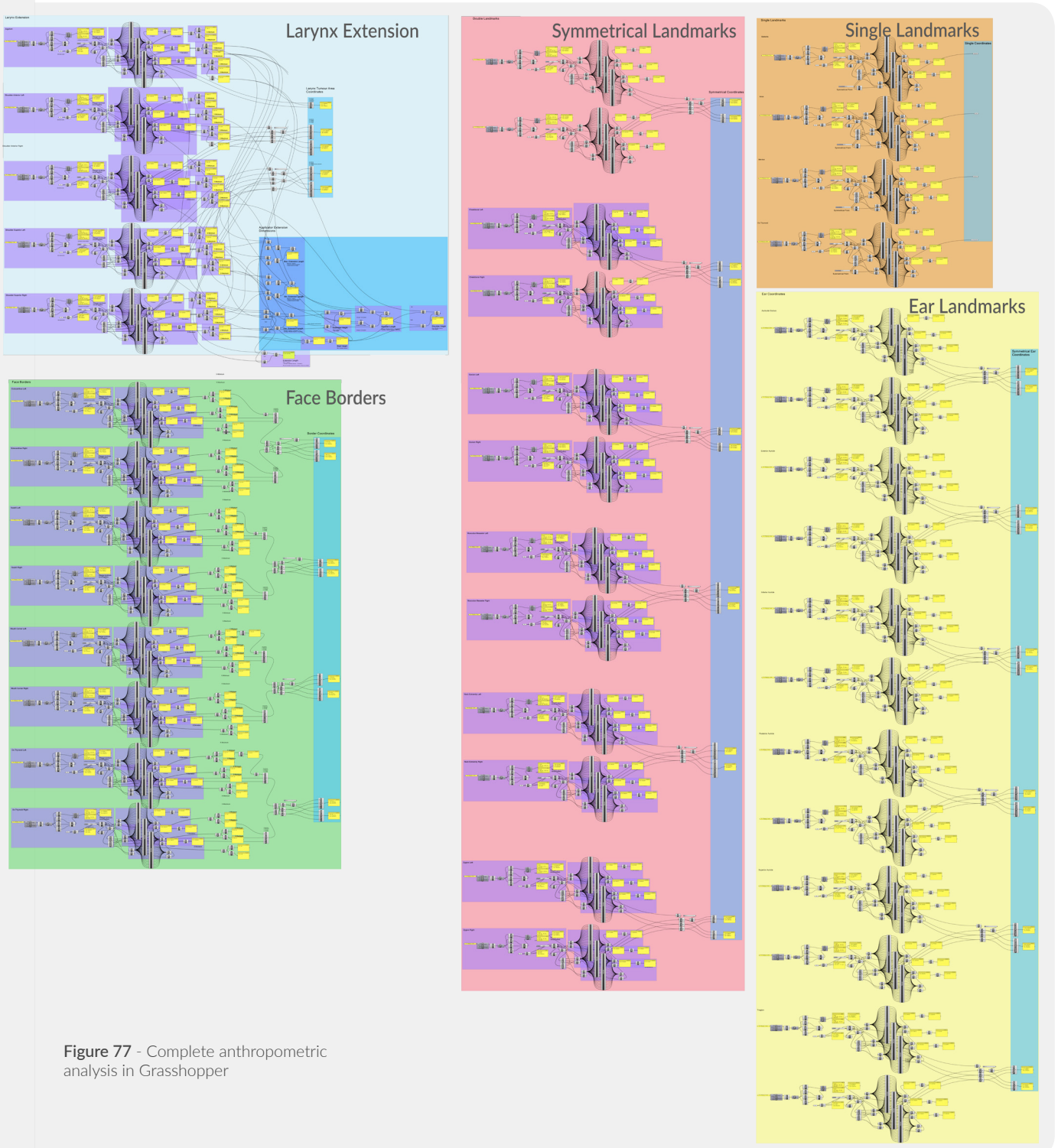


Figure 77 - Complete anthropometric analysis in Grasshopper

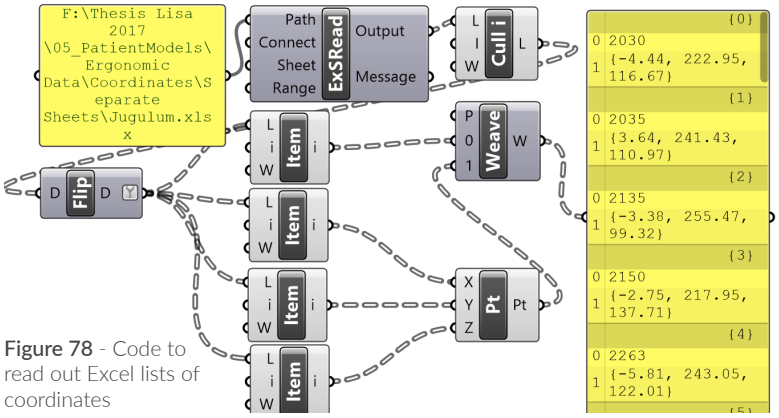


Figure 78 - Code to read out Excel lists of coordinates

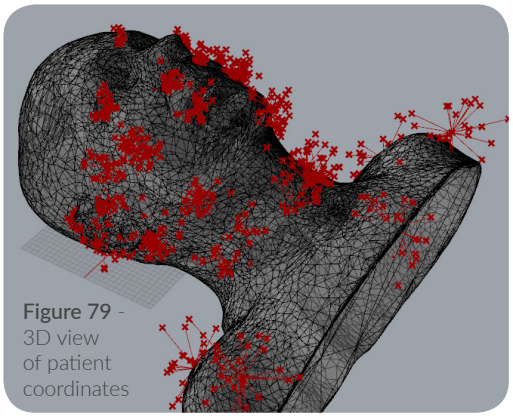


Figure 79 - 3D view of patient coordinates

The coordinates from all patients are used to calculate the average coordinate. The code that was used for this is shown in Figure 80. Despite the fact that all of the patient models have been aligned to similar positions, the landmarks still show a large spread and include several outliers. This can be explained by the use of different headrest sizes and positioning angles in the CT-scanner. In order to minimize the effects of these differences, the coordinates that deviate most from the average coordinate are eliminated from the list. To let the algorithm do this work automatically, lines are drawn between the average point and all other points, and the coordinates that belong to the 10% with the longest lines are left out of the analysis. This step is depicted in Figure 81.

A new average is calculated from the list without outliers, which is used in the calculation of standard deviations. For this calculation the following formula has been used:

$$\sqrt{\frac{\sum(Point - Average)^2}{Total\ points}}$$

The Grasshopper algorithm for this formula is depicted in Figure 82.

Finally, the minimum and maximum values have been calculated for the landmarks that required these values for a universal fit of the water bolus or extension frame. Figure 83 depicts the sorting of these values in Grasshopper.

Now that all the needed components have been calculated, it is important to combine these values in order to generate the optimum values that are needed for the dimensioning of the water bolus. The landmarks were subdivided in five different categories based on the type of function they required. Figure 84 shows an overview of these categories. An overview of the used function for each landmark specifically is given in Appendix F.

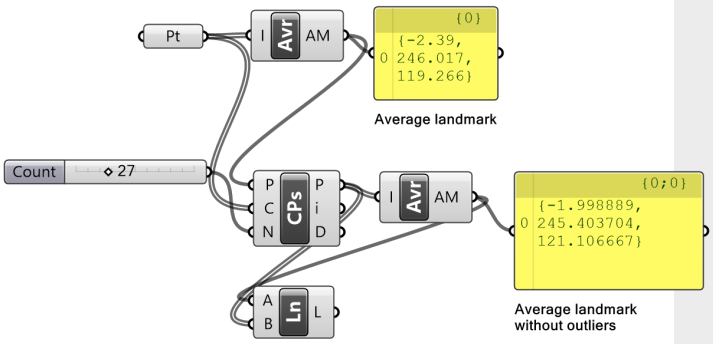


Figure 80 - Calculate average and average minus outliers

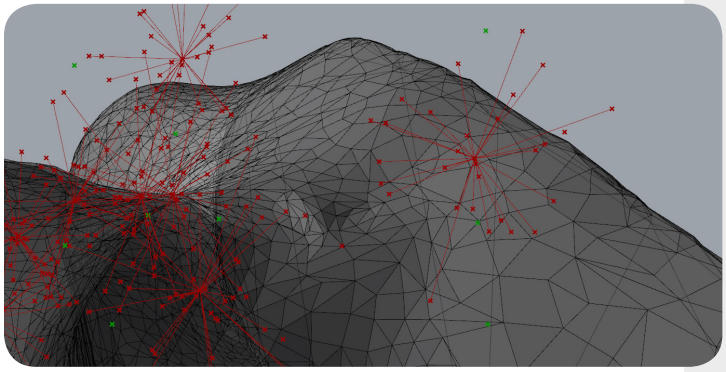


Figure 81 - Spread of coordinates from different patients (red) and removed outliers (green)

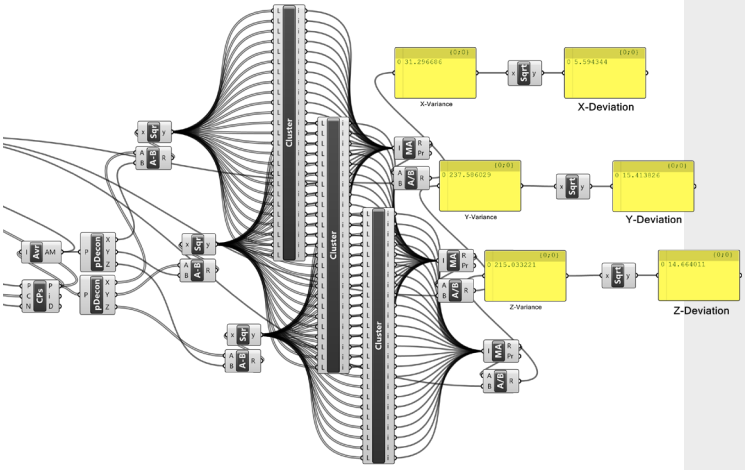


Figure 82 - Calculate standard deviation in the X-, Y- and Z-direction

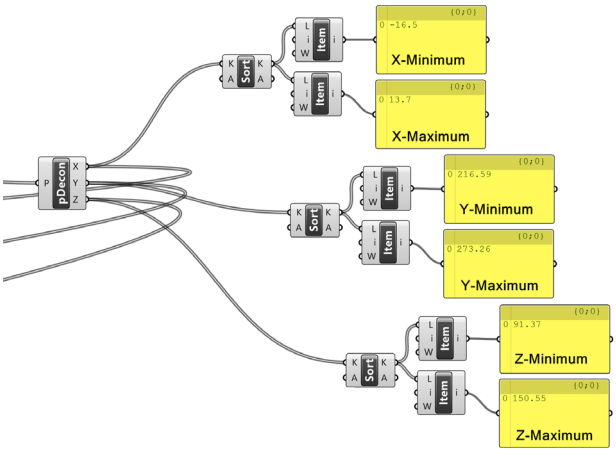


Figure 83 - Calculate minimum and maximum values in the X-, Y- and Z-direction

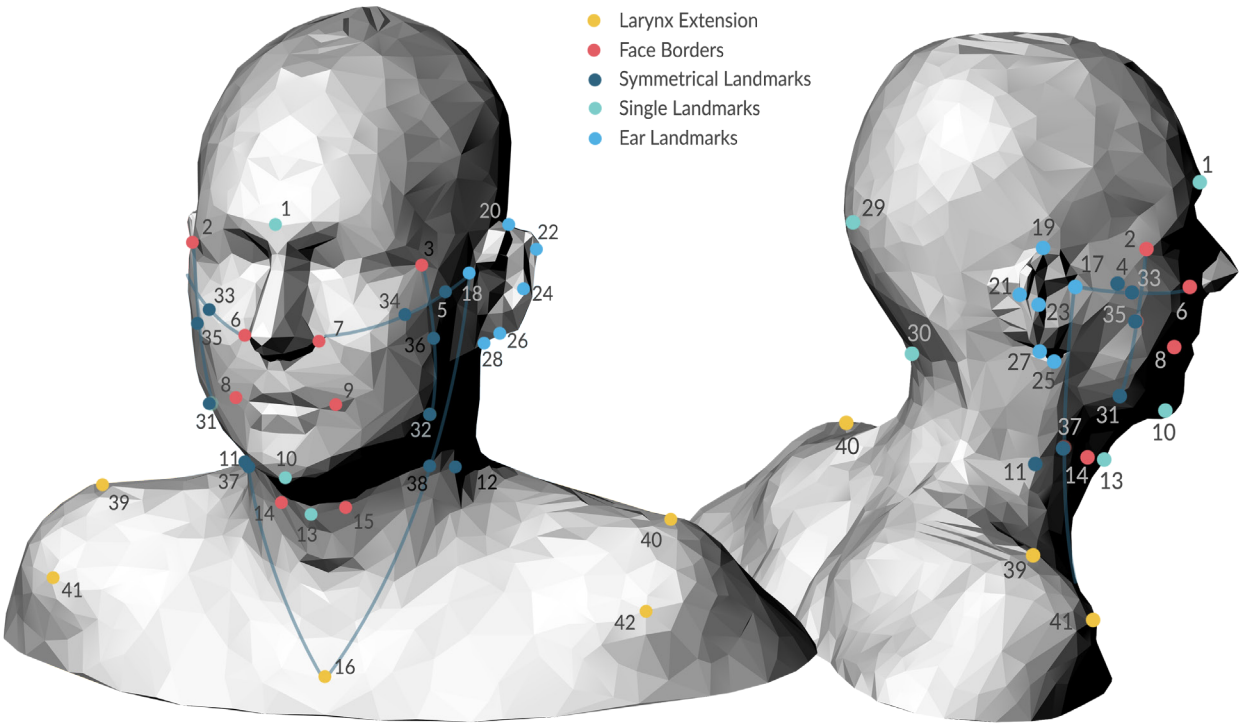


Figure 84 - Categories of landmarks for function definitions

Larynx Extension Functions

The landmarks in the category Larynx Extension required multiple different functions, because a rigid extension of the equipment and a flexible extension of the water bolus will be designed from these data. For the rigid extension, the dimensions as depicted in Figure 85 are of importance. For the dimensions in the Z-direction it is relevant that every patient, even the largest one, will fit in the equipment. For this purpose, the heights in the Z-direction were calculated with maximum landmark values in mind. For the Jugulum, a maximum value in the Y-direction has been chosen as well to ensure that the largest larynx tumour in the largest patient can be covered. The minimum and maximum Y-values of the shoulders are not accurate due to shoulder lifting in the CT-scans. Average values with added or subtracted standard deviations have therefore been used instead. In the cases where minimum and maximum values were used, a second close look was taken at the outliers because these could significantly influence the outcomes. In some cases one-dimensional data (X, Y or Z) from one extra outlier was therefore removed, while preserving the data from the two remaining dimensions.

For the dimensions of the water bolus extension, average values in X-, Y- and Z-directions have been used instead. This is because the water bolus needs to closely fit patients of all sizes. Because the Shoulder Superior and Jugulum form the start and end point from the extension, these Y-values were kept the same as for the rigid extension.

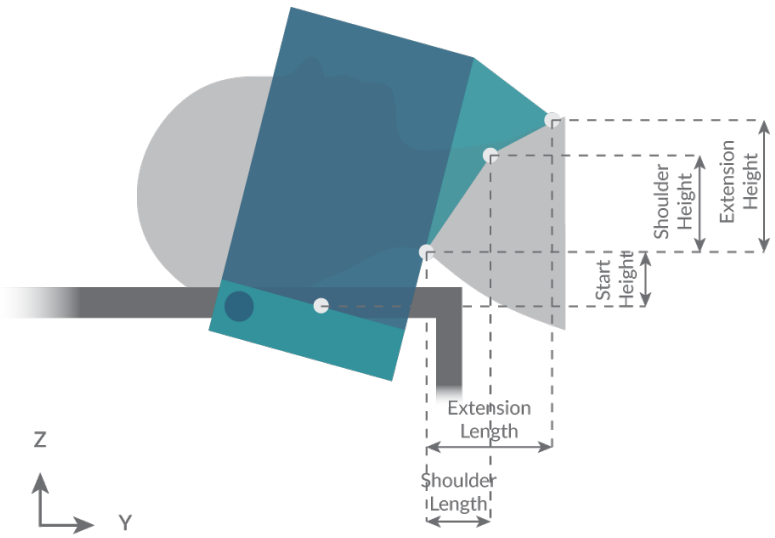


Figure 85 - Relevant dimensions for the rigid larynx frame extension

Face Border Functions

The characteristic of the category Face Borders is that the shape of the water bolus should not exceed the position of the landmarks in this category. If their positions are exceeded, it is expected that the water bolus will form uncomfortable touchpoints that will affects the ease of breathing. For this purpose, maximum X-values are selected. The face borders are depicted in Figure 86.

Symmetrical-, Single- and Ear Landmarks Functions

For the categories Symmetrical Landmarks, Single Landmarks and Ear Landmarks, it was chosen to stick to average values to ensure an ergonomic fit for patients of all sizes. Because the Symmetrical Landmarks and Ear Landmarks had both left and right versions, the values of these coordinates were averaged and mirrored to form a symmetrical left and right side of the water bolus. To enhance this symmetry, the X-value of the Single Landmarks was set at 0.

An overview of the optimal coordinates that resulted from this anthropometric analysis is depicted with the blue dots in Figure 87. The specific functions that have been used for each of the coordinates are explained in Appendix F.

Representative Patient Model

The optimal anatomical coordinates that have been defined in the anthropometric analysis will be used to create a representative patient model. This representative model will be formed by morphing one of the CAD models from the sample into the desired optimal shape. The resulting model will be used to form the shape of the water bolus.

A free-form modelling plug-in for Rhinoceros called 'T-Splines' is used to morph one of the average sized patient models to the optimal dimensions. This is done by dragging the volume at the points of the original landmarks towards the optimal coordinates until both points overlap. Figure 87 depicts the first step of this process, where the pink points represent the landmarks of the patient and the blue points represent the optimal coordinates.

To make sure that any dragging actions will morph the entire model instead of forming local volume peaks, any holes in the mesh are filled and the mesh has been reduced to larger facets. Figure 88 depicts the starting mesh which has a large amount of control points and Figure 89 depicts the reduced mesh with a manageable amount of control points. In the reduced mesh, control points surrounding the

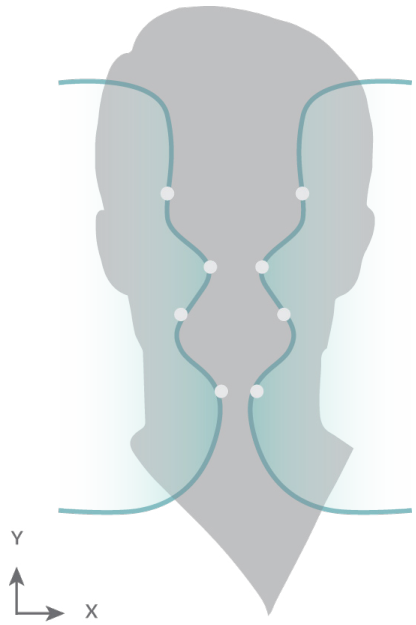


Figure 86 - Face borders that may not be exceeded by the water bolus

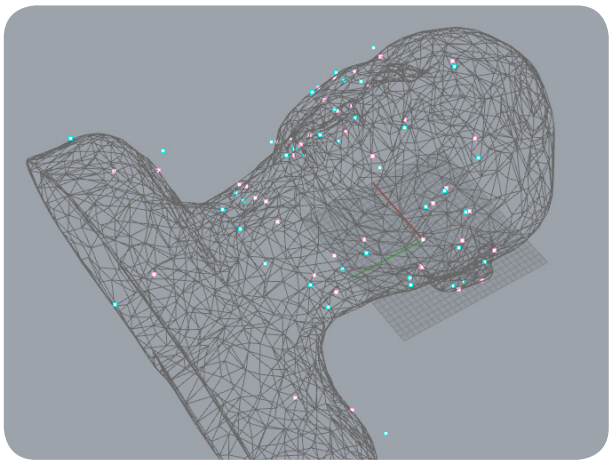


Figure 87 - Comparing landmarks of an average sized patient (pink) with the optimal coordinates (blue)

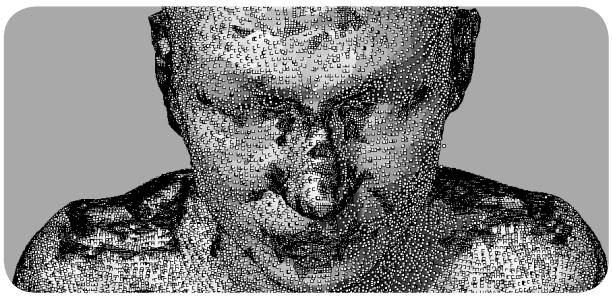


Figure 88 - Starting mesh with large amounts of control points

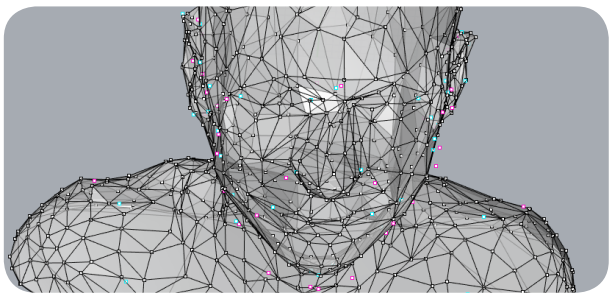


Figure 89 - Reduced mesh that can be used for morphing

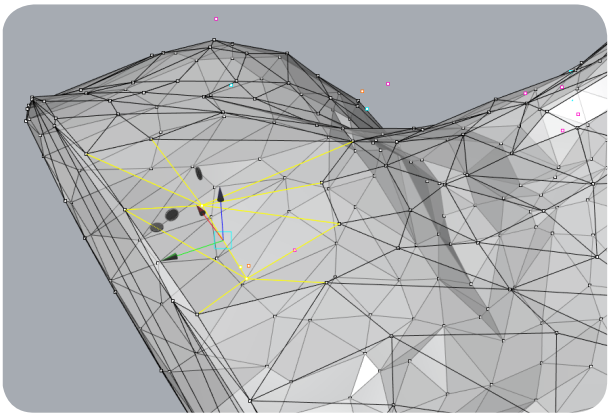


Figure 90 - Dragging control points to the optimal position

original landmark can be selected and dragged to the optimal position, as is depicted in Figure 90.

When one half of the patient model has been morphed into the desired shape, the model is cut in half and mirrored to ensure a symmetrical shape. The resulting rough mesh is smoothened with T-splines to be able to use the patient model as a counter shape for the water bolus. This step is depicted in Figure 91 and Figure 92. The final representative model that is shown in Figure 93 will be used as starting point for designing an ergonomic fit of the water bolus.

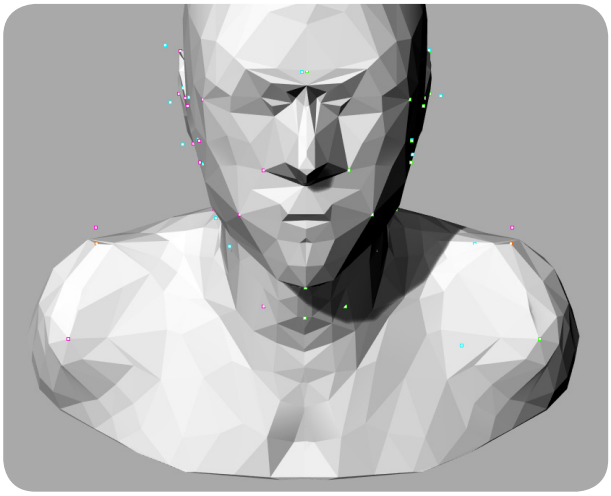


Figure 91 - Resulting rough mesh

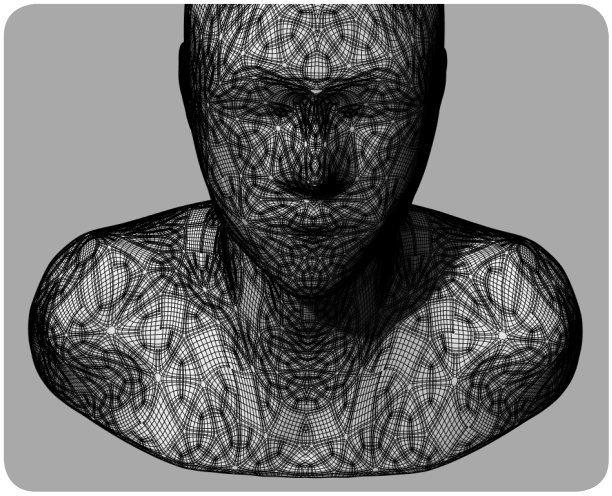


Figure 92 - Resulting smoothened mesh

Figure 93 - Representative patient model

Test Dummies

The representative model that was created will be used for digital fitting of the water bolus. However, for the prototypes that will be made of this water bolus, a means for physical fitting is required as well. For this purpose two testing dummies were created based on the representative patient model.

Testing dummy 1.0 was made by 3D-printing the model in different parts which were attached to each other afterwards, as is shown in Figure 94. As at the Erasmus MC testing dummies go by specific names, this model was named ‘Adam’. The purpose of Adam was to enable physical water bolus fitting on a model that represents the anthropometrics of patients treated at the hospital. This is an improvement compared to the cylindrical models or non-representative human shaped models that are currently used for testing in the hospital.

Another testing dummy was created that could be filled with a human tissue equivalent substance. This testing dummy 2.0 was named ‘Wally’. The substance that can be poured into the model enables accurate

testing of skin cooling patterns and electromagnetic energy absorption. Wally was created by CNC-milling two halves of the representative patient model from foam, as is depicted in Figure 95. Transparent PETG sheets were vacuum formed over these foam halves, remaining plastic fleeces between head and shoulder were scraped away with a file and both halves were glued together afterwards. Wally is depicted in Figure 96.

Figure 94 - Adam: 3D printed physical fitting test dummy

Larynx Fit

With the results from the anthropometric analysis, product parts can be designed that address the four design challenges in the category 'Fit'. For the larynx fit, an extension of the applicator was designed. The water bolus that was designed to fit this extension will be discussed in the next section.

The start height, shoulder height, extension height, shoulder length and extension length that resulted from the anthropometric analysis were translated into the extension frame as depicted in Figure 97. This shape has been designed to fit the MRcollar applicator. Extra strength has been given to the shape with a minimal amount of added material by creating a profile that increases in thickness over the length of the extension.

One of the technicians of the Erasmus MC explained that head and neck hyperthermia patients often tend to lift their shoulders when they lay down on the treatment bed of the HyperCollar3D. The position of the shoulders will therefore be lifted by approximately 20mm. Assuming that this is also the case for the MRcollar, both the shoulder length and extension length are increased by 20mm. The heights were also maximized, to ensure a fit for larger patients. These adjustments led to the extension design that Figure 98 depicts. The new design fits the representative patient model very well, but when overlapping the CAD-files of all patients it turns out that the design is not yet optimized for everyone, which is visible in Figure 99.

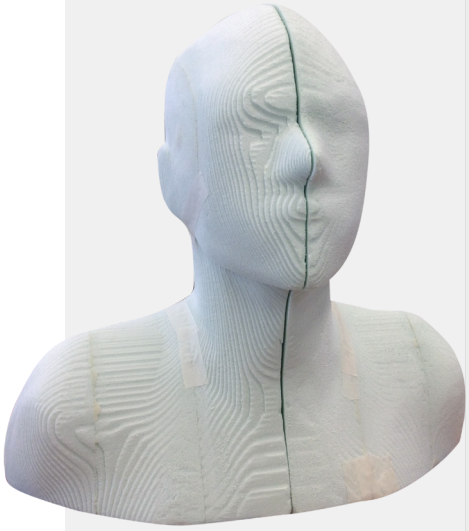


Figure 95 - CNC-milled foam halves of Wally test dummy

Figure 96 - Wally: Vacuum formed cooling and heating test dummy

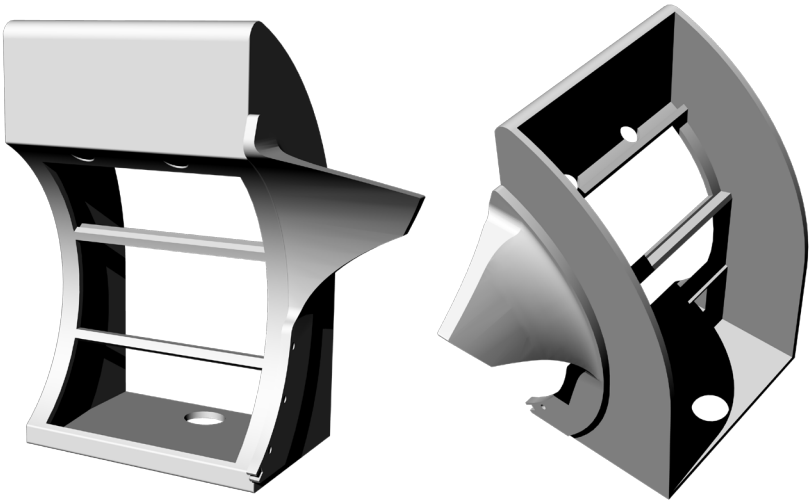


Figure 97 - Design of the rigid applicator extension for neck/larynx treatments

Figure 100 shows the optimized extension frame. The fit of this frame was optimized by drawing a new curve based on the graphical presentation of the CAD-models, as Figure 101 depicts. This curve was drawn in such a way that the distance to the chest of the patients would be within the range of 0-60mm. For the smaller distances, the applicator would have to be moved slightly upwards to make place for water bolus material. For the larger distances the applicator would have to be moved slightly downwards or the bed upwards to make contact with the water bolus.

In this optimization step it was decided not to reach to the furthest jugulum, but to reach as far as possible until the end of the extension would make contact with one patient's tissue. It was considered more relevant to enable treatment of patients from all sizes than to enable treatment of a few patients with severe larynx tumours. Enabling the treatment of patients with tumours that lie higher in the larynx region already forms an improvement on the current lack of any larynx treatment possibilities.

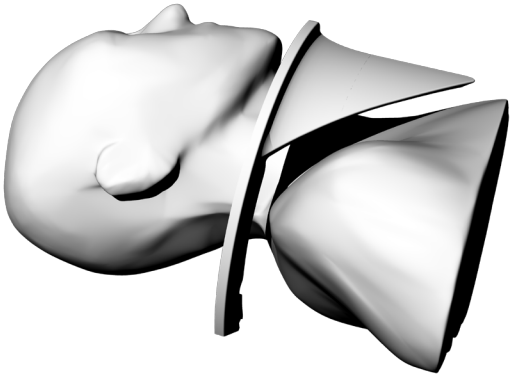


Figure 98 - Adapted extension design fitting representative patient model

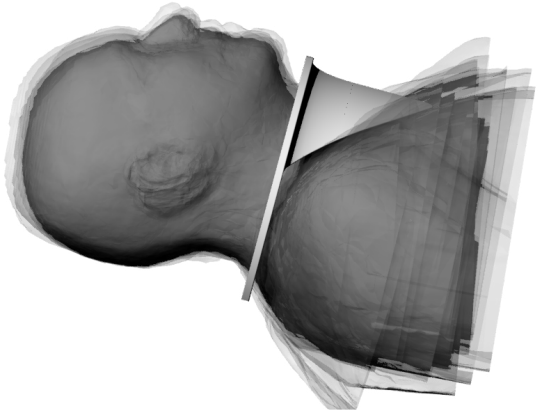


Figure 99- Adapted extension design not optimally fitting all patients

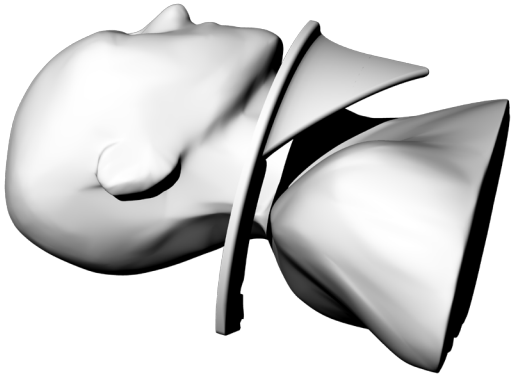


Figure 100 - Optimized extension design fitting representative patient model

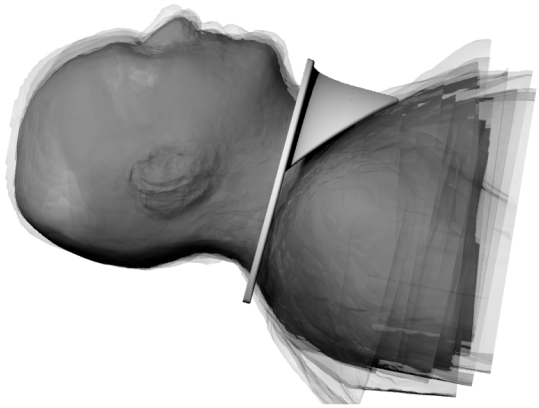


Figure 101 - Optimized extension design fitting all patients

Ergonomic Fit

In this next step the results from the anthropometric analysis will be used to define an ergonomic shape for the water bolus of the head module and the neck/larynx module. In order to do so, first the optimal positions of these water bolus modules around the patient have to be defined.

In Chapter 2 Analysis it has been described that both the HyperCollar3D and the MRcollar have many degrees of freedom in terms of positioning the equipment around the patient. It was also mentioned that the positions of the applicator can be grouped in two main situations: the head treatment and the neck treatment. For these situations a positioning angle of 0° and 15° respectively are used in most of the cases. Concept CombiCollar included two different water bolus modules for each of these situations. It was decided to stick to these two interchangeable modules to design an ergonomic fit for the two most common situations. Increasing the number of modules for more degrees of freedom would increase the costs and the intake time while the added benefit is insecure. The two mentioned positions are therefore further defined in order to design a water bolus for these positions specifically.

Figure 102 and Figure 103 depict the decision of positioning the applicator of the MRcollar at chin height and over eyebrow height during head treatment. This is to cover as little of the neck and the brain as possible, since the neck area would require a thicker bolus part and because the brain is not treated with hyperthermia. For the neck treatment set-up the applicator touches the top of the shoulder and covers the neck and part of the head, as depicted in Figure 103 and Figure 104. This position is chosen to get as close to the larynx region as possible. A larynx extension that follows the previously designed frame will be added to reach until the Jugulum.

To create an ergonomic head water bolus, a shape that fits the MRcollar applicator is modelled and placed in the right position around the representative patient model. A countershape from the patient model is formed into the water bolus as is depicted in Figure 105. Subsequently, an extra part above the eyes is removed to prevent uncomfortable touchpoints yet remain coverage of the antennas in the equipment. This is shown in Figure 106. The resulting shape is smoothened with the help of the mesh editing software 'MeshMixer', as can be seen in Figure 107. The same software has been used to

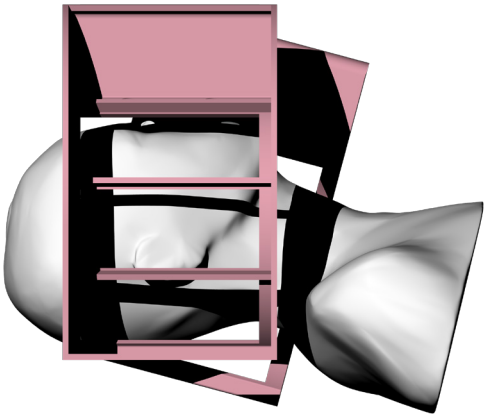


Figure 102 - Applicator head position side view

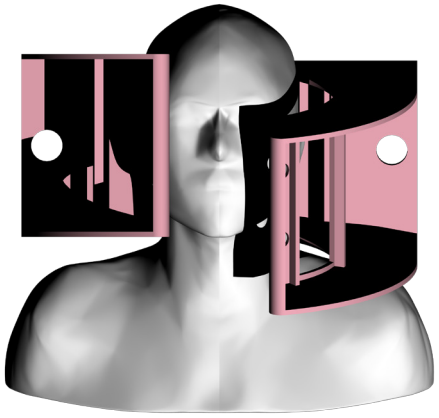


Figure 103 - Applicator head and neck position top view

Figure 104 - Applicator neck position side view

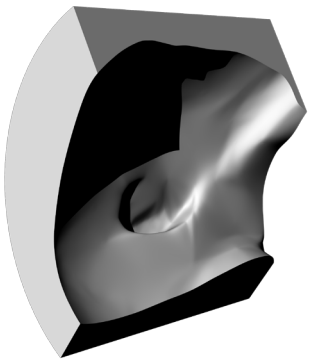


Figure 105 - Step 1: head countershape

make the counter shape more subtle in order to make it fitting for every patient. Especially the cavity for the ear has been sculpted into a more subtle and universal fitting pit. Figure 108 shows that the created water bolus ergonomically fits the head of the representative patient model.

As is depicted in Figure 109, the same steps of generating a countershape in a geometrically shaped water bolus fitting the MRcollar are followed for the design of the neck water bolus. In this case the applicator is complemented with the designed extension frame, which plays a significant role in defining the basic water bolus shape. Figure 110 depicts the smoothened water bolus and Figure 111 shows the resulting ergonomic fit of the neck water bolus module. How this development is translated into the final HoneyPad design is shown in Figure 112.

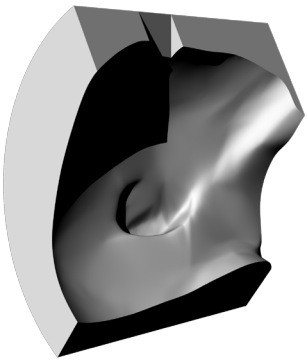


Figure 106 - Step 2: eye cavity in head bolus

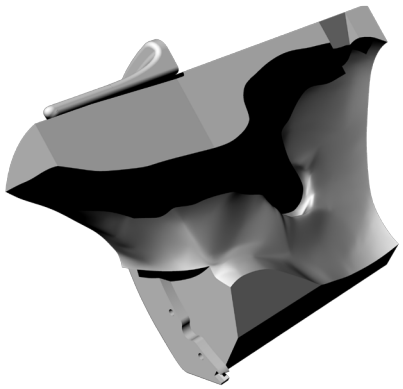


Figure 109 - Step 1+2: neck countershape and eye cavity

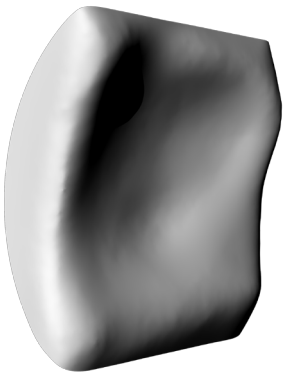


Figure 107 - Step 3: smoothened head bolus

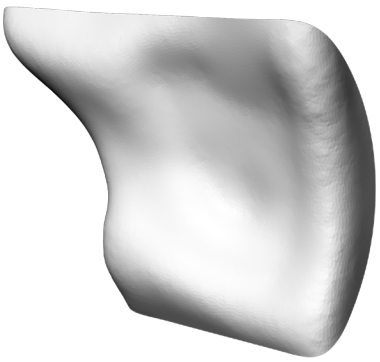


Figure 110 - Step 3: smoothened neck bolus

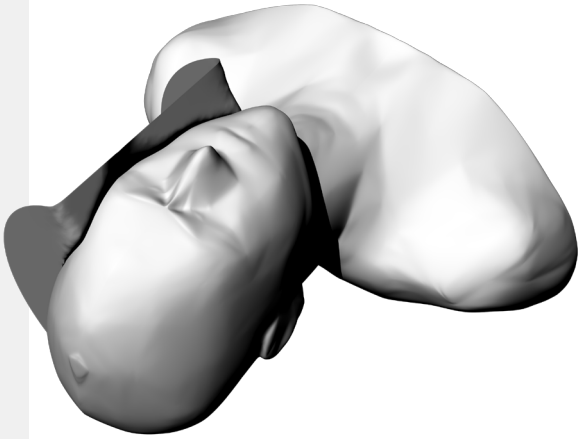


Figure 108 - Ergonomically fitting head water bolus

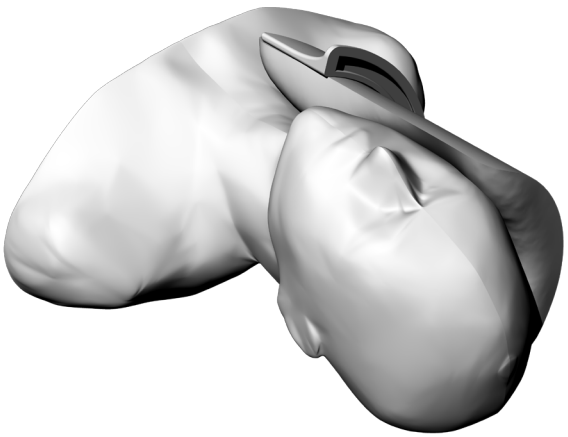


Figure 111 - Ergonomically fitting neck water bolus

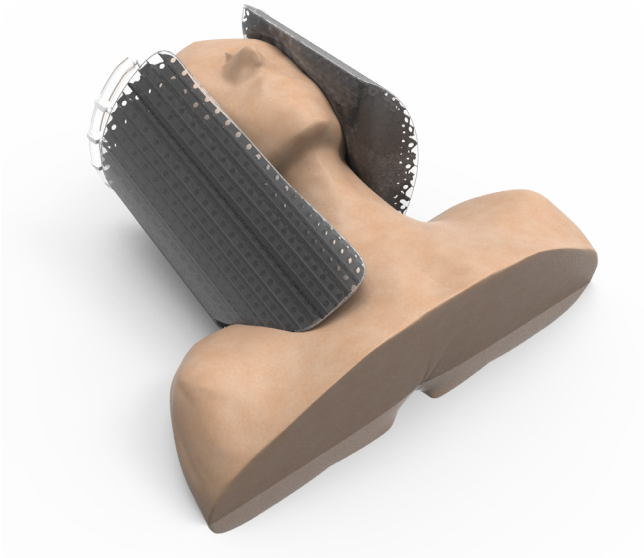


Figure 112 - Ergonomic fit of the final HoneyPad design

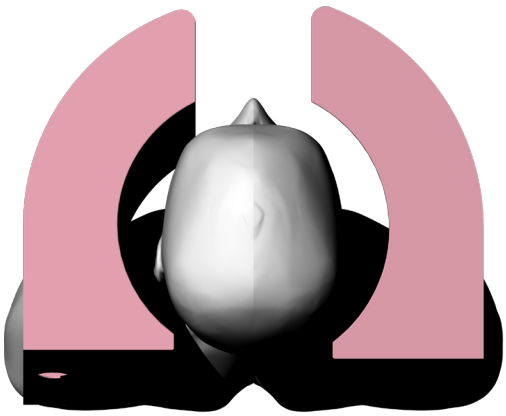


Figure 113 - Head and neck applicator position front view

Reproducible Fit

The requirement was set that the shape of the water bolus should be predictable and reproducible in follow-up treatments. One way to contribute to this condition is to minimize the thickness of the water bolus. This prevents the volume from deviating from the intended shape.

To define the minimum water bolus thickness, the MRcollar applicators were placed around the representative patient model in the previously defined head- and neck configurations. Figure 113 shows the positions of both applicators when these are translated as close to the patient as possible. Due to the small diameter of the applicators, the space near the eyes and occiput is smaller than near the rest of the head. The applicators were positioned in a way that the maximum distance between the head and applicator was 40mm and that enough slack was left at the critical points to allow for anatomical size variations. This maximum distance was chosen because the current water bolus design of the Erasmus MC has a thickness of 40mm and the team of engineers has indicated to prefer a thickness reduction to bring the antennas closer to the patient. In the configuration of Figure 113 the thickness is less than 40mm at most points around the head. However, around the neck the maximum thickness is 60mm. To enable a position closer to the neck, the diameter of the applicator would have to be increased to generate more slack around the eyes and occiput. When increasing the diameter, a thickness of 20mm around the head and a thickness of 40mm around the neck can be achieved.

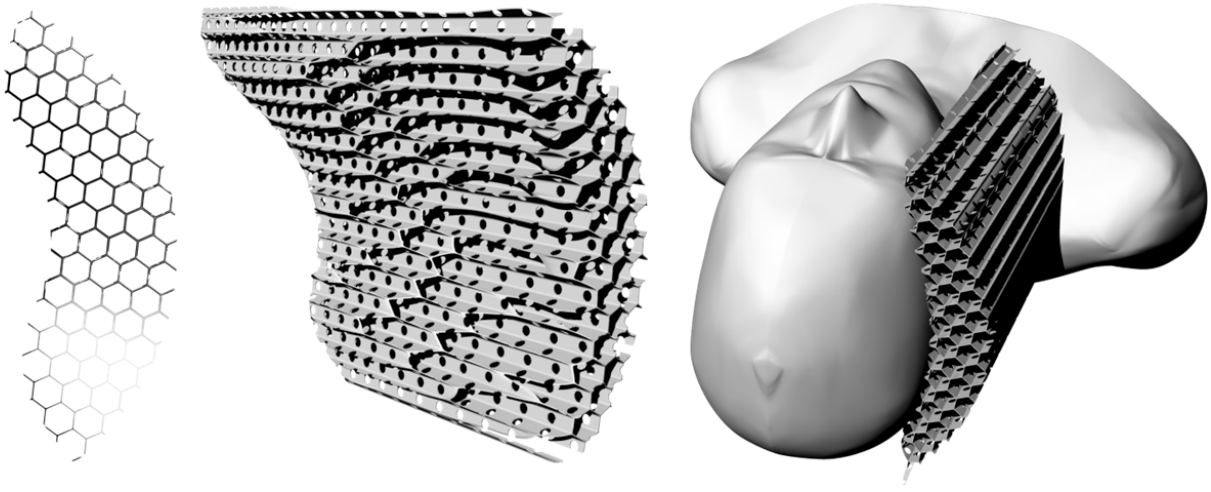


Figure 114 - Honeycomb grid providing shape stability

Another way to achieve shape predictability and reproducibility is to stabilize the structure of the water bolus. The water bolus with foam that is currently used by the Erasmus MC is flexible in as well the X-, Y- as Z- direction, which makes it difficult to handle. The honeycomb grid that was proposed in concept CombiCollar eliminates the flexibility in one direction, which contributes to shape stability. The flexibility in the remaining two directions needs to be enhanced in order to enable the required deformations to fit patients of different sizes. Furthermore, the honeycomb grid is slightly more rigid compared to the foam of the current water bolus. This helps to increase the shape stability without compromising the universal fit, because the anatomically shaped grid requires less deformation. The designed honeycomb grid for neck treatments is depicted in Figure 114. The HoneyGrid fits exactly inside the HoneySkin as described in section 'Ergonomic Fit' to provide shape stability and ergonomic flexibility over the entire volume. This grid was obtained by combining the software Rhinoceros, MeshMixer and NetFabb.

Shape predictability and reproducibility are relevant for accurate treatment planning and thermal dosage. The currently used foam has non-uniform perforations which makes it hard to take these cavities into account when planning the treatment and thus to make sure the right dosage is administered. The designed honeycomb grid consists of uniform openings and material thicknesses which can be simulated in treatment planning. Having the exact CAD-models of the grids available significantly increases the accuracy of treatment planning.

Lastly, the HoneyShell contributes to overall shape stability and ease of handling as well. The establishment of the HoneyShell design will be explained in the next section.

Figure 115 - Radial sliding movement in the MRcollar

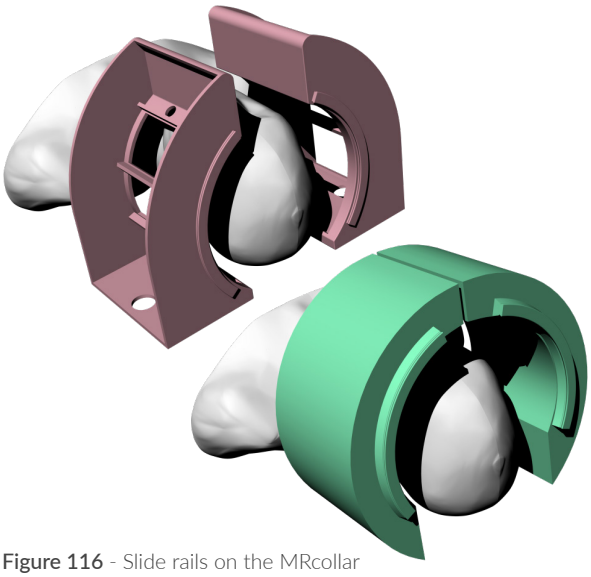


Figure 116 - Slide rails on the MRcollar (pink) and the HyperCollar3D (green)

Stable Fit

The last design challenge of the category 'Fit' is the stable fit which consists of the HoneyShell. This is the mechanism that connects the flexible water bolus to the hyperthermia equipment. Concept 'CombiCollar' made use of a horizontal slide in the back of the water bolus. Because it has been decided that similar techniques need to be used for the modules of the HyperCollar3D and the MRcollar, the sliding method has been adjusted. Instead of horizontal, the water bolus will now slide in a vertical direction into the equipment. To fit the diameters of both applicators, a radial slide has been designed.

The radial movement of the slides is depicted in Figure 115. A top-down movement is chosen because this will have a higher operator comfort than a bottom-up movement. In the top-down situation, the operator can align the slide and use the mass of the water bolus to easily slide it down the applicator. The applicator halves of the MRcollar have to be set in the widest mode when sliding the water bolus with the top-down movement. In a bottom-up situation, the operator would have to pull up the weight of the water bolus during the sliding movement. Furthermore, the applicator would have to be set in the widest ánd highest mode to enable this movement.

This slide design consists of two rigid side panels that have to be attached to each flexible water

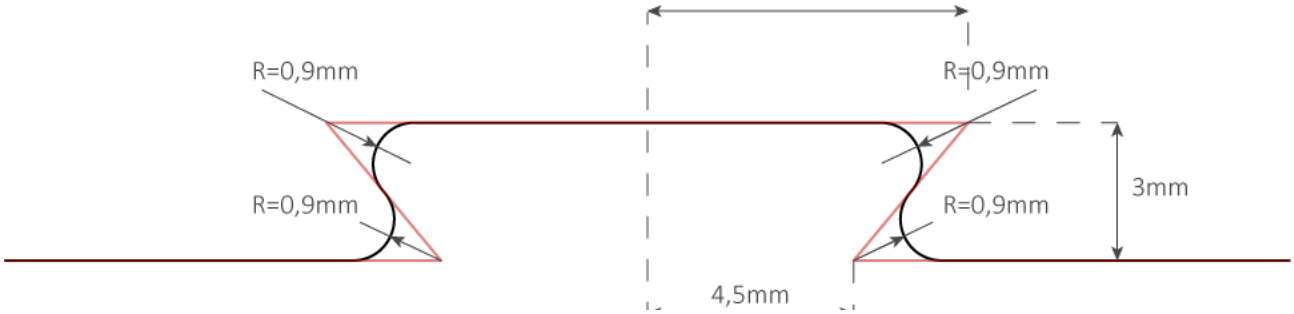


Figure 117 - Section view of dovetail slide mechanism

bolus and two rails that have to be attched to each side of the applicator. Figure 116 depicts the rails that have to be attached to the MRcollar and the HyperCollar3D. Because a uniform length of the water bolus can be used and the applicator diameters are similar, the slides for both applicators can have similar dimensions. However, due to a difference in applicator width, the slides for the HyperCollar3D would have to be thicker as compensation in case the exact same frame has to be used for both versions.

Several geometries for a sliding mechanism have been considered. The choice finally fell on a dovetail geometry, which was also designed and tested by Bi (2014) in a previous graduation project for the Erasmus MC Cancer Institute. The solution generated by Bi (2014) was optimised in terms of material thickness, tolerances and overall dimensions. Figure 117 depicts a section view of the designed dovetail rail that will be part of the applicator. The dovetail geometry that is incorporated in the HoneyShell will be 1mm bigger in both height and width to ensure a smooth sliding movement. Dovetail slides have the benefit to have a flat geometry, which makes it possible to design a stable sliding connection with little material.

Because the dovetail geometry is only a few millimetres large, the alignment of the water bolus with the slides will be quite a challenge for the operator. For this purpose, a wider guiding geometry has been incorporated at the start of the slide. The design of this guidance is depicted in Figure 118.

Part of the designed slides is protruding from the applicator, as Figure 119 depicts. The reasoning behind this is to support the sides of the flexible water bolus and increase shape stability. Furthermore, this protruding part can be used to attach the water bolus to the slides. Because the back of the water bolus will be covered by as little material as possible to minimize disturbance of electromagnetic waves, adding a frame on the back is not an option. Attachment of the water bolus to the sliding frame is therefore limited to the sides and possibly the top and the bottom.

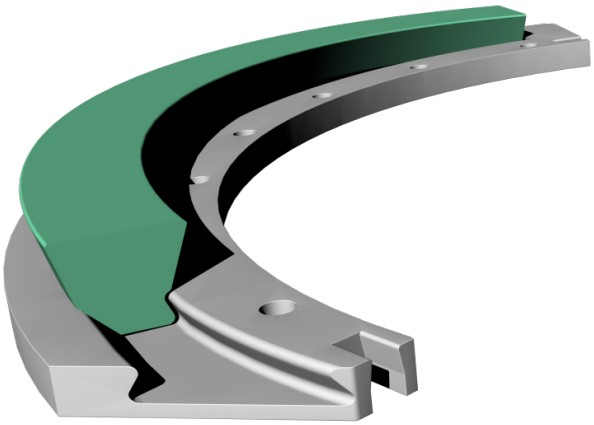


Figure 118 - Guidance geometry in the side slide

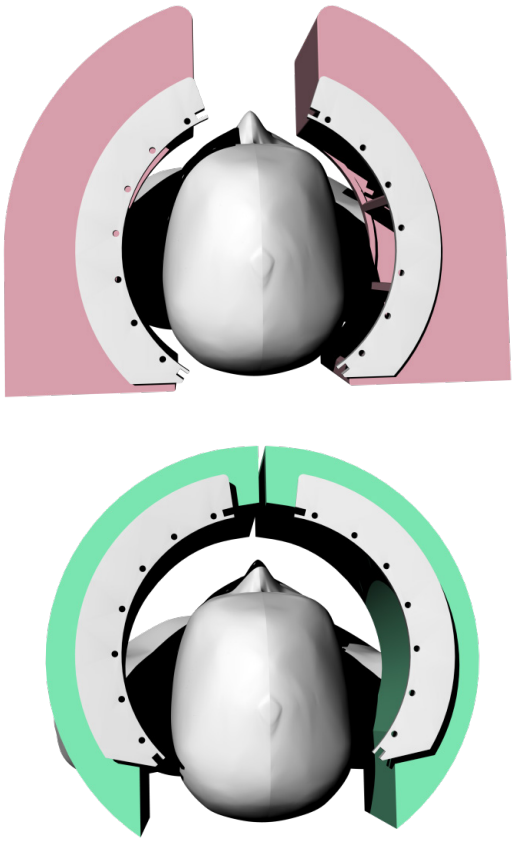


Figure 119 - Protruding side panels on the MRcollar (pink) and HyperCollar3D (green)

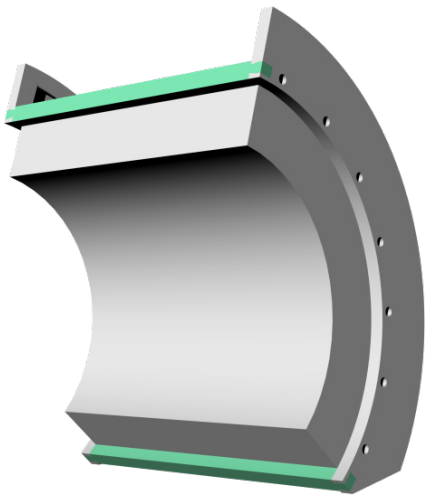


Figure 120 - Top- and bottom support panels

Figure 121 - HoneyShells of the head module and larynx module

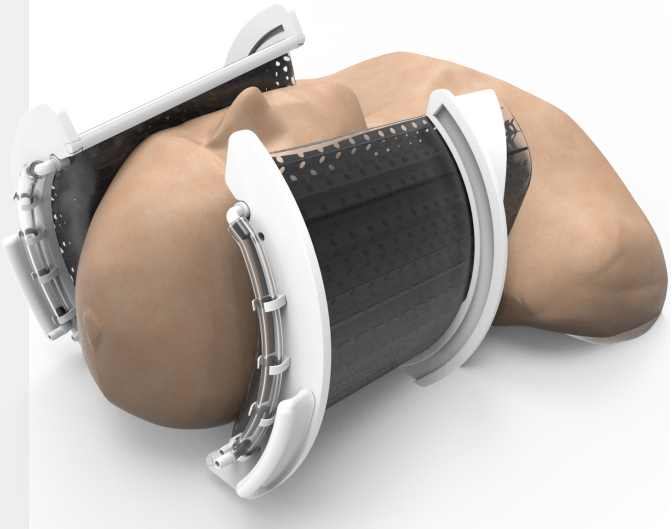


Figure 122 - Slack between patient and support panels

The slides meant for head treatments that are depicted in Figure 119 have been optimized to fit both the MRcollar and HyperCollar3D. Reasoning behind this was to design a universal water bolus module that can be used in both applicators. This has been proven possible for the HoneyShell, however, for the HoneyGrid shape this would be inefficient. As the slides are slightly differently oriented, a universal shape would come at the expense of the ergonomic fit. Furthermore, the distance between patient and applicator is much larger in the HyperCollar3D than in the MRcollar. Using a universal water bolus would therefore result in excess thickness and inefficient energy conduction. The designed HoneySkin, HoneyGrid and HoneyShell will therefore only be used for the MRcollar.

From the prototype made by Bi (2014) could be concluded that it was quite a challenge to accurately align both of the slides from one water bolus with the corresponding rails on the applicator. The main challenge was that the slides have to be inserted in parallel and that the flexible water bolus material in between the slides affects the alignment. In the HoneyPad this will be less of a challenge because of the increased shape stability provided by the HoneyGrid. To completely solve this alignment challenge, extra stability is given to the water bolus by adding a support panel on the top and bottom, which is depicted in Figure 120. The top- and bottom panel are connected to the side panels with a form fit.

In Figure 121 it is depicted how the side panels and top- and bottom panels have been given a more ergonomic shape to prevent hampering of the skin. The top panel has been left out in the larynx water bolus module. This is to ensure enough slack when the applicator has to be repositioned around patients with a lower chest. As the anatomical deviation of patients is larger for landmarks around the shoulders and chest than around the head, the larynx module will require more slack for repositioning than de head module. Only one support panel at the bottom of the larynx HoneyShell will also be helpful to align the slides. Because the top panel increases stability and leaves enough slack as Figure 122 depicts, this part is included in the head HoneyShell.

Handles have been added to the side panels in order to provide an ergonomic grip for the operator to install and de-install the water bolus modules. The dimensions of these handles are based on the average hand width of males and females in the age range 20-60 as given by the anthropometric database DINED. In the front of the MRcollar, the handles

are placed on the top of the side panel in order to prevent touching the shoulder. At the back of the applicator, the handles are placed at the bottom to ensure a steady grip when aligning the slides with the rails. Because the larynx module can be held at the extension part, this module does only have one handle at the back. The placement of handles can be viewed in Figure 123.

The flexible part of the water bolus will be attached to the protruding parts of the HoneyShell. By attaching the bolus over the entire arc, it is ensured that the back of the water bolus makes uniform contact with the applicator and that air inclusions are minimized.

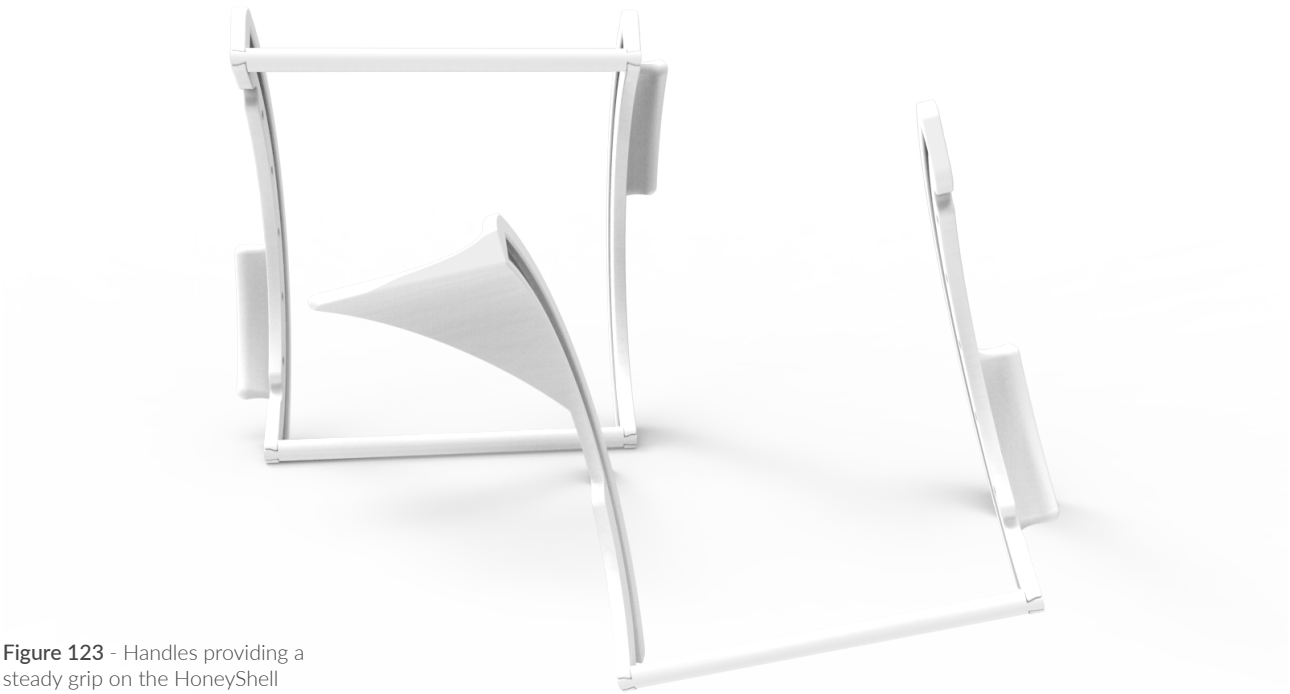


Figure 123 - Handles providing a steady grip on the HoneyShell

Materials

Several materials have been explored for manufacturing of the HoneySkin, HoneyGrid and HoneyShell. The different properties of the considered materials are compared and the options with the highest potential are selected for prototyping.

HoneyGrid & HoneySkin

The HoneyGrid and HoneySkin have to meet similar requirements and therefore the same selection of potential materials has been explored for both parts. The main requirements on which these selected materials have been evaluated were the following:

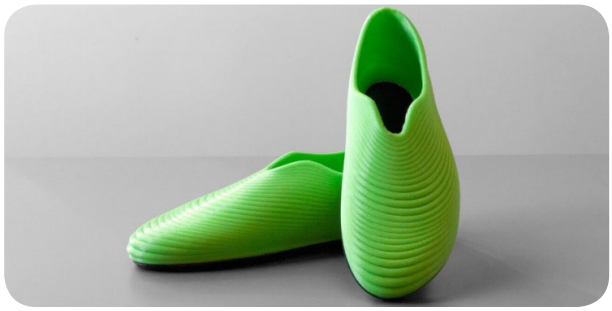
- The material should be flexible to ergonomically fit every patient
- The material should be affordable to enable manufacturing of different modules
- The material should be durable to ensure a long lifespan and prevent failure during treatment
- The material can be manufactured with a method that is suitable for both in-house rapid prototyping and outsourced end production of maximal 50 units
- The material of the honeycomb fill should be water resistant and the bag material should be water tight
- The material should be biocompatible for comfortable contact with the skin

Most materials that have been selected are intended for manufacturing with 3D-printing, since this production method is most suitable when requiring affordability, rapid prototyping and small batch sizes. The applicability of many innovative filaments, resins and other materials were evaluated by conducting an extensive internet research. Figure 124 depicts the extent to which each material meets the set requirements. The green squares indicate a positive

score, the yellow squares stand for a doubtful score and the red square means that the score is unfavourable and that the material can only be applied under specific circumstances.

	 LayFomm	 TPE	 TPU	 PCTPE	 T-Lyne	 Tango	 Flexible Resin	 Silicone	 Urethane
Stiffness	Shore A 40-60	Shore A 82-85	Shore A 90-95	Shore A 100+	Shore A 100+	Shore A 27-95	Shore A 70-85	Shore 00 10 - A 60	Shore A 10-90
Price /kg or L	€106	€82-93	€67	€67	€75	€440-480	€229	€34-56	€20-80
Durability	Poor	Good	Good	Excellent	Excellent	Poor	Poor	Excellent	Excellent
Production	FDM	FDM	FDM	FDM	FDM	PolyJet	SLA	Moulding	Moulding
Water contact	Water absorbing	Water proof	Water proof	Water proof	Water reformable	Water proof	Water proof	Water proof	Water proof
Bio-compatibility	Unknown	Unknown	Unknown	Yes	Yes	Unknown	Unknown	Yes	Yes

Figure 124 - Comparison to what extent different flexible materials meet the requirements for use in the HoneyGrid and HoneySkin



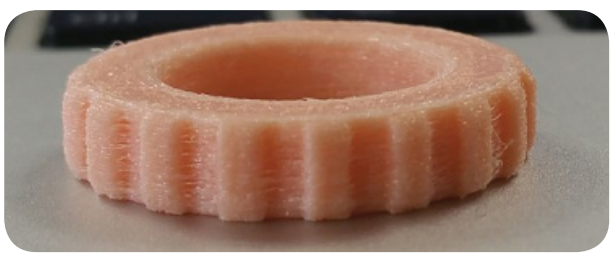


Figure 125 - Flexible shoes and a tool for underwater environments printed with TPE

Based on the different scores, the materials provided with a grey border have been selected for further analysis. TPE, i.e. ThermoPlastic Elastomer, is a plastic 3D-printer filament with rubber-like properties. With TPE filament highly elastic objects can be printed that have good compression strength and have no permanent deformation. Many different variants of TPE filament are available on the market, among which the brands NinjaFlex and FilaFlex are most commonly known. Some examples of functional prototypes made with TPE filament are shown in Figure 125.

The materials PCTPE and T-Lyne are less well-known products from producer Taulman and are very innovative filaments on the 3D-printing market. PCTPE, i.e. Plasticized Copolyamide ThermoPlastic Elastomer, is a combination between nylon and

TPE. This combination allows for manufacturing of highly flexible parts with the added durability of nylon. The addition of nylon, however, makes the filament less flexible than pure TPE. The PCTPE filament from Taulman was specifically developed to take on antimicrobial coatings in order to use the material for prosthetics (Taulman, n.d. A). Figure 126 depicts some examples of products that are made with PCTPE. T-Lyne filament was also specifically developed for high durability and flexibility. This filament is made from a transparent polyethylene co-polymer which has the unique feature to become soft when immersed in hot water. This allows for making minor shape adjustments after printing and cooling this into a final shape. T-Lyne filament has also been approved for potential use in prosthetics (Taulman, n.d. B). Figure 127 depicts some examples of products that are made with T-Lyne. Because both PCTPE and T-Lyne have an unfavourable score for flexibility, these materials are expected to only be suitable for the water bolus when they are printed in very small wall thicknesses or filling percentages.

Other than 3D-printer filaments, silicone resin was selected as a potential water bolus material. Silicone is a common material in the production of everyday products and various biocompatible grades are available as well. Silicones are moulded by creating a chemical reaction between two liquids, which makes it possible to use actual rubbers instead of the rubber-like materials that are used in filaments. Silicones therefore have the benefit to be a lot more flexible than the products made from flexible filaments. However, the moulding process is a lot more labour intensive than 3D-printing. Firstly, a mould has to be designed and manufactured, which can be done with 3D-printing for small batch sizes. Secondly, the two liquids have to be mixed in the right proportions and the mixture has to be poured into the mould while making sure that it reaches every cavity without including air bubbles. Lastly, the product should be released from the mould after the material has cured. Due to the high labour intensity of moulding, the three filaments are preferred materials for the water bolus. Silicone will be tested to compare its quality to 3D-printed parts. Figure 128 shows several examples of silicone products.

HoneyShell

Several requirements were set-up to select a suitable material for the support frame of the water bolus:

- The material should be rigid and provide enough strength to carry a water bolus of 3kg

Figure 126 - Prostheses and wearables printed with PCTPE

Figure 127 - Wearables and shapes printed with T-Lyne

Figure 128 - Nasal mask, oxygen bag and prostheses made from medical grade silicone

- The material should have a smooth surface to enable a convenient sliding mechanism
- The material should be affordable to enable manufacturing of different modules
- The material should be durable to ensure a long lifespan and prevent failure during treatment
- The material can be manufactured with a method that is suitable for both in-house rapid prototyping and outsourced end production of maximal 50 units
- The material should be safe for use in medical environments

Common 3D-printing materials that meet these requirements include PolyLactic Acid (PLA), Acrylonitrile Butadiene Styrene (ABS) and nylon. PLA is a filament with lower costs than ABS and nylon because it is most commonly used for 3D-printers. ABS and nylon are more of a challenge to use in 3D-printing, because they tend to warp quickly under certain temperature settings and require extra tools in some cases, like a closed box around the printer to prevent toxic fumes from spreading. PLA is therefore the most accessible material for prototyping. However, PLA also has less strength than ABS and nylon. Due to its benefits, PLA will be used to prototype the supporting frame of the water bolus. When more strength is desired in the future, ABS or nylon is a good alternative.

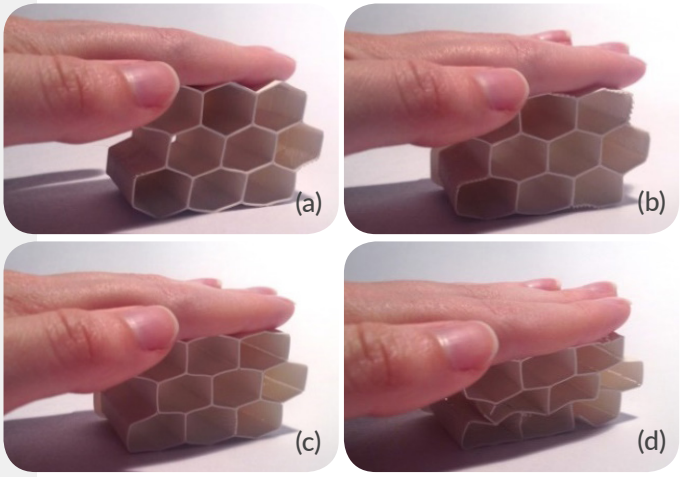


Figure 129 - Flexibility of PLA honeycombs with (a) 0.6mm thickness, 100%, (b) 0.6mm, 50% fill, (c) 0.5mm, 50%, (d) 0.42mm, 50%, under constant pressure

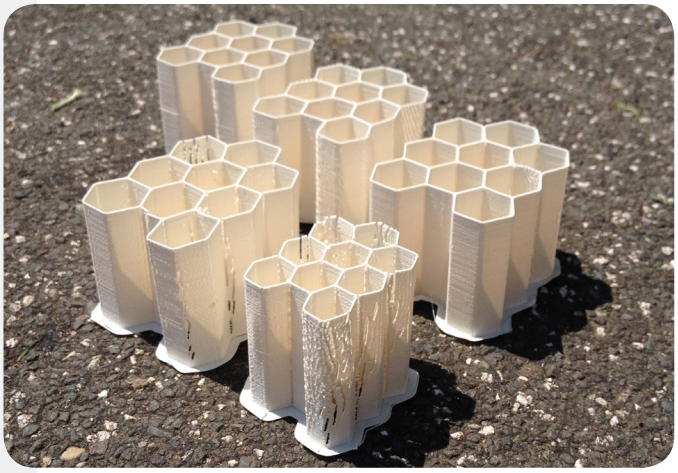


Figure 130 - PLA honeycombs with diameters of 18mm and 12mm, thicknesses of 0.4mm, 0.42mm, 0.5mm and 0.6mm

Prototyping

The four selected materials for the HoneyGrid and HoneySkin will be prototyped and tested on flexibility, durability, producibility, water contact and skin contact. For each material, different thicknesses and structures will be evaluated. For the HoneyShell different PLA models will be tested on durability and mechanical functionality. The HoneyShell models will be prototyped in different dimensions. Simple models will be used for the testing, after which more advanced models will be made from the most promising materials and structures.

TPE Models

In the category TPE, filament types flexible PLA and Flex 45 have been used to make rapid prototypes of the HoneyGrid and HoneySkin. These materials were selected because they were made available by StudioLabs and AppliedLabs of the faculty of Industrial Design Engineering. Varying wall thicknesses, dimensions, filling percentages and settings were tested by printing with the Ultimaker 2+ and Ultimaker 3.

HoneyGrid

It could be concluded that honeycomb structures with larger diameters, thinner walls and lower filling percentages significantly increase flexibility of the grid while maintaining stability in the length direction, as the test in Figure 129 depicts. The structures remain intact when compressing them multiple times and do not show permanent deformations. This durability is only valid provided that the structures are produced correctly. 3D-printing with flexible materials is

an upcoming technology that has not been fully optimized yet. Therefore it is very important to use the right printing settings for each material and take the boundary conditions of printable structures into account. As Figure 130 depicts, thin and small grids printed with flexible PLA result in brittle structures with poor durability while the thicker, larger ones are a success.

Flex 45 filament turned out to be a more printing-friendly material with possibilities for smaller wall thicknesses. Figure 131 shows that these possibilities significantly increase the flexibility. The perforations that were added to allow water flowing through also contribute to the flexibility. More about this phenomenon will be explained in Chapter 5 Cool & Press. Flex 45 has a better shape recovery after exposure to pressure and shows less defects in the printed structure which increases durability. It was tested that these properties remain constant when immersing the Flex 45 structure into water. Although Flex 45 does not have a biocompatibility mark, its surface feels smooth, soft and rubbery to the human skin and is therefore considered comfortable.

Flexible filaments are known to have little possibilities in printing structures with overhang because the generated support material becomes too flexible. This would cause the structure to shake during printing, causing material to land in the wrong places or cause the structure to tip over. For this reason it was a challenge to print the HoneyGrids in their ergonomic anatomical shapes that required support material. Figure 132 shows that it is feasible to print such structures provided that the printing speed is set rather low. This results in a printing time of 48-72 hours for one grid, depending on the used nozzle size. The support material can easily be removed afterwards, resulting in the grid as depicted in Figure 133. This improved grid was given a slightly increased rigidity to prevent the structure from collapsing under the pressure of the water inside the water bolus, as was the case with the previous Flex 45 grid. A sufficient flexibility remains to enable deformation to follow head and neck contours.

However, additional layers or blobs of material were attached to most of the edges in the printed structure, which slightly affected the flexibility. Furthermore, the support material covering the perforations is time consuming to remove manually. For this reason the possibilities of printing the HoneyGrid with dual extrusion on the Ultimaker 3 has been tested. In dual extrusion it is possible to print with two different materials, in this case Flex 45 and PVA. The last one is a water soluble filament

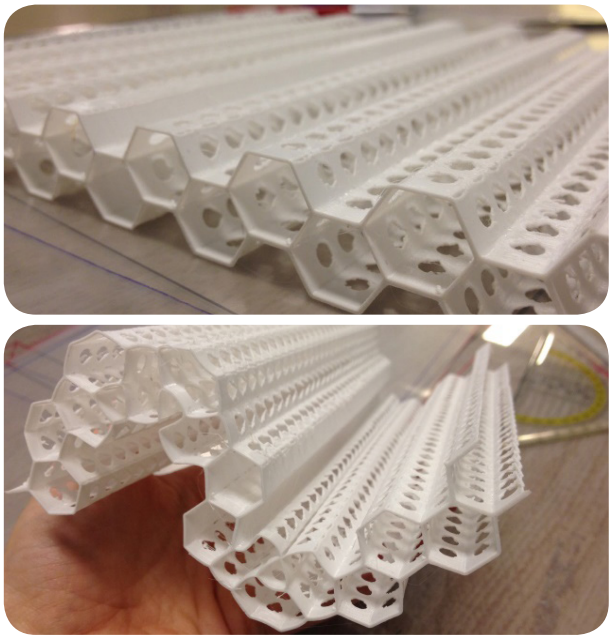


Figure 131 - Flex 45 honeycomb grid with diameter of 15mm, thickness of 0.3mm and fill of 80%

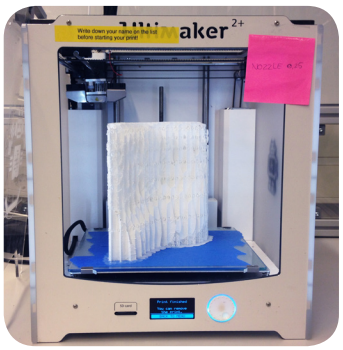


Figure 132 - Printing anatomically shaped HoneyGrids with Flex 45 including support material. Diameters are 15mm, wall thickness 0.4mm and fill 100%

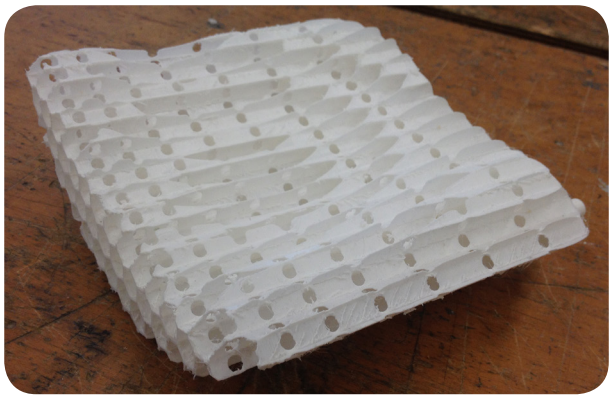


Figure 133 - Anatomically shaped head HoneyGrid with removed support material

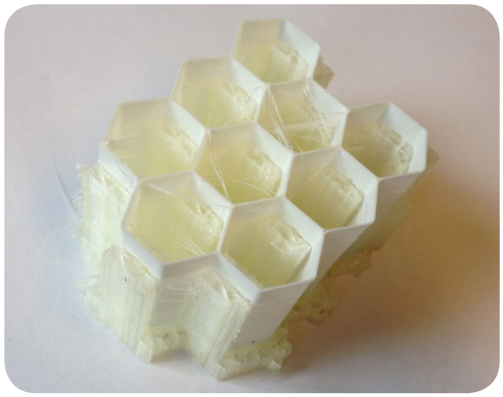


Figure 134 - Honeycomb grid printed with water soluble support material in dual extrusion mode with the Ultimaker 3

Figure 135 - HoneySkin scale model of 0.35mm thick printed in spiralize mode

that can be used to generate support material. When immersing the finished print into water, the support disappears without any required human interference. Figure 134 depicts that the issue of undesired additional material in the corners is eliminated by the dual extrusion option. It has to be taken into account that printing the HoneyGrid in dual extrusion mode using the standard settings will take twice the printing time of the regular Flex 45 print. Furthermore, the dual extrusion requires a larger mass of support material. Because the single extrusion grids turned out well, these will be used in the final prototype.

HoneySkin

The applicability of Flex 45 as material for the HoneySkin was tested as well. For the HoneySkin it is required that the structure is completely water proof to ensure the capability to hold water inside. Water tightness is not ensured when printing with standard Ultimaker settings, but is possible when applying the 'spiralize' mode. Spiralize mode is used to print shelled objects which are watertight because the print head extrudes material interruptedly while rotating around the Z-axis. This specific mode is often used for printing watertight vases. Figure 135 shows a spiralized scale model of the HoneySkin which is tested to be capable of holding water without leakages. This model is highly flexible and strong enough to have a long lifespan. In the spiralize mode it is not possible to print closed volumes nor support material. This means that the HoneySkin of the head bolus would have to consist of different parts and that the larynx bolus cannot be printed at all in these settings. The search for a suitable HoneySkin material is therefore continued.

PCTPE & T-Lyne Models

Experiments have been done with sample filaments of both PCTPE and T-Lyne on the Ultimaker 2+. As the PCTPE sample was only available in a small diameter size, it unfortunately did not work out to get anything printed on the Ultimaker, even after adjusting different settings. The properties of T-Lyne are comparable to PCTPE, apart from the added value of re-thermoformability, and therefore the experiments were pursued with this filament that was available in a larger size. The first few layers that were printed in these experiments looked very neat. However, the print head would get clogged after a while causing an interruption of the printing process. The part that did get printed was tested to have a high strength and thus durability. However, flexibility and shape recovery after impact were significantly less than Flex 45. Because large deviations in anthropometrics occur in the larynx area, reformability on top of flexibility would possibly be an added benefit for the larynx HoneyGrid. However, a whole new challenge is formed by finding the optimal printing conditions for this material, integrating it in the HoneyGrid and making sure that shape recovery after reforming is enhanced. This challenge cannot be covered in the scope of this project.

Silicone Models

Apart from printing, the possibilities of moulding and brushing with silicone were tested for applications in the HoneyGrid and HoneySkin as well.

HoneyGrid

For the HoneyGrid, a 3D-printable mould was designed that would be filled with liquid silicones. The goal was to find the differences in flexibility and durability compared to the flexible filaments. The water soluble PVA was used as material for the mould that is depicted in Figure 136. Normally, a mould design should include draft angles and multiple parts to make sure that the product can easily be released. With a water soluble mould, more complex shapes can be produced that cannot be released from a common mould. As the HoneyGrid has complex piping systems with many holes to guide the water in the right direction, a water soluble mould is a convenient choice.

A two-component fluid silicone mixture was poured into the small funnels that were made in the top of the mould, as Figure 137 depicts. It could be concluded that the mixture was too thick to run through the small cavities of 0.42mm, even with the help of the funnels. When using the silicone moulding technique, the honeycombs therefore need to have thicker walls. For the flexibility this would not be any problem, since silicone is more flexible than filament. However, thick HoneyGrid walls will increase the amount of material in between the antennas of the hyperthermia equipment and the patient. The disturbance this will cause for the electromagnetic waves is unfavourable.

After being in contact with the silicone mixture for 24 hours, which is equal to the silicone's curing time, the PVA mould did not show any physical changes. This can be seen in Figure 138. Therefore it can be concluded that PVA is not soluble in fluid silicone mixtures and can be used for silicone moulding purposes, provided that the cavities are large enough for a sufficient silicone flow. However, in the case of prototyping the HoneyGrid, Flex 45 filament is a more suitable material choice.

HoneySkin

The finding that PVA does not react with fluid silicone mixtures was encouraging to continue experimenting with these materials for the HoneySkin. This time a medical grade two-component brush-on mixture called 'DragonSkin' was chosen. The viscosity of the mixture had to be increased with a thickener to enable brushing the substance onto a PVA mould without silicone dripping down the shape. This

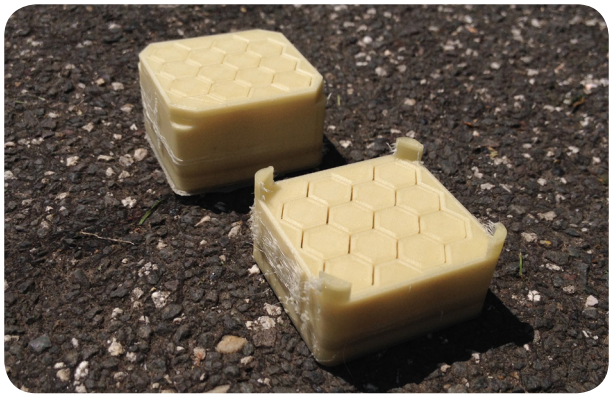


Figure 136 - 3D-printed PVA mould

Figure 137 - Pouring silicone mixture into the PVA mould

Figure 138 - Fluid silicone mixtures can be in contact with PVA without affecting the material

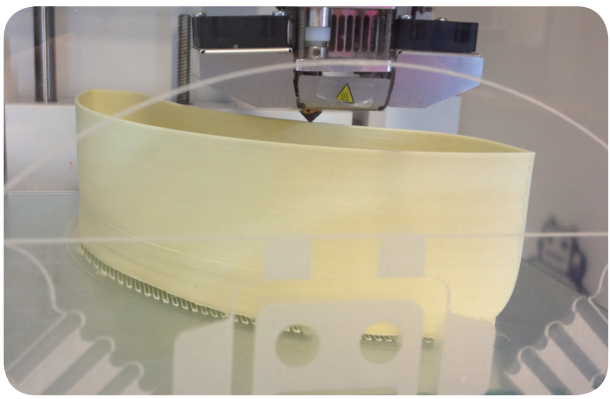


Figure 139 - 3D-Printing PVA HoneySkin mould

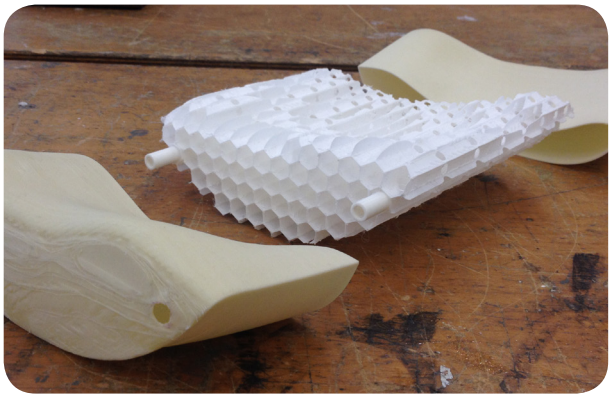


Figure 140 - Components to assemble before brushing siliscone

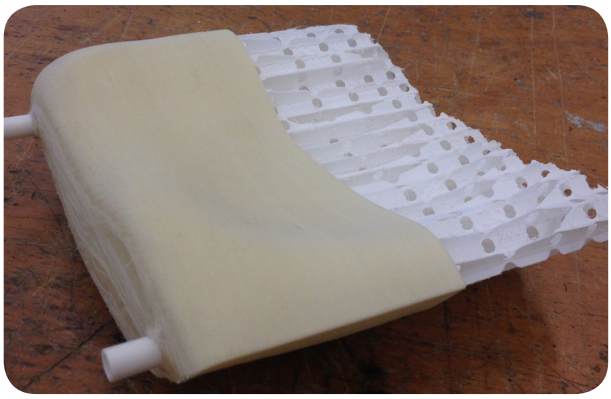


Figure 141 - Placing hollow mould around Flex 45 HoneyGrid

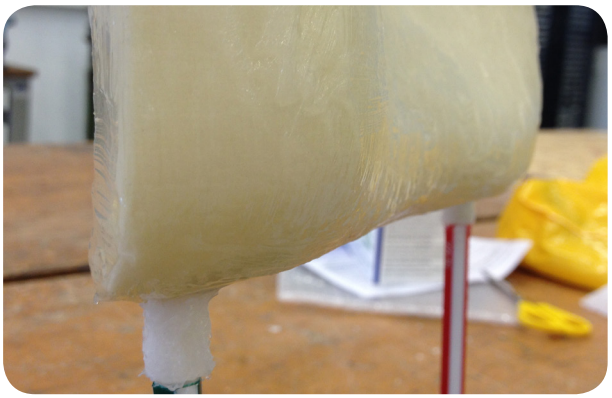


Figure 142 - Brushing thickened silicone mixture onto HoneySkin mould

hollow PVA mould was printed by an Ultimaker 2+ in two parts, as is shown in Figure 139. Both mould halves were glued together around the Flex 45 HoneyGrid model, as can be seen in Figure 140 and Figure 141. Next, the mould was painted over with the silicone mixture, which is depicted in Figure 142. The goal was that when the silicone skin was cured, the PVA would be solved in water. This had to result in a continuous closed HoneySkin around the HoneyGrid, without any seams. However, due to differences in thickness of the silicone skin, holes appeared at different points when filling with water. A silicone HoneySkin therefore gets an insufficient score for durability and producability. The extremely high flexibility and pleasant soft, rubbery touch are noteworthy positive properties though.

All four selected materials turned out to be unsuitable for application in the HoneySkin. The only alternative that is left is to use the plastic foil that is applied in the current water boluses of the Erasmus MC. This will be further explained in Chapter 6 Results.

PLA Models

Material choices for the HoneyGrid and HoneySkin have been validated, which leaves us with validating the choice for PLA in the HoneyShell. Figure 143 depicts the different PLA models that have been made. The first model, which is shown on the left of Figure 143, was not thick enough and had a sliding mechanism with inconveniently small dimensions. This gave the model insufficient strength and an unfavourable operator handling. In the second model the dimensions were optimised and the connection between the water bolus and frame was taken into account. This connection would be formed by placing the inflow and outflow water tubes through the holes in the frame. On second thoughts this solution was not optimal due to space limitations around the patient's head and shoulder. A connection with snap fits was therefore chosen in the third model, which also includes form fits to connect the top- and bottom support panels of the HoneyShell. The fourth model is based on the same principles but is optimised for the larynx module.

To test the functionality of the sliding mechanism, a rails component was printed as well. Figure 144 depicts the test that was done to find out that the sliding mechanism of the last three models runs smoothly.

The rail geometry can be integrated in the MRcollar applicator, because it is still under development by the Erasmus MC. For the HyperCollar3D that is

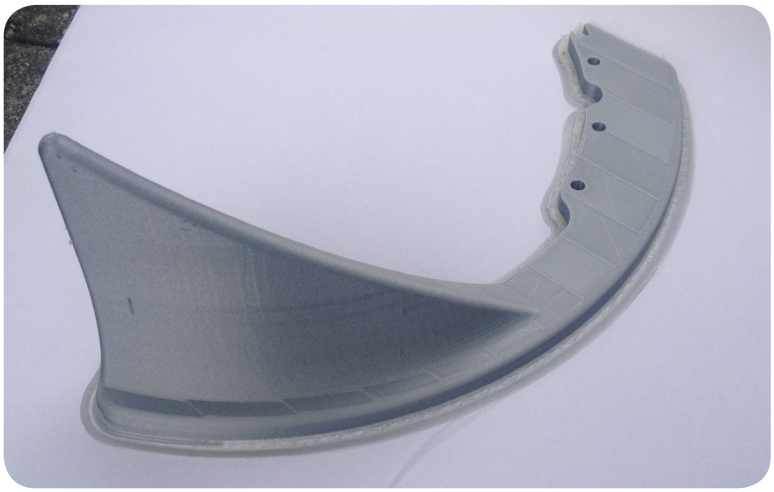
already in use at the Erasmus MC, the rails will be an add-on for the applicator. The microsuction tape that was introduced in Chapter 3 Product Design can be used to attach the rails add-on to the HyperCollar3D. When using microsuction tape, a strong and reliable connection is made with the equipment. In case the Erasmus MC decides to opt for a different solution in the future, the rails can be easily removed from the equipment without leaving any traces. Figure 144 depicts that the microsuction tape has a good bonding with the Lexan shell of the HyperCollar3D.

The slide that includes the larynx extension has to be printed with support material, which is rather hard to remove when using PLA. The larynx slide was therefore printed with dual extrusion by the Ultimaker 3, of which the result is shown in Figure 145.

Since the HoneySkin will be made out of plastic foil, it will not be possible to include snap fits. Therefore the final slide designs include holes to attach water tube guiders instead of the proposed snap fits. This is further explained in Chapter 5 Cool & Press. These tube guiders, the top- and bottom support panels, gripping handles and tube connectors were also prototyped from PLA. These components can be found in the overview of the final prototype in Chapter 6 Results.

Figure 143 - Four generations of slide prototypes

Figure 144 - Prototype of microsuction tape bonding and functionality of the sliding mechanism



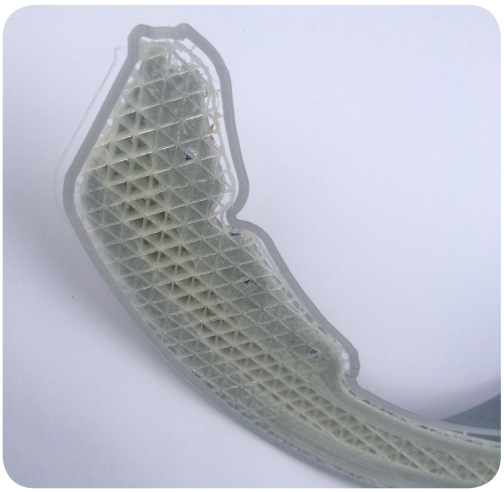
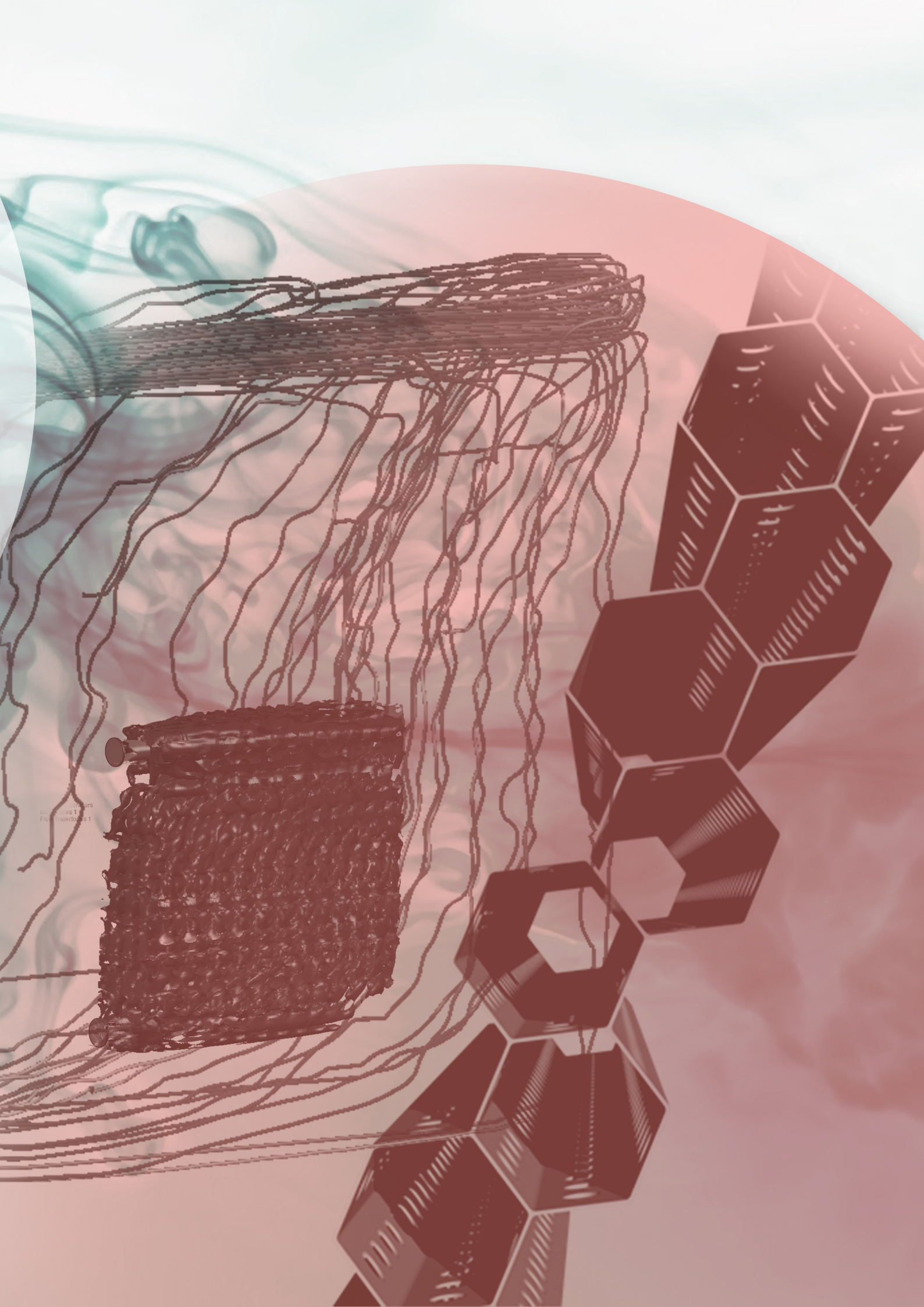


Figure 145 - Larynx slide printed with dual extrusion on the Ultimaker 3

5 | Cool & Press

Uniform skin cooling and pressure control of the water bolus are relevant aspects that influence the comfort experienced by the patient. Furthermore, cooling and pressure have a significant effect on the effectiveness of the hyperthermia treatment. Non-uniform cooling will cause the treatment parameters to be less predictable and reproducible and insufficient pressure will cause a decreased transfer of electromagnetic energy to the tissue due to a lack of contact between water bolus and skin.

In concept CombiCollar it was decided to uniformly cool the skin by guiding a water flow in a specific pattern through the HoneyGrid. In this chapter an efficient pattern that ensures a water flow throughout the entire water bolus volume will be designed. As explained in concept CombiCollar, the HoneyGrid is also a means to equally distribute pressure over the head and neck of the patient. Increased pressure relief can be achieved by the flexibility of the grid. It was also mentioned that a pressure sensor could be used to monitor the pressure inside the water bolus. In this chapter these ideas will be further explained, prototyped and tested.



Uniform Cooling

To ensure uniform cooling of the patient's skin when circulating water through the HoneyPad, a strategic position for the inlet and outlet, a flow pattern and a water tubing system have been developed.

Inlet and Outlet

In order to enable skin cooling by circulating water through the water bolus, a tactical position for the inlet and outlet had to be selected. The following requirements have been evaluated for the optimal position:

- Water is circulated through the entire water bolus volume
- Air inclusions are minimized
- Tubes do not touch the patient
- Tubes are out of the patient's sight
- Tubes do not obstruct the sliding mechanism

After considering a number of possible positions, it was found that there was only one option that met all requirements: placing the inlet and outlet at the side of the water bolus that is at height of the occiput. The selected positions are depicted in Figure 146. To make sure that the upper tube is not in sight of the patient, this tube is guided down the HoneyShell. Each inlet and outlet was placed as high and as low in the water bolus as possible to make sure the water would circulate through the entire volume. To prevent air inclusions when filling the water bolus, it is best to use the bottom tube as inlet and the top one as outlet so that the air can escape at the top. When circulating, the top tube will become the inlet and the bottom tube the outlet. In this case gravity will help to push out the warm water and circulate colder water though the entire volume. This second flow direction is also most functional when draining the water bolus. The chosen flow directions are feasible with the MRcollar pumping system as was described in Chapter 1 Analysis.

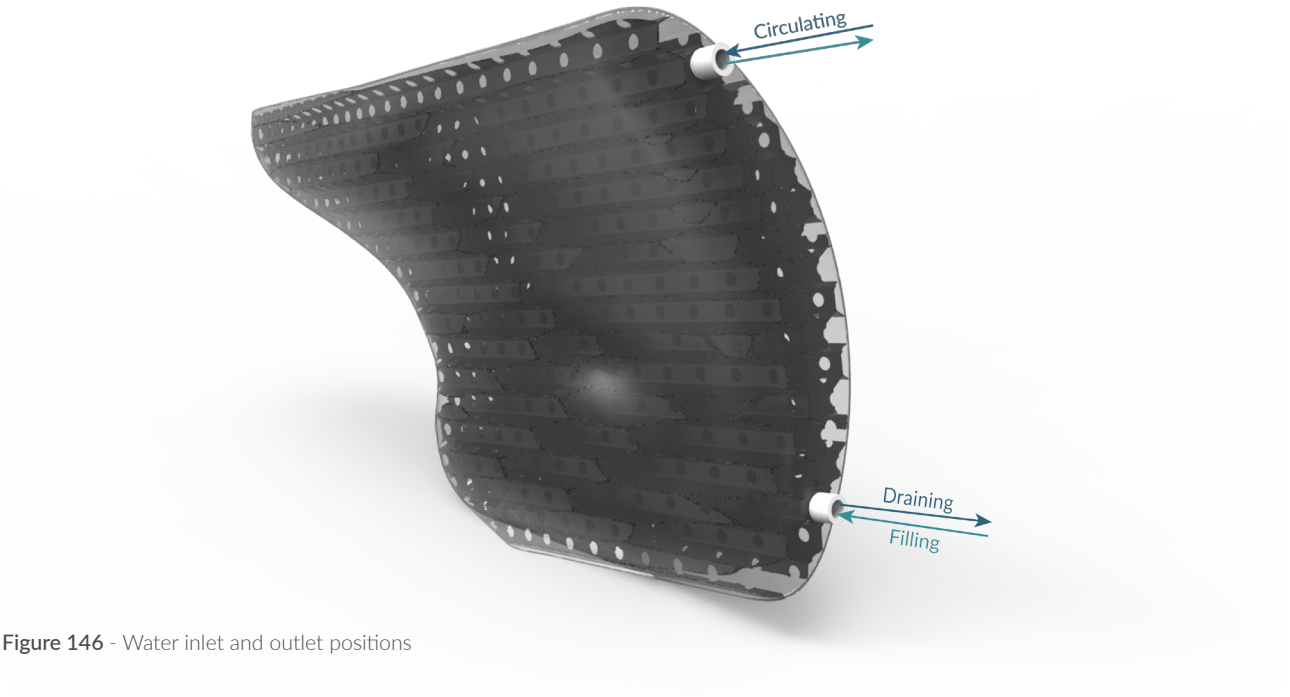


Figure 146 - Water inlet and outlet positions

Flow Pattern

The initial goal for uniform cooling was to guide the water flow in the length through the honeycomb tubes of the HoneyGrid. The water would then flow from side to side as if pictured in Figure 147.

In the final material choices that have been made for the HoneySkin, it is hardly possible to attach the HoneyGrid to the HoneySkin in a water tight manner. To prevent water from flowing around the honeycomb grid instead of through it, closed ends of the honeycomb pipes would be required. This would leave some air in between the seal edge and honeycomb edge as is pictured in Figure 148. The closed ends would also decrease flexibility of the HoneyGrid and affect patient comfort.

Instead of guiding the water flow through the length

of the honeycomb pipes, it was therefore decided to develop a top-down flow pattern in which the water will flow through perforations in the honeycomb pipes. In this design it does not affect the uniformity of cooling when water flows around the edges of the grid. Figure 149 depicts the expected water passage for this design.

To make sure that the water from the inflow tube flows directly into the closest honeycomb pipe instead of along the edges of the grid, a connecting system was designed as shown in Figure 150. The same connector is used at the outflow tube to ensure a water flow through the honeycomb pipe at the bottom.

In a study of Birkelund et al. (2009) it was found that a perforated inlet tube and a perforated outlet tube in a water bolus volume are capable of creating a uniform flow distribution. To achieve this uniform flow, it is important to have an irregular spacing between the perforations that gets smaller near the end of the tubes. With a regular spacing the flow would be higher in the hole closest to the inlet and outlet compared to the furthest hole. A study of Arunachalam et al. (2009) indicated that a perforation diameter of 5mm would reduce the flow resistance, leading to a uniform flow. The same study explained that the spacing between the holes should be at least 10mm to prevent high pressure building up and breaking through the tube wall. These findings were taken into account in the flow pattern design for the HoneyPad.

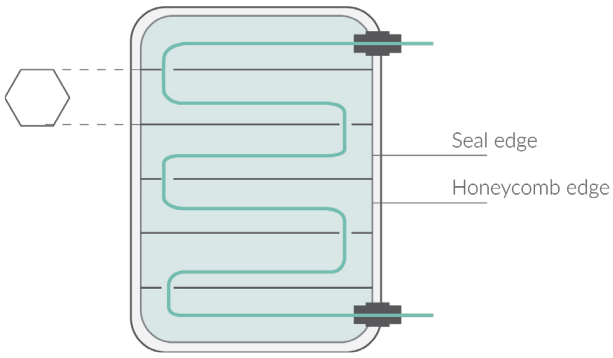


Figure 147 - Expected water flow in a closed honeycomb guiding system

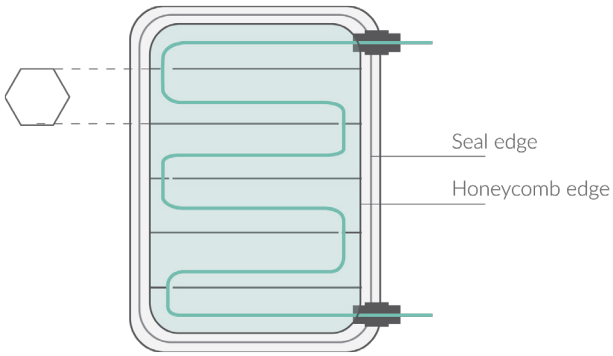


Figure 148 - Expected water flow in an open honeycomb guiding system

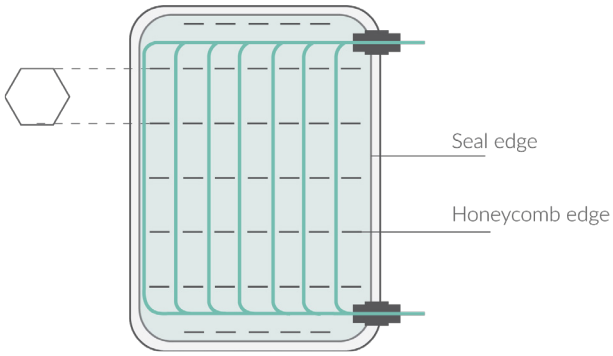


Figure 149 - Expected water flow in a perforated tube guiding system

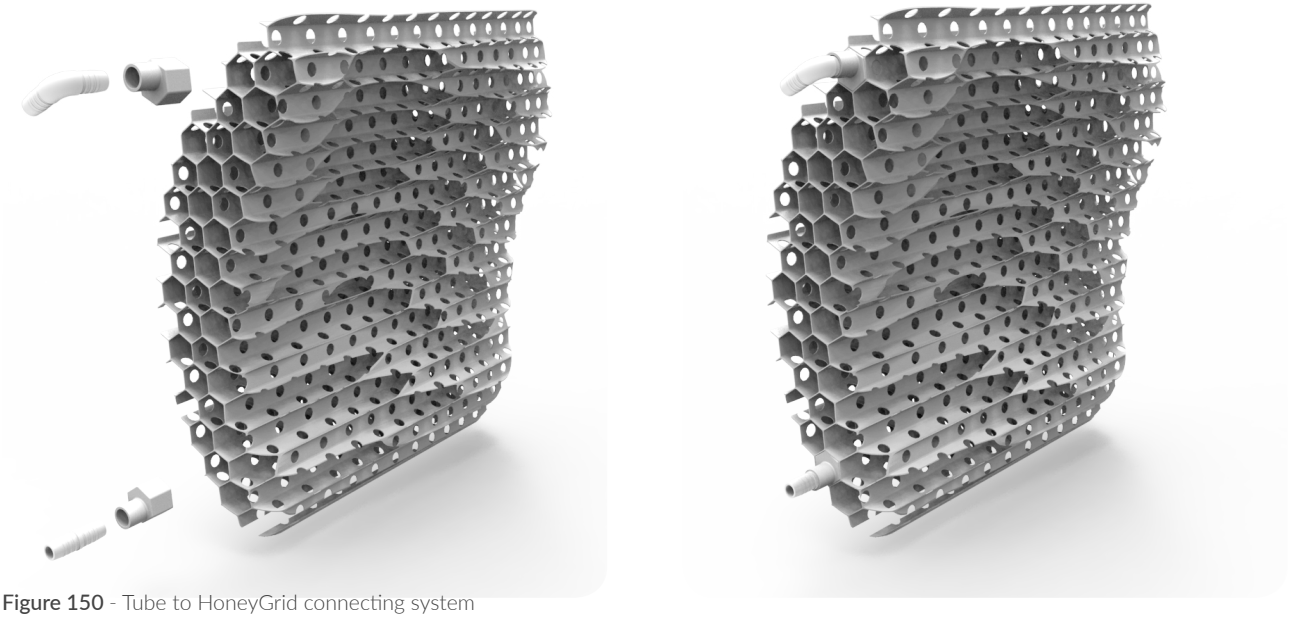


Figure 150 - Tube to HoneyGrid connecting system

The grid as pictured in Figure 151 has a hole spacing ranging from 10 to 31mm, with the inlet and outlet placed at the neck side. Between two perforations the spacing increases with 3.5mm, except for the last four perforations which have a constant spacing. The constant spacing in the end was chosen to make sure the spacing would not get too large to allow water flowing to the furthest edge. A rectangular model of this grid, as shown in Figure 152, was modelled and tested with a flow simulation in SolidWorks. The simulation results are presented in Figure 153 and 154.

From the flow trajectories in Figure 153 can be concluded that the water flow skips the volume near the inflow and outflow and mainly passes through the corner at the end. To optimize this flow, the perforations have to be shifted closer to the inflow and outflow edge. The isocurves in Figure 154 show that a large part of the water volume is flowing straight down through the perforations, skipping the remaining volume of the honeycomb pipes. This undesired phenomenon is caused by the perforations that lie straight beneath each other. The flow should improve when the perforations of each honeycomb layer are shifted with respect to one another.

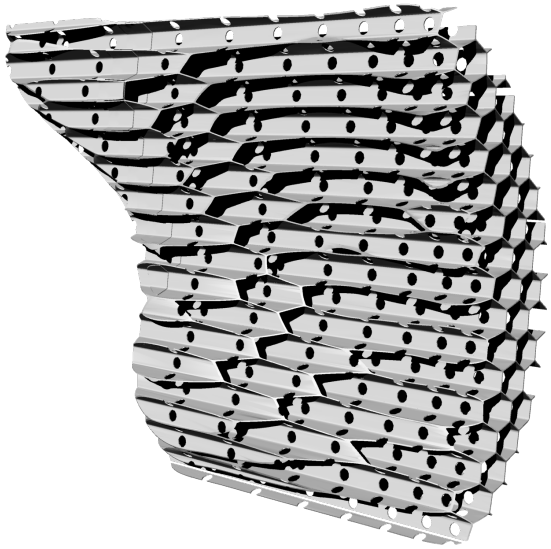


Figure 151 - HoneyGrid flow pattern 1.0

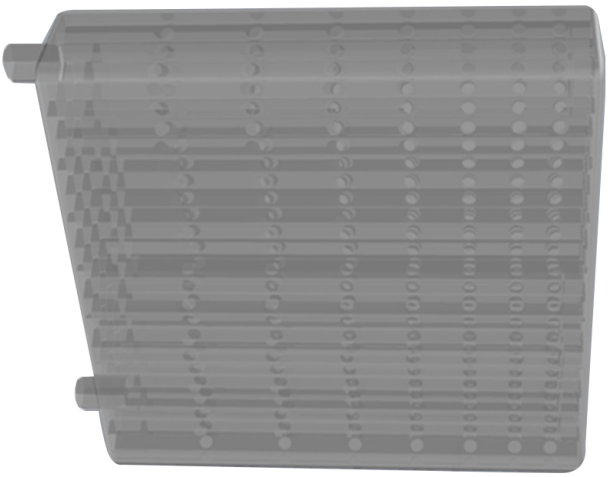


Figure 152 - Rectangular model of HoneyGrid 1.0

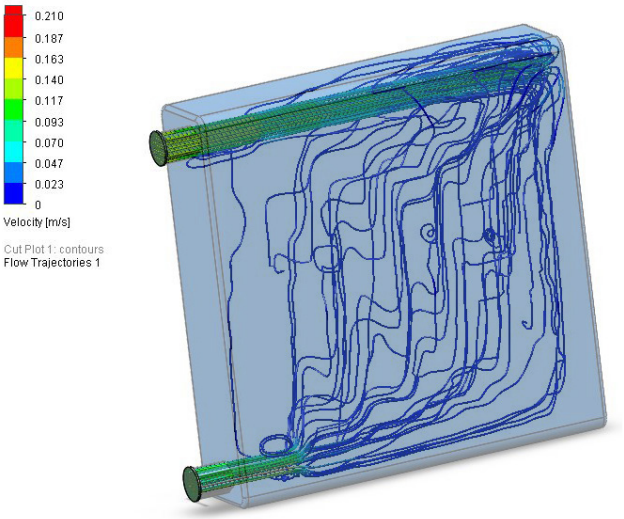


Figure 153 - Flow trajectories of flow pattern 1.0

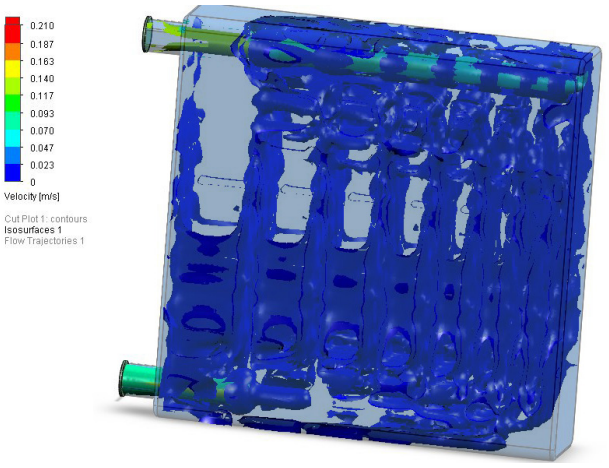


Figure 154 - Isocurves of flow pattern 1.0

Based on the insights from the flow simulation, a new flow pattern has been designed as depicted in Figure 155. In this case the inlet and outlet were placed at the head side of the grid. The accompanying rectangular model for simulation is shown in Figure 156. This optimized pattern has perforations that are placed closer to each other and closer to the inlet and outlet. Spacing ranges from 10 to 17.5mm, with increasing steps of 2.5mm. To prevent a large spacing near inlet and outlet, the spacing does not increase between each pair of holes but has been divided in four groups. In Figure 157 and 158 the flow simulation results are depicted.

Flow trajectories in Figure 157 show that the water flow near the inlet and outlet has been improved. In the new design the water uniformly flows throughout the entire water bolus volume. In Figure 158 the isocurves indicate that the alternating positions of the perforations have paid off. Water does not drop down straight through the holes anymore but instead fills the entire volume of the water bolus. This optimized flow pattern will therefore be applied in the final HoneyGrid design.

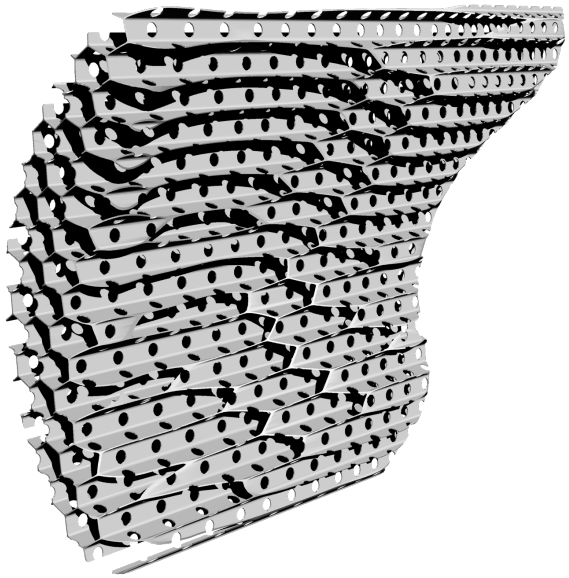


Figure 155 - HoneyGrid flow pattern 2.0

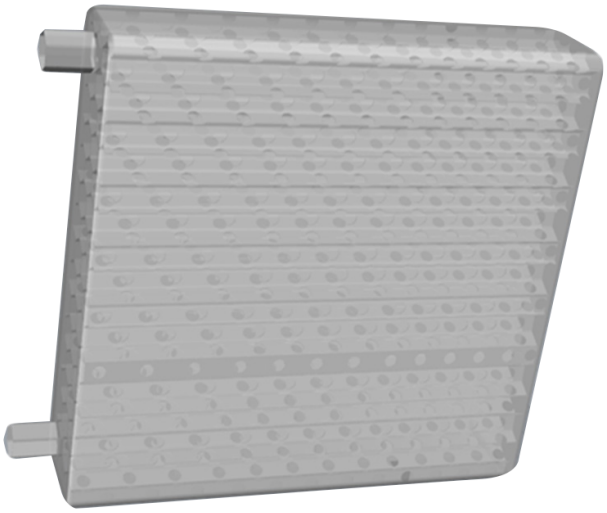


Figure 156 - Rectangular model of HoneyGrid 2.0

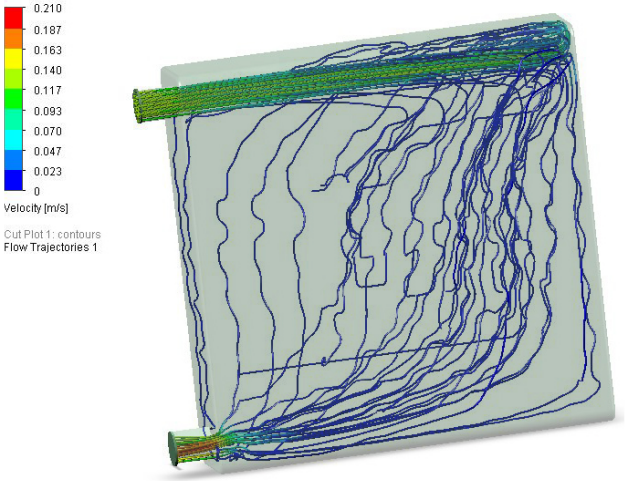


Figure 157 - Flow trajectories of flow pattern 2.0

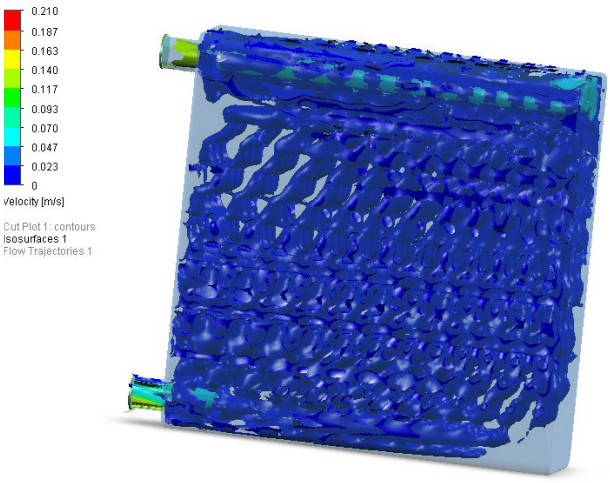


Figure 158 - Isocurves of flow pattern 2.0

Guiders & Connectors

As explained before, the water tube at the top of the water bolus will be guided downwards along the HoneyShell. Specific guider rings as shown in Figure 159 have been designed to neatly guide the tube along the curvature of the side panels.

Plastic tube connectors as shown in Figure 160 have been designed to enable sharp turns between different parts of the water tubes. The connectors that were used in the current water bolus of the Erasmus MC were too large to fit the honeycombs and designed tube guiding pattern. Furthermore, there was a need for connectors that did not contain any metal to enable tube connections within the MRI. Because the tube connectors are not capable of blocking water flow, the regular connectors of the Erasmus MC that contain metal are still required when disconnecting the water bolus.

Figure 159 - Guider rings directing water tubes downwards along the HoneyShell curvature

Figure 160 - Tube connectors

Pressure Control

As was explained in Chapter 2 Product Design, the selected concept enables pressure control by relieving pressure and by monitoring pressure. Both solutions are further explored in this section.

Pressure Relief

The structure and flexibility of the HoneyGrid are mainly accounting for the uniform pressure distribution in the HoneyPad. The selected soft material Flex 45, the small wall thickness of the grid and the anatomical, ergonomic shape of the grid ensure that pressure is distributed equally over the head and neck of the patient.

To increase the equal pressure distribution, the flexibility of the HoneyGrid was inspected more closely. It was found that orienting the honeycombs as pictured in Figure 161 led to a slight increase in flexibility compared to the orientation in Figure 162. Extra flexibility in the horizontal direction is a good option to relief the pressure experienced by the patient. The slightly increased rigidity in the vertical direction provides more resistance against collapsing of the HoneyGrid under the water pressure.

Flexibility and thus pressure relief are also increased with smaller spacing between perforations and with larger perforations. This could be used to increase flexibility around the critical anatomical parts like the ears, jaw bones, cheek bones, chewing muscles and carotid arteries. In the current HoneyGrid however, altering spacing around the critical parts would significantly affect the water flow. Furthermore, increasing hole size would lead to a fragile structure with the current honeycomb dimensions. Locally reducing material infill when 3D-printing the HoneyGrid will entrap air inside the structure, which affects the conduction of electromagnetic energy. An option that will not have a negative effect on the functionality of the HoneyPad, is to locally reduce the wall thickness of the HoneyGrid. Wall thicknesses in the current grid are 0.4mm and could be reduced up to 0.25mm, provided that a smaller nozzle is used for the 3D-printer. This is expected to increase pressure relief around the critical areas, but will require a longer HoneyGrid printing time.

Pressure Monitoring

Despite the pressure relief caused by the flexibility of the HoneyGrid, the water inside the HoneyPad can still cause an uncomfortable pressure on the head and neck of the patient. In order to obtain a comfortable pressure without completely relying on the personal judgement of the patient, pressure can be monitored with a sensor. In the past the Erasmus MC has monitored pressure by placing an optical sensor in the inflow of the water bolus which was removed before starting the treatment. As explained in Chapter 2 Product Design, an MR and EM compatible pressure sensor has been found that can stay at the inflow to monitor water pressure during treatment. However, the experienced pressure is mainly influenced by the volume of water inside the water bolus. The low-speed water circulation during treatment hardly affects the experienced pressure. Considering that the water bolus will be filled with water outside of the MRI-scanner, it is sufficient to only measure water pressure once before the start of the treatment with the optical sensor that the Erasmus MC already possesses. When adapting the water volume based on the data from the pressure sensor before treatment, pressure data during treatment are superfluous.

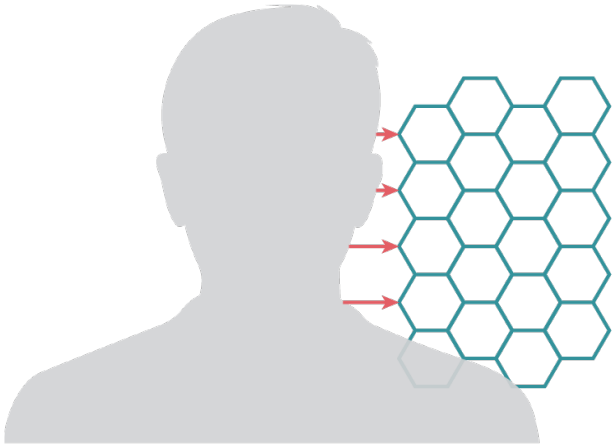


Figure 161 - Honeycomb orientation with extra flexibility

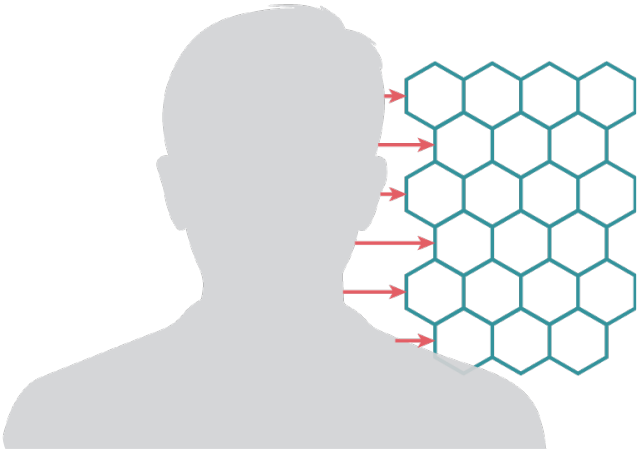


Figure 162 - Honeycomb orientation with less flexibility

The tip of the fibre optic sensor from the Erasmus MC has a diameter of 1mm. The design of HoneyPad's upper tube connector was altered to fit this optic sensor, as is pictured in Figure 163. A hole with an interchangeable lid was made on top of the connector. When pressure measurements need to be taken, the lid with the tiny hole in the middle is placed on the connector. The optic fibre can be inserted in the hole of this lid. After measurements are finished, the fibre is taken out and the lid is replaced for a solid version. This system was placed on top of the connector to prevent water from leaking out of the hole when the lids are switched.

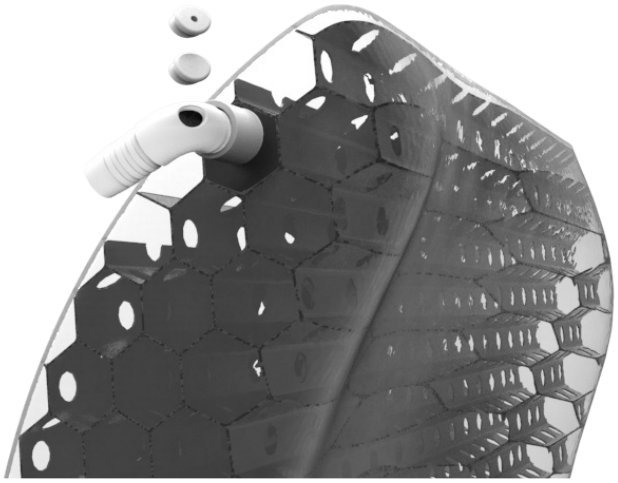


Figure 163 - Interchangeable lid system for insertion of a pressure optic sensor

Prototyping

A perforated HoneyGrid was 3d-printed to fit a small water bolus used for superficial hyperthermia treatment at the Erasmus MC. This grid was used to test the developed flow concept for uniform cooling of the human skin. The grid in this experiment is a forerunner of the flow patterns 1.0 and 2.0 as described in section 'Uniform Cooling'. It has smaller perforations with smaller and constant spacing, but the principle of water flowing through perforated honeycomb pipes is comparable. Honeycomb dimensions are also similar to the described grids in section 'Uniform Cooling'.

The SHT water bolus as depicted in Figure 164 was made from the printed grid and its uniform cooling capabilities were compared to a regular SHT water bolus. Apart from cooling capabilities, the conduction of electromagnetic energy was evaluated for both boluses as well.

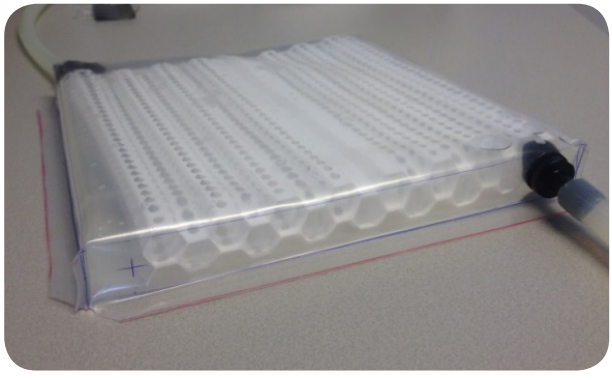


Figure 164 - Redesigned SHT water bolus

Cooling capability

In the first experiment an infrared camera was used to visually map the pattern of water circulating through the boluses. First, the water boluses were filled with water at a temperature of 25 °C and air bubbles were removed. The boluses were connected to the circulation pumps and were laid down on a sheet filled with phantom material, as is depicted in Figure 165. This phantom material has properties equal to human tissue and therefore makes the measured cooling patterns more realistic. When a steady state temperature was reached, the

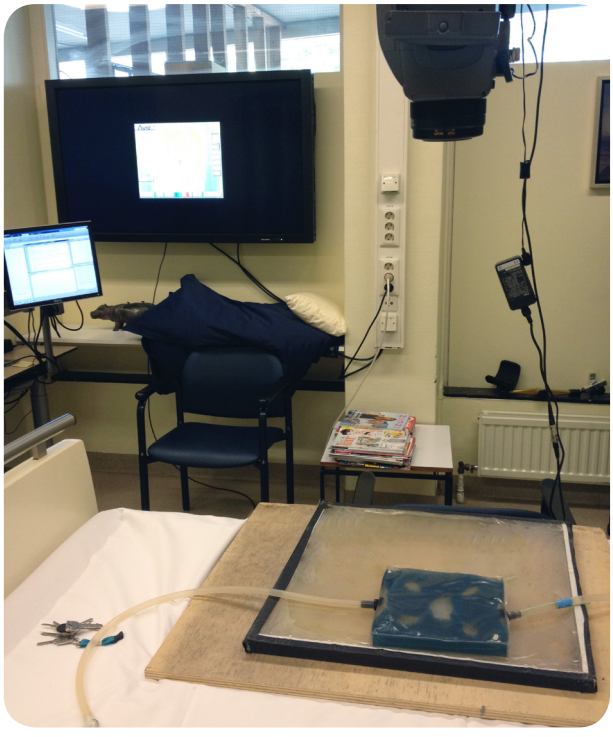


Figure 165 - Set-up for IR measurements of the regular SHT bolus

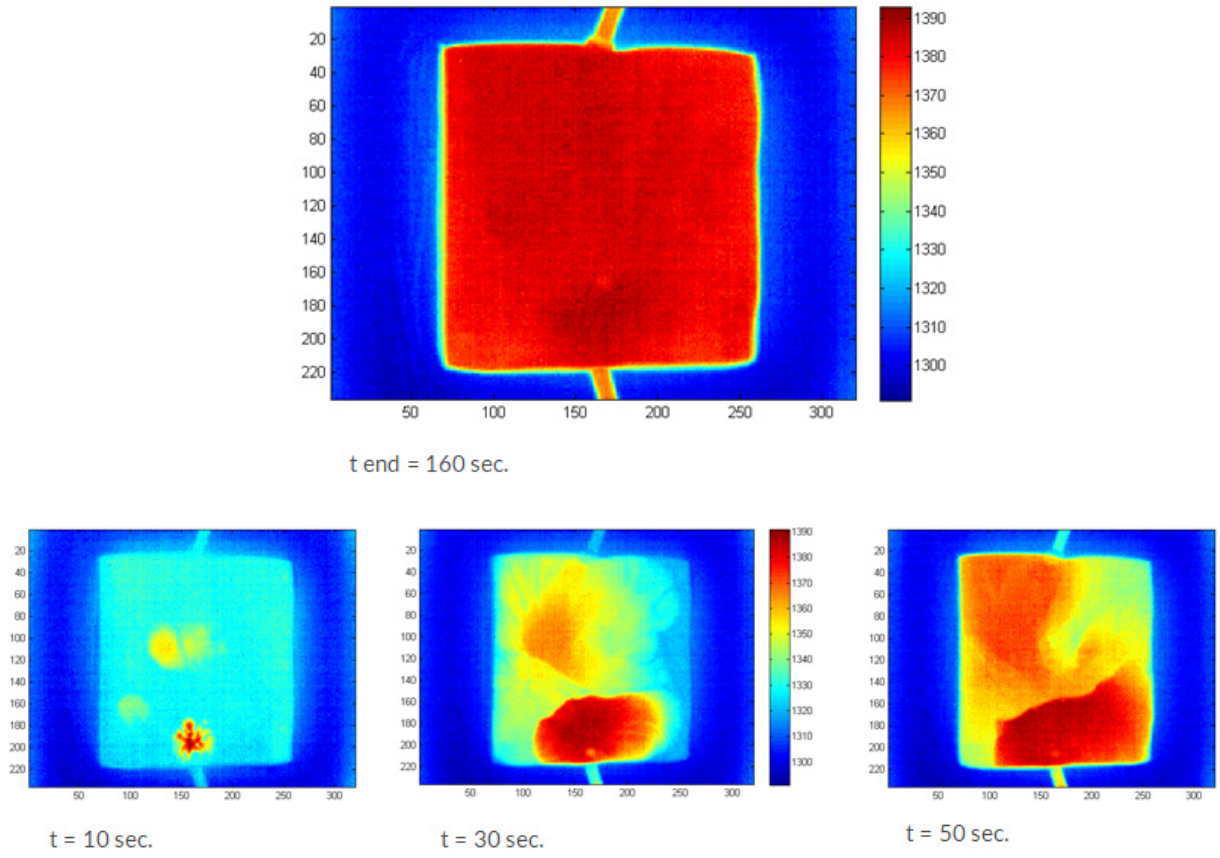


Figure 166 - Uniformity of temperature distribution at t-end of the regular SHT bolus

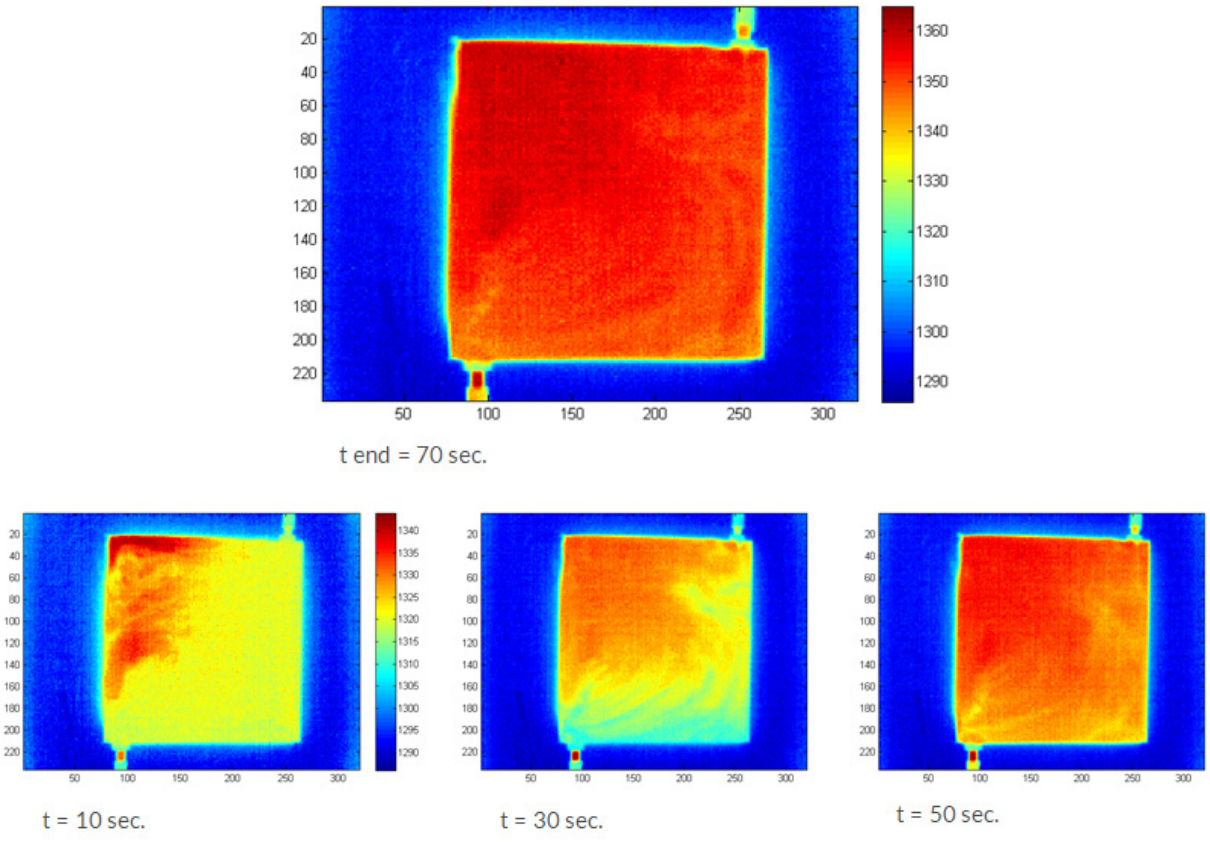


Figure 167 - Uniformity of temperature distribution at t-end of the redesigned SHT bolus

temperature of the pump was increased to 40 °C, causing hot water to flow through the boluses. The flow pattern of this hot water was captured by the IR camera, which took a picture at each interval of 10 seconds. With this experiment the uniformity of the hot water distribution and the duration to reach uniformity were compared between the redesigned and regular SHT bolus. The results of regular bolus and redesign are pictured in Figures 166 and 167 respectively.

The results show that the temperature inside the redesigned water bolus will become uniform much faster than the regular water bolus. At T-end, which is the time at which uniformity is reached, the hot water inside both boluses has been equally distributed over the entire volumes. Thus, the eventual degree of uniformity is comparable. Based on these results it can be concluded that the HoneyGrid is capable of uniform cooling and that it reduces the waiting time to reach uniformity inside the water bolus volume.

IR pictures of the redesigned water bolus show that the water flow is mainly focused at the corner where the inlet honeycomb pipe ends. This indicates that the flow through the perforations is not yet optimal in this HoneyGrid. Based on the flow simulations as presented in section 'Uniform Cooling' it can be concluded that the strategic irregular spacing and larger perforation size in HoneyGrid 2.0 will improve this flow pattern.

EM energy conduction

An E-field sensor was used to compare the electromagnetic energy conduction of both the redesigned and regular SHT bolus. The E-field sensor was placed between the water bolus and the phantom sheet, as is shown in Figure 168. An LCA applicator which emitted the electromagnetic energy was centrally placed on top of the water bolus. Water of 25 °C was circulated through the water boluses again and measurements started when a steady state temperature was reached.

The EM emission was set at 100W, which is a realistic value to apply in deep head and neck hyperthermia treatment. Energy absorption patterns as measured by the E-field sensor were compared. The absorption patterns of the regular and redesigned water bolus are pictured in Figure 169 and Figure 170 respectively.

Based on the results it is expected that the HoneyGrid will not significantly affect the electromagnetic energy conduction. The overall absorption rate is slightly smaller for the redesigned water bolus compared to the general design. Still, the energy absorption pattern seems sufficient to enhance the heating functionality of the hyperthermia equipment. Because the resolution of the obtained patterns is rather low, more experiments will be performed with the final HoneyPad prototype to confirm this assumption.

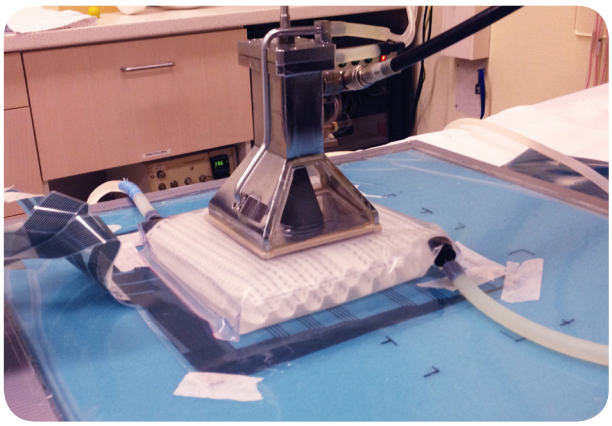


Figure 168 - Set-up of the EM energy conduction experiment

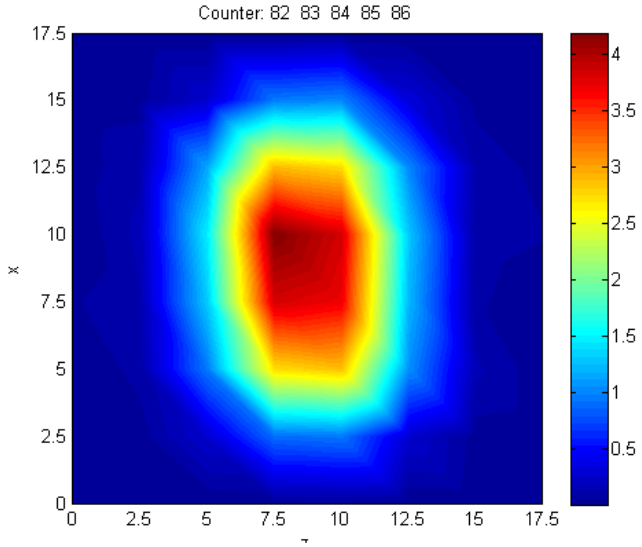


Figure 169 - EM energy absorption pattern of the regular water bolus

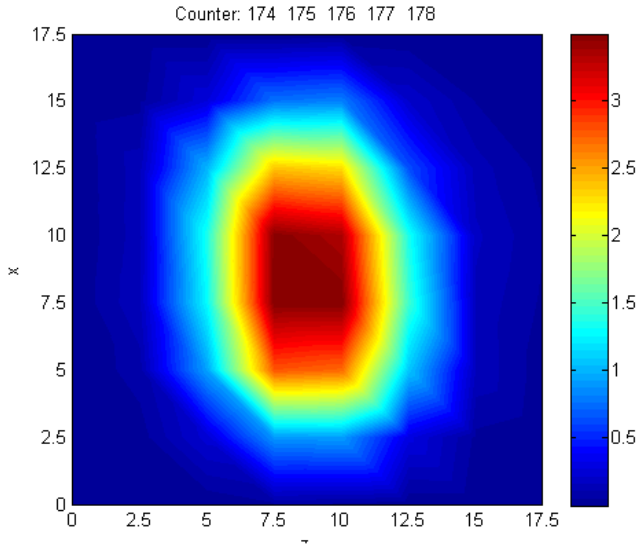
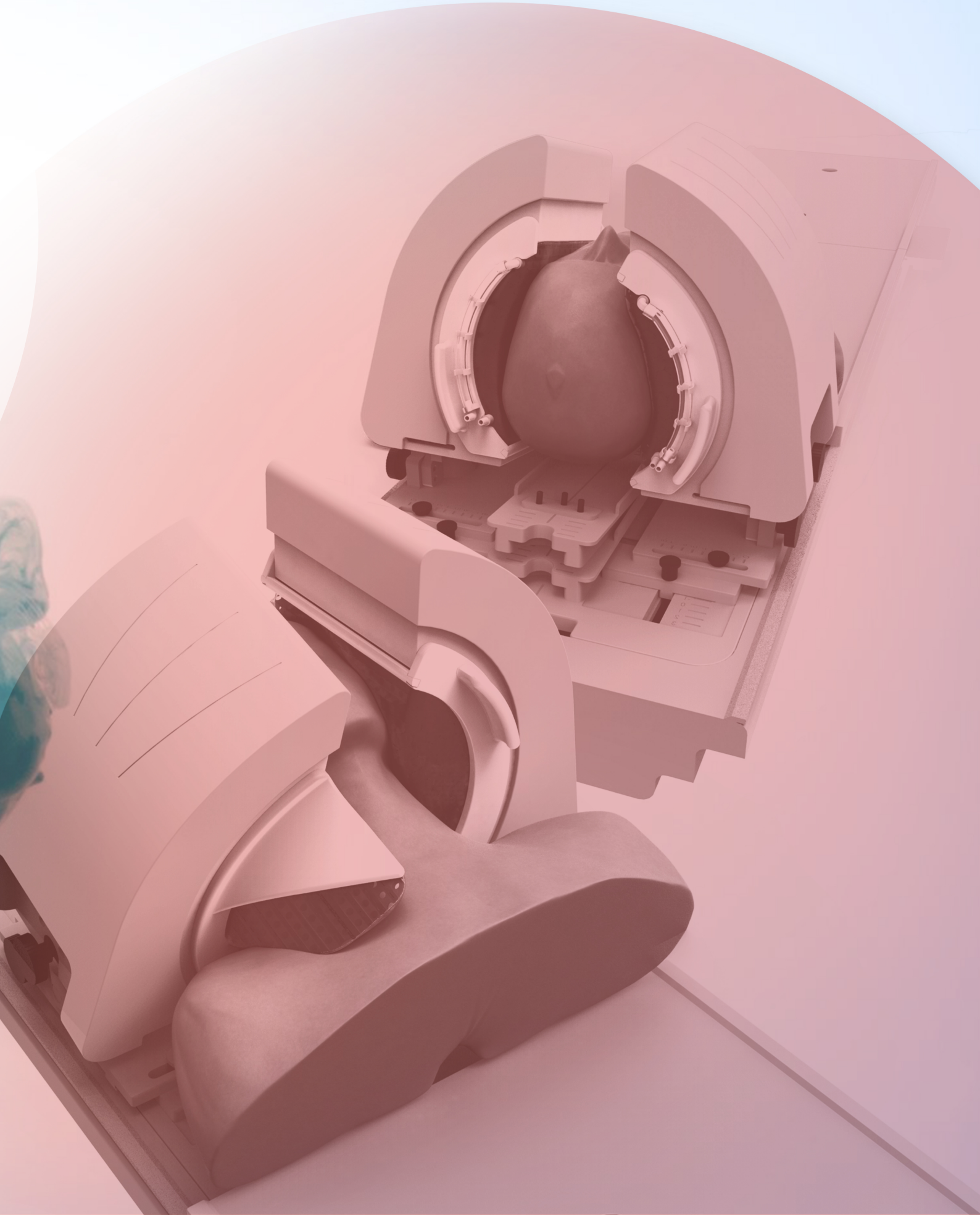


Figure 170 - EM energy absorption pattern of the redesigned water bolus

6 Results

The HoneyPad was established based on the insights from extensive research, several experiments and simulations. In this chapter the resulting design of the HoneyPad will be presented. To evaluate the functionality of the HoneyPad in the hyperthermia treatment context, a final prototype was made. A user test, cooling experiments and electromagnetic energy measurements were performed with the prototype and will be discussed in this chapter.



HoneyPad

An overview of the components of the HoneyPad together with the MRcollar is shown in Figure 171. The final HoneyPad design consists of the HoneyGrid, HoneySkin and HoneyShell. These components are assembled as shown in Figure 172, and slid onto the MRcollar as pictured in Figure 173.

When the HoneyPads of both the head and the neck are connected to the MRcollar, this will form the assembly as presented in Figure 174 and Figure 175. All the components of the MRcollar (excluding MRI bed) are pictured in the exploded view in Figure 176.

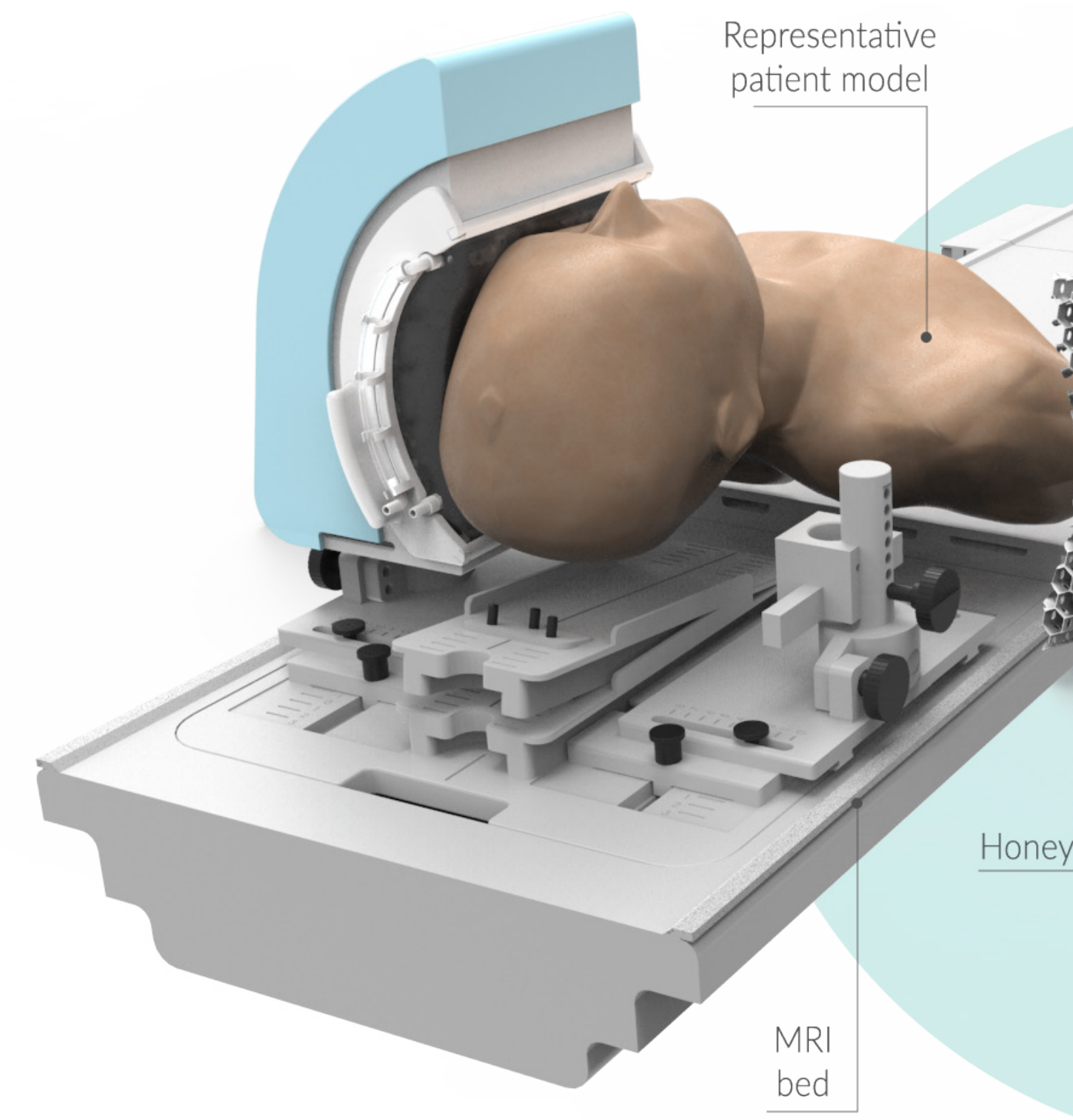
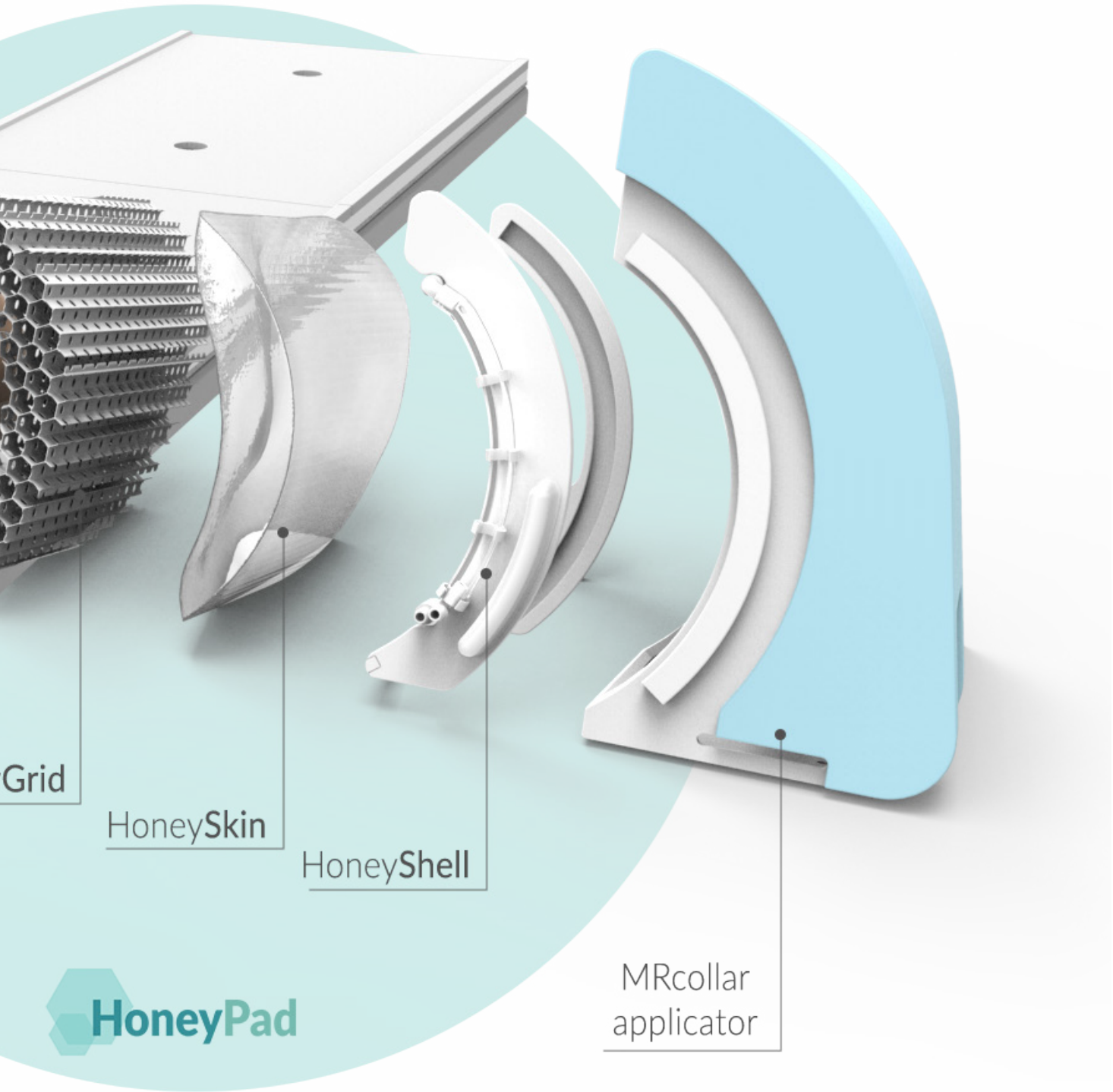


Figure 171 - Components of the HoneyPad in the context of the MRcollar



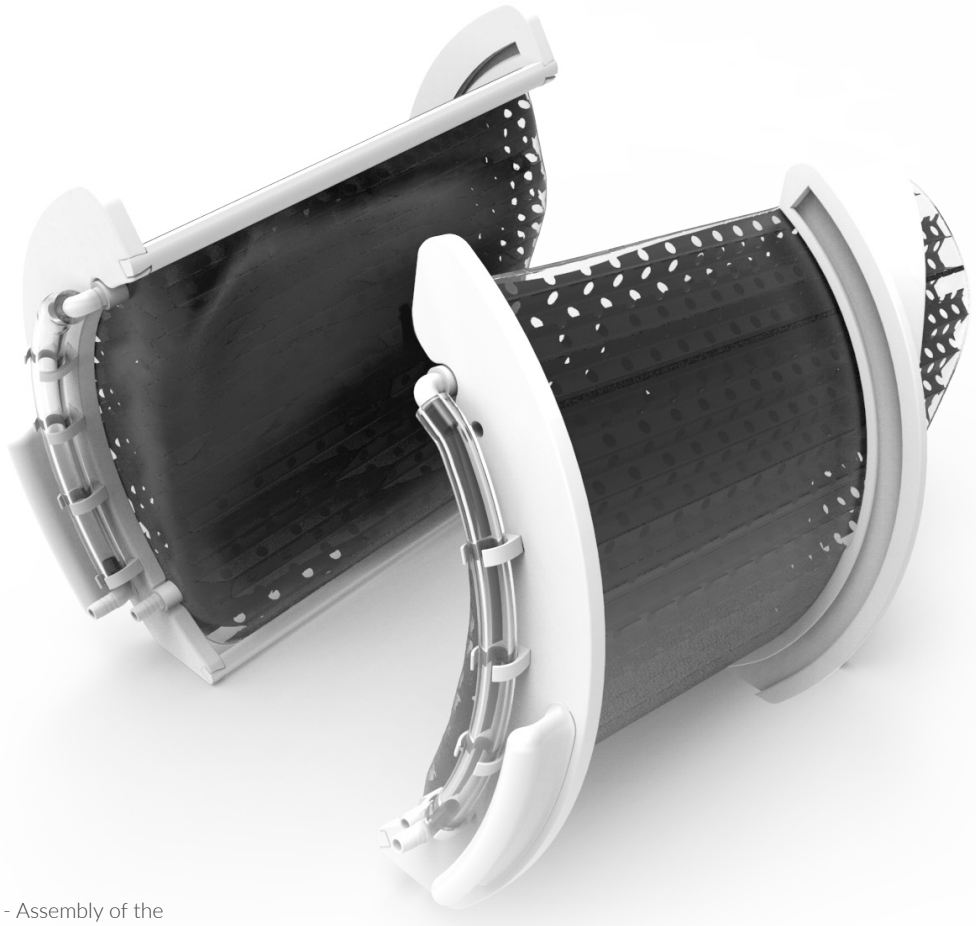


Figure 172 - Assembly of the HoneyPad head and neck module

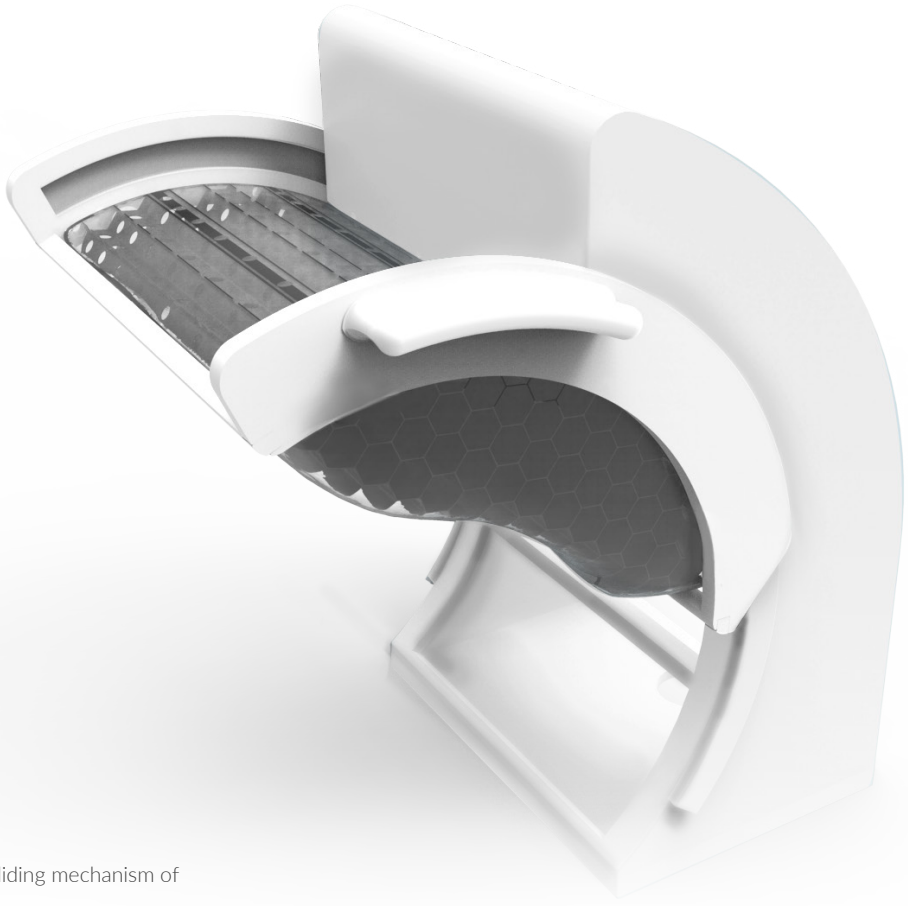


Figure 173 - Sliding mechanism of the HoneyPad

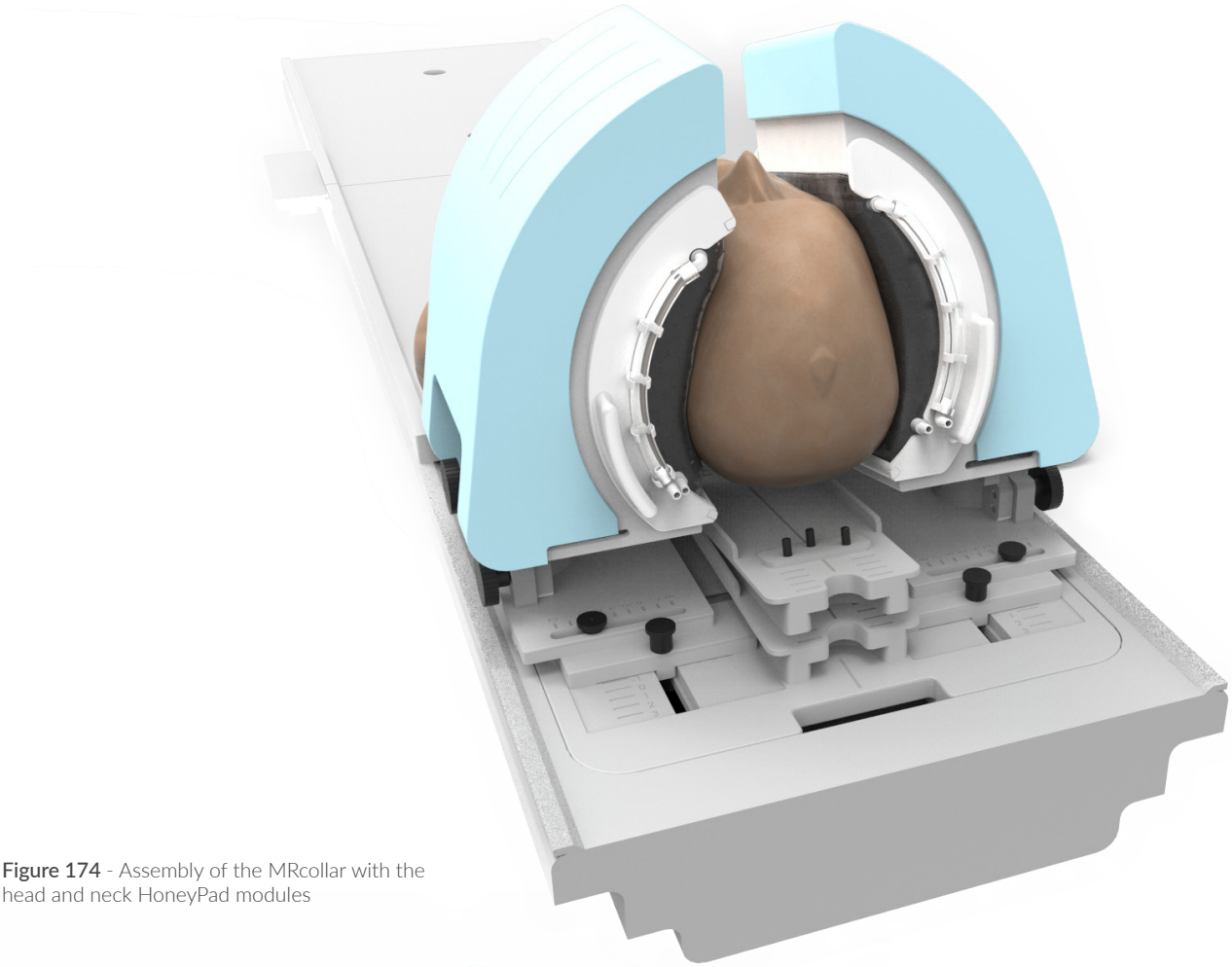


Figure 174 - Assembly of the MRcollar with the head and neck HoneyPad modules

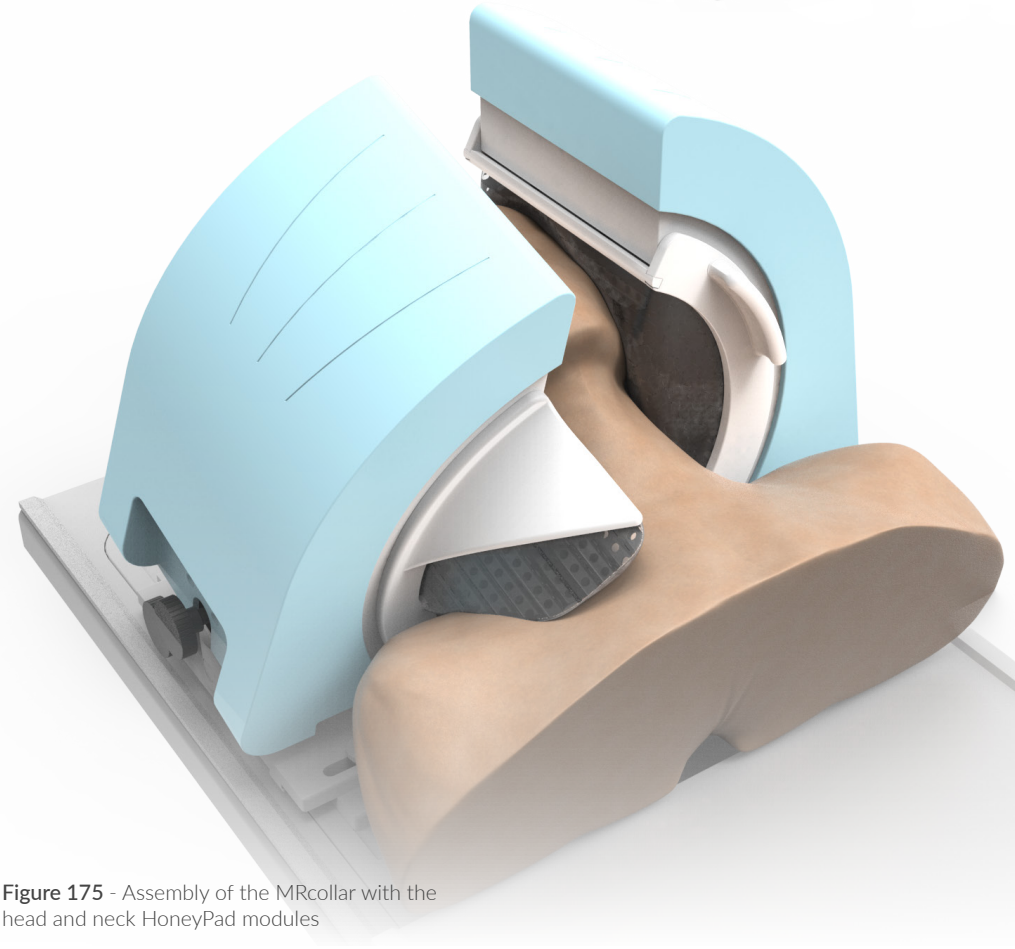
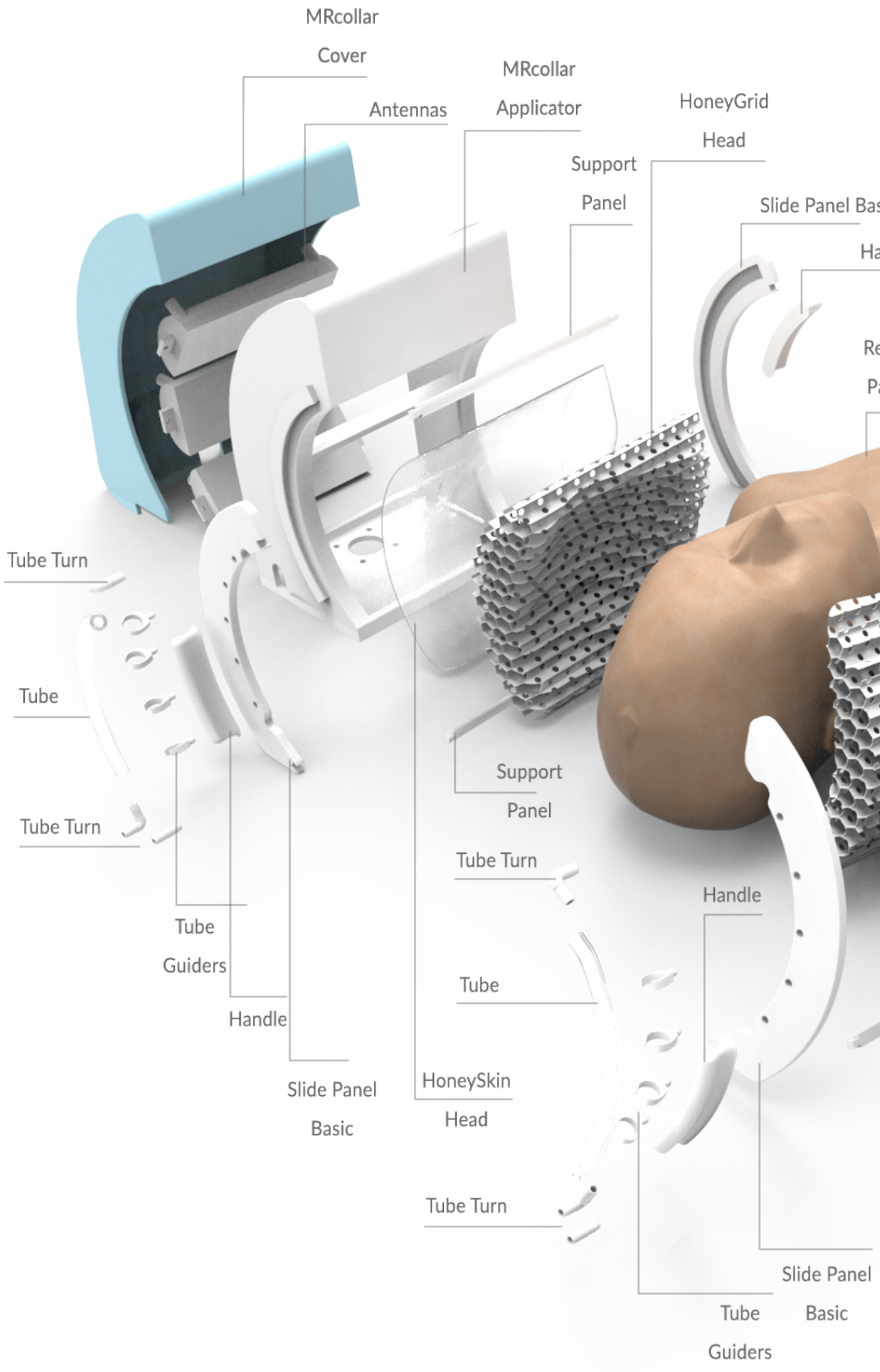


Figure 175 - Assembly of the MRcollar with the head and neck HoneyPad modules


MRcollar
Cover
Antennas
MRcollar
Applicator
HoneyGrid
Head
Support
Panel
Slide Panel Bas
Ha
Re
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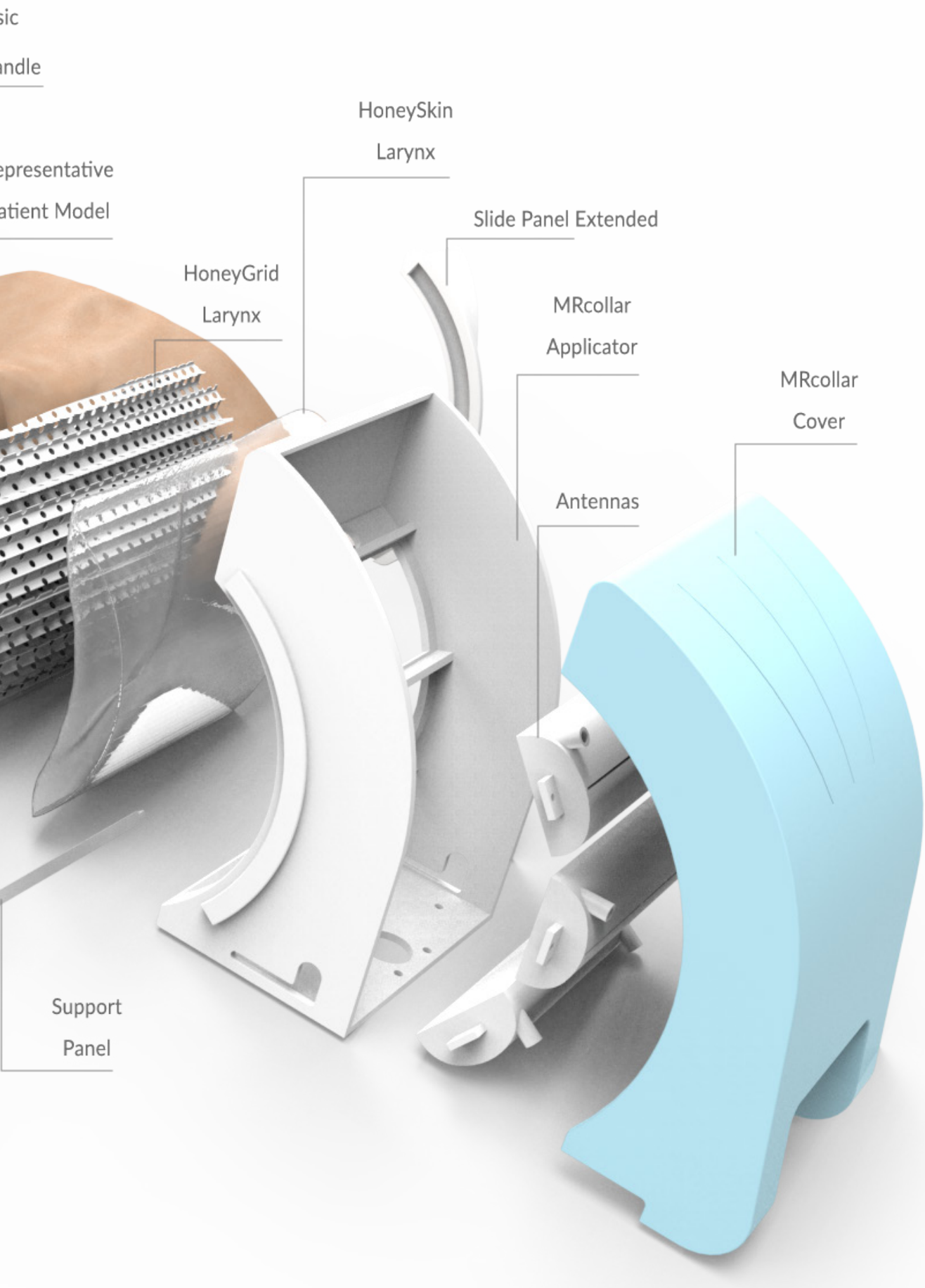
Tube Turn
Tube
Tube Turn
Tube
Guiders
Handle
Slide Panel
Basic
Support
Panel
Tube Turn
HoneySkin
Head
Handle
Tube
Tube Turn
Slide Panel
Basic
Tube
Guiders

Figure 176 -Exploded view of the HoneyPad in the MRcollar



HoneyPad Prototype

Two prototypes were made of the (semi-)final designs of the head and neck HoneyPad modules. Both prototypes are pictured in Figures 177 and Figure 178. Because many activities in this project were performed in parallel, not all components of these prototypes are the final designs. For example, HoneyGrid 1.0 and the forerunners of the final slides have been implemented in the prototypes. This should be taken into account when interpreting the results from the experiments.

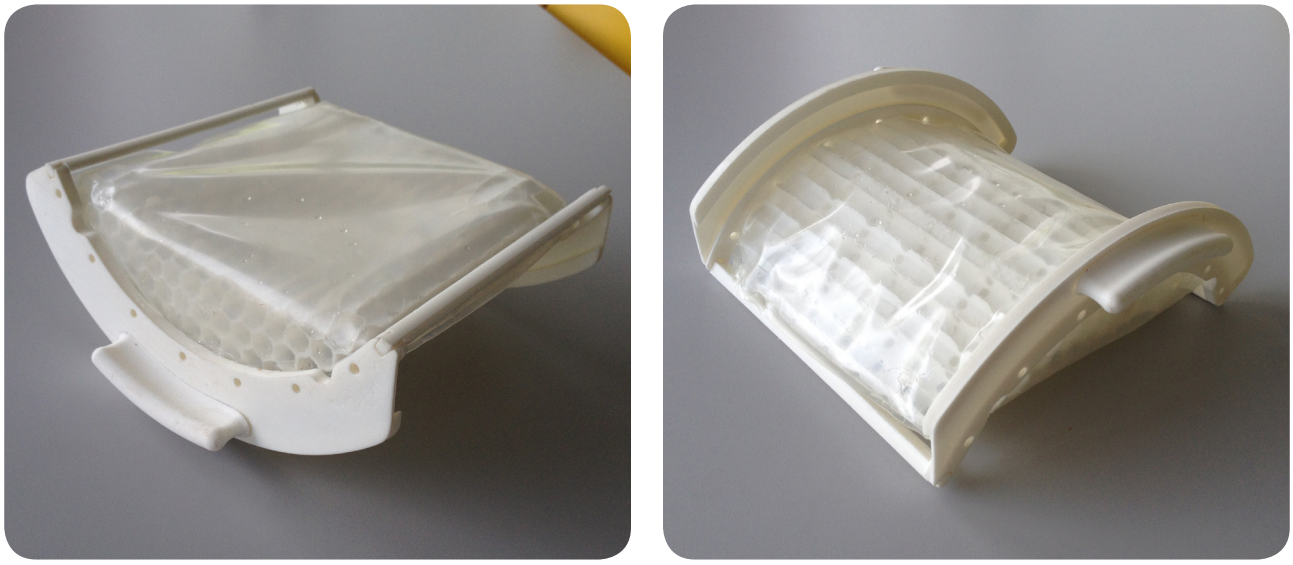


Figure 177 - Prototype of the HoneyPad head module

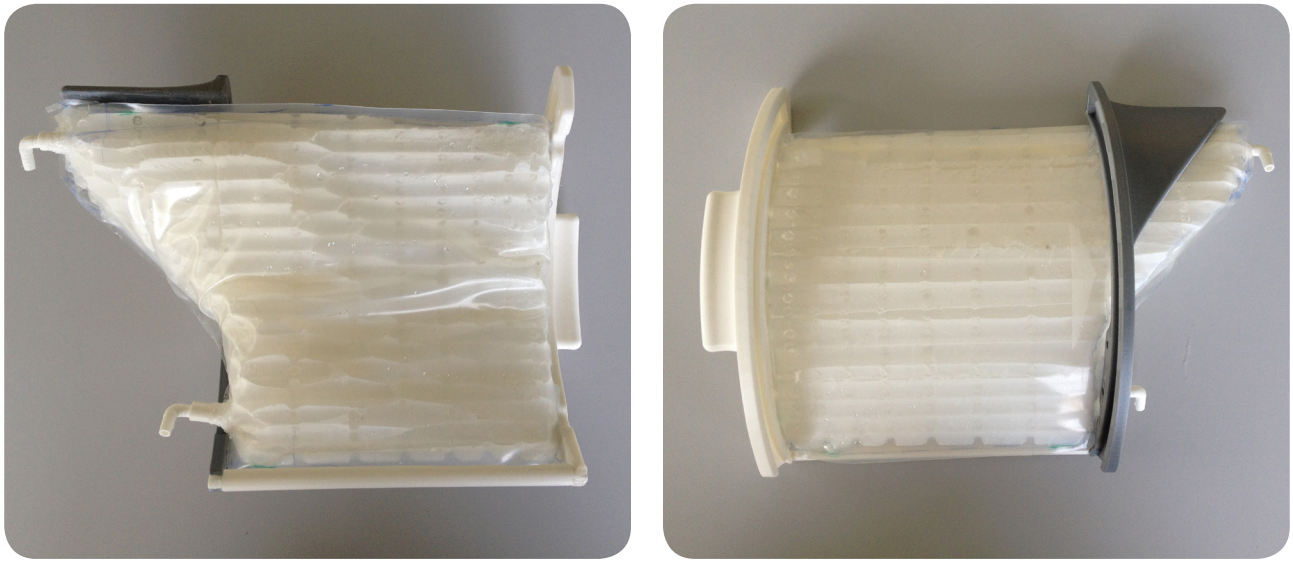


Figure 178 - Prototype of the HoneyPad neck module

Experiments

A skin contact-, cooling- and an EM energy experiment were performed with the prototypes in a clinical setting. The prototypes were connected to the HyperCollar3D applicator and water was circulated through the water boluses. To compare the HoneyPad to the current clinical hyperthermia setting of the Erasmus MC, the same experiments were performed with the regular water bolus.

Skin Contact

In the first experiment the skin contact of the filled HoneyPad water boluses was evaluated. The prototypes were installed in the HyperCollar3D equipment, due to unavailability of an MRcollar model, and connected to the water circulation system. Testing dummy Wally was filled with phantom material and was placed inside the HyperCollar3D to represent the patient. This test set/up is pictured in Figure 179. It was observed how well the HoneyPad head and neck modules made contact with the surface of Wally.

The prototype appeared to have a few leaks at the seams where the plastic foils were sealed together. Because a thick TPU foil was used and several edges had overlapping folds due to the organic HoneyGrid shape, the water bolus was not completely sealed water tight. Furthermore, the current robust sealing device that is owned by the Erasmus MC does not allow reaching all the curves of the water bolus shape. Because there was not enough time for the development of another prototype, the experiments were performed with these prototypes.

Figure 180 shows that the HoneyPad head module makes adequate contact with the phantom when filled with water. The extra distance between applicator and patient that exists due to different dimensions of the HyperCollar3D and MRcollar is bridged by increasing the water volume inside the bolus. This indicates that patients with smaller dimensions than the representative patient model can be treated adequately in the MRcollar as well.

In Figure 181 it is visible that the top of the head module is filled with air instead of water. This air is entrapped because the outlet is placed at a lower level than the air volume. The outlet should therefore be placed as high as possible in the water bolus to minimize air build-up above the outlet.

The HoneyPad neck module has a less adequate contact with the patient, as Figure 182 depicts.

Figure 179 - Prototype test set-up in the HyperCollar3D

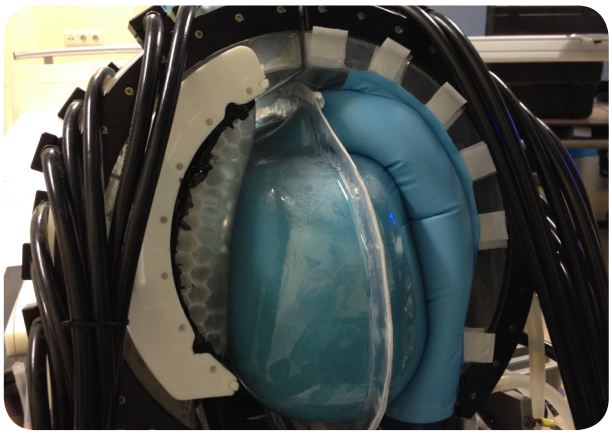


Figure 180 - Skin contact of HoneyPad head module

Figure 181 - Air entrapped in HoneyPad

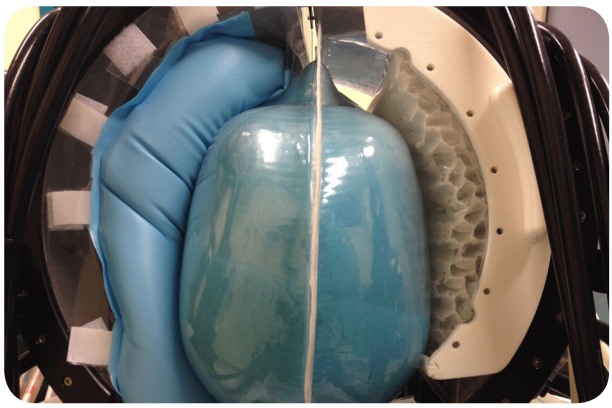


Figure 182 - Skin contact of HoneyPad neck module

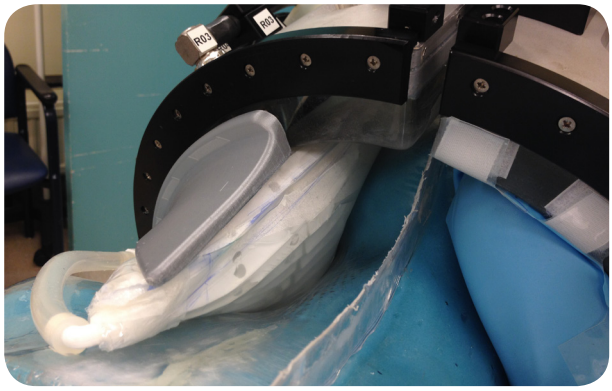


Figure 183 - Skin contact of larynx extension

In this prototype the water cannot compensate the extra distance between applicator and patient because the foil was sealed too tightly around the HoneyGrid. However, the larynx extension part does have a good contact as is visible in Figure 183.

Cooling Capability

The cooling capability of the HoneyPad was tested with a similar experiment with an infrared camera as described in Chapter 6. Only this time, a single infrared image was taken instead of several images over time intervals. The image was taken from the phantom instead of the water bolus itself. This method is more representative to measure the uniformity of cooling the patient, while the other method allowed to map the water flow.

For this experiment the prototypes were installed in the HyperCollar3D and Wally was used to represent the patient. First, measurements were taken with the regular water bolus and afterwards these were compared to measurements with the HoneyPad. Because the phantom was 20 °C, the water circulating through the boluses was set at 35-36 °C to make sure that the bolus would heat the phantom. After having waited long enough for the

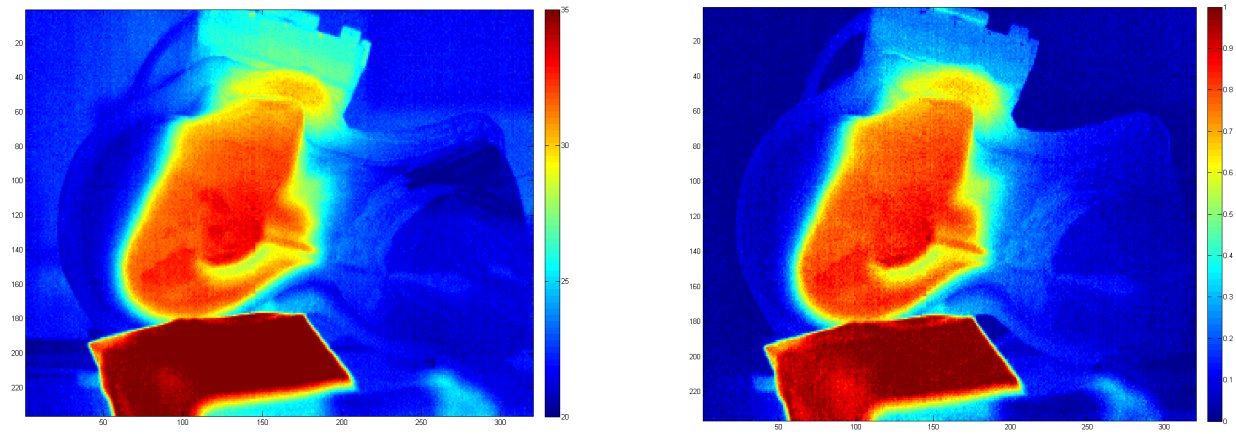


Figure 184 - Heating pattern of the regular water bolus (left), and normalized heating pattern (right)

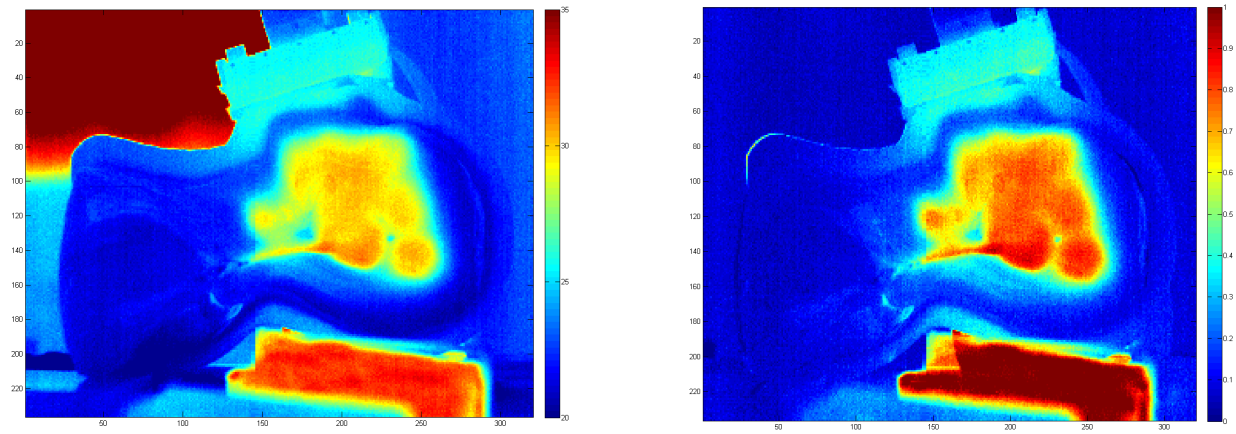


Figure 185 - Heating pattern of the HoneyPad water bolus (left), and normalized heating pattern (right)

heat to be transferred to the phantom, the water bolus was removed and an infrared image was made from the phantom. The results of the regular water bolus and the HoneyPad are shown in Figure 184 and Figure 185 respectively. The heating patterns are representative for cooling patterns as well.

The images show colormaps in which the temperatures range from 20 to 35 °C and colormaps with normalized values. This allows to accurately compare the heating patterns. It can be concluded that the HoneyPad makes it possible to heat, and thus cool, more targeted at the relevant anatomical areas. Due to the customized HoneyPad shape, no EM energy will be conducted towards the brain- and facial area, which are not supposed to be heated during hyperthermia treatment. These areas therefore do not require cooling either. This is an improvement compared to the superfluous heating/cooling of the regular water bolus.

The flattery pattern of the HoneyPad indicates that the leaks in the prototype significantly affected the heat transfer. The leaks caused the HoneyPad to lose contact with the phantom, resulting in several points to cool down before taking the measurement. Apart from water loss, contact was also affected by the incompatibility of the design with the HyperCollar3D. When optimizing these aspects and applying similar foils in the HoneyPad as have been used in the regular water bolus, the heating/cooling pattern is expected to largely improve.

EM Energy Conduction

A similar set-up was used to test the electromagnetic energy conduction of the HoneyPad. The antennas of the HyperCollar3D were activated on the side of the applicator that contained the water bolus that had to be tested. The phantom was heated with a power of 100W and the temperature increase inside the phantom was measured over a time span of 200 seconds with five fibre optic thermosensors that were inserted with catheters. Figure 186 visualizes the locations of the sensor tips which were accurately traced by a CT-scan. The temperature increase that was measured in both water boluses is shown in Figure 187.

When temperature is divided by the specific heat capacity of the phantom, which was unknown in this case, the SAR can be calculated. A higher temperature increase therefore equals a higher absorption rate in the tissue. The results indicate that the energy conducted by the HoneyPad is comparable to the energy conduction of the regular water bolus. It can therefore be concluded that the HoneyPad does not hinder heating of internal tissue during hyperthermia treatment.

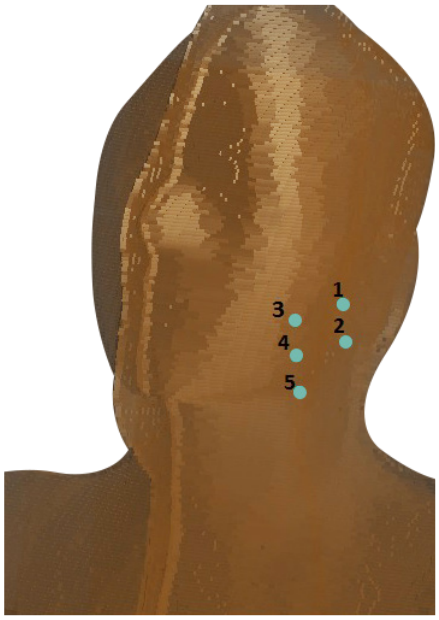


Figure 186 - Sensor tip locations as traced by CT-images

Figure 187 - Temperature increase measured in the regular water bolus and HoneyPad

User Evaluation

A user test was conducted to evaluate the comfort of the ergonomic fit and the comfort of connecting the water bolus to the equipment. Because it was important for the participants in this user test to have a good understanding of the hyperthermia context, five members of the hyperthermia staff of the Erasmus MC were asked to participate.

The participants were asked to first connect the HoneyPad to a loose frame of the HyperCollar3D and subsequently connect the regular water bolus to another frame. A participant performing this test is shown in Figure 188. Afterwards, the same participants were asked to first hold the HoneyPad head module against their face, then to do the same with the HoneyPad neck module and finally to press the regular water bolus against their face as well. This is pictured in Figure 189. Each participant was assisted in obtaining the right position of the water boluses. The user test was performed without water inside the water boluses because at the time of testing the HoneySkins were leaking. Because both the HoneyPad and regular bolus did not contain water, a comparison could still be made and test results were not significantly influenced.

When all tests were performed, the participants were asked to compare the comfort of each water bolus and to fill out an evaluation form. The used evaluation form, which consists of questions based on a likert-scale, is shown in Appendix G. Filed out evaluation forms can be found in Appendix H.

The outcomes of the user test, as depicted in Figure 190, show that the HoneyPad is an improvement on all the themes that were evaluated except for the material that touches the skin. The comfort of breathing, shape stability, connecting effort, connection durability and appearance were considered the largest improvements. Overall comfort and pressure points are considered only small improvements, because the inlets and outlets of the HoneyPad testing models were touching the shoulder and preventing the bolus from falling in the right position. These scores are expected to further improve when a model is made of the final HoneyPad design, which has the inlets and outlets on the opposite side. Because the TPU foil was considered stiffer and therefore less capable of following the human contour, the SEBS foil should be applied in the final HoneyPad design instead. This material would possibly help minimize leaks as well.

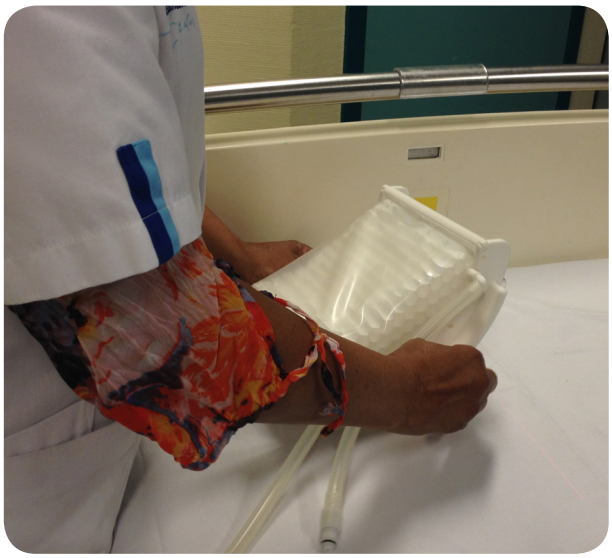


Figure 188 - Participant testing the connecting effort of the water boluses

Figure 189 - Participant testing the comfort of the water boluses

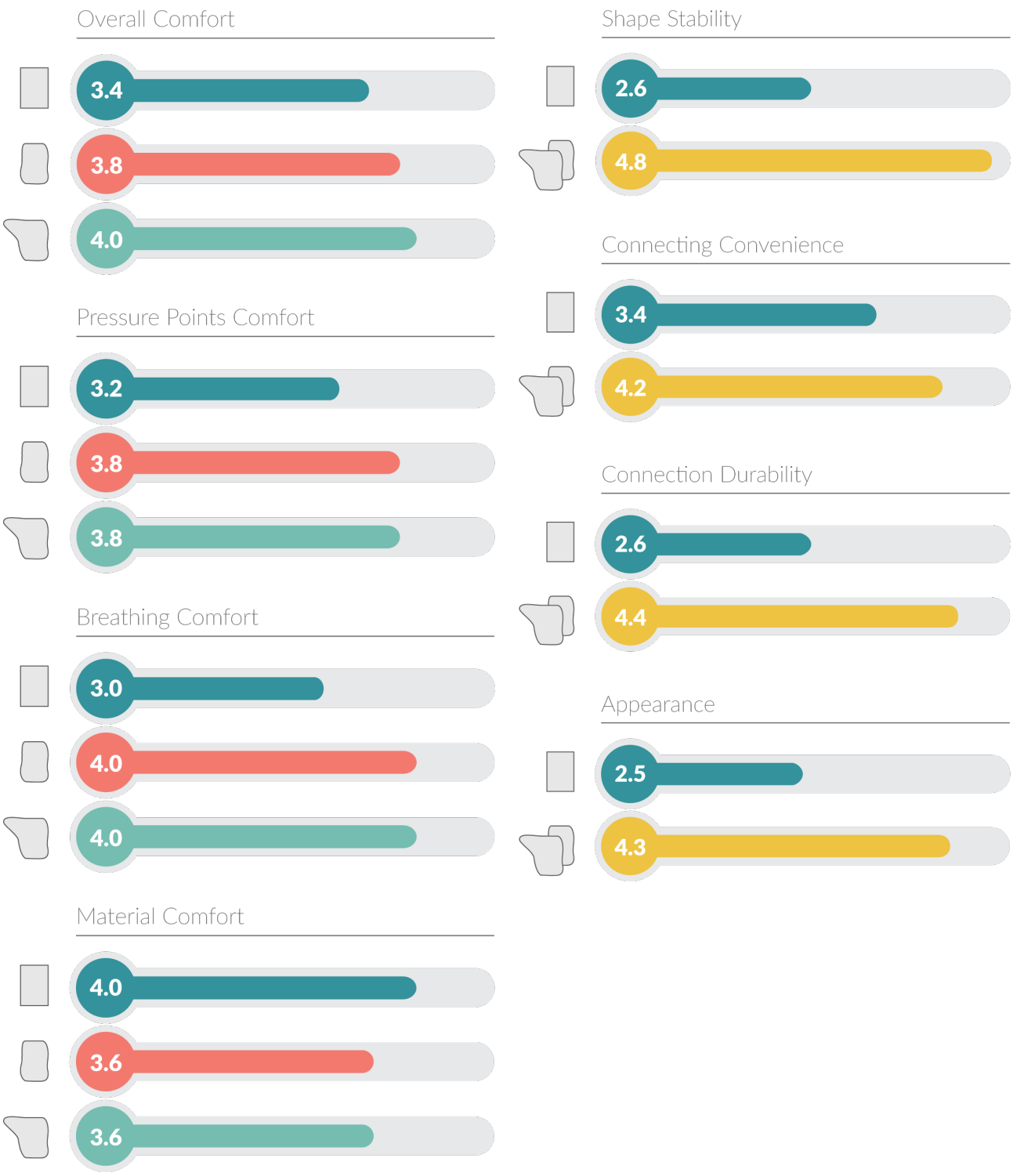


Figure 190 - Outcomes of the user evaluation

7 Implementation

During this graduation project one prototype of the HoneyPad neck module and one model of the head module have been made. For further clinical testing two water boluses for head treatments and two water boluses for neck treatments have to be developed for both the HyperCollar3D and the MRcollar. A production blueprint was made to enable the Erasmus MC to develop these prototypes. Furthermore, the costs for outsourced and in-house production are calculated.

HoneyPad Blueprint

A blueprint for the HoneyPad prototypes is presented in Figure 191. This blueprint describes that SEBS-film and PP-foil will be used instead of the TPU foil that was applied in the original prototypes. To minimize folds and overlaps in the foils, a 3D building plate has to be made for each different model. A hand- sealing device should be used to seal the foils together instead of the table-top device that is currently available at the Erasmus MC. For example, manual thermowelders for medical applications as offered by Hawo would be a promising investment (MedicalExpo, n.d.). To facilitate gluing the HoneySkin to the HoneyShell, it is recommended to make larger seams at the sides of the bolus.

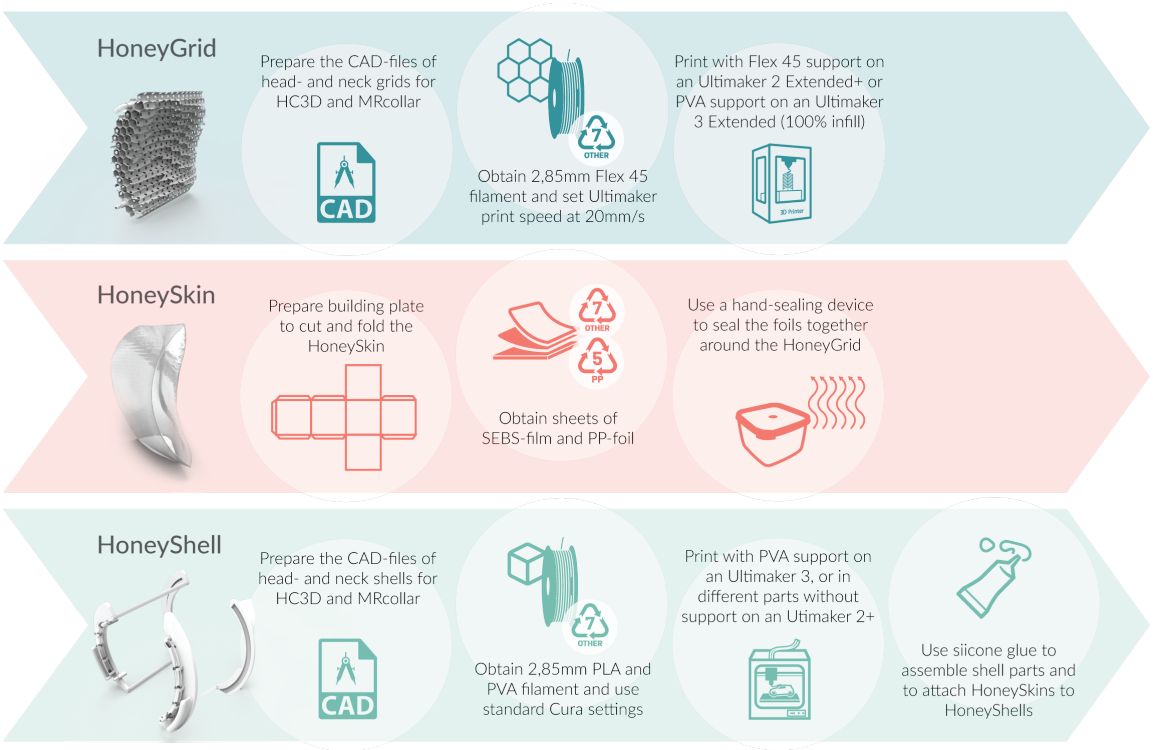


Figure 191 - BluePrint for production of the HoneyPad

HoneyPad Costs

Production of the HoneySkin will remain in-house, but for the HoneyGrid and HoneyShell possibilities exist for both in-house and outsourced manufacturing. Both options have therefore been compared. Figure 192 shows the costs for outsourced 3D-printing of a complete HoneyPad, consisting of a complete head module (two boluses) and neck module (two boluses). Figure 193 depicts the costs for in-house printing of the same product.

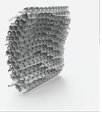
	Part	Material	Firm	Units	Cost
HoneyGrid 	HoneyGrid Larynx	Flex 45	3D Hubs	2x	€130
	HoneyGrid Head	Flex 45	3D Hubs	2x	€80
HoneySkin 	HoneySkin Front	SEBS-film	Vreeberg	4x	€0,50
	HoneySkin Back	PP-foil	Vink Kunststoffen	4x	€0,50
HoneyShell 	Slide Panel Extended	PLA	3D Hubs	2x	€15
	Slide Panel Basic	PLA	3D Hubs	6x	€10
	Support Panel	PLA	3D Hubs	8x	€4
	Handle	PLA	3D Hubs	6x	€4
	Tube Guider	PLA	3D Hubs	16x	€2
	Tube Turn	PLA	3D Hubs	12x	€3
HoneyPad					€638

Figure 192 - HoneyPad costs for outsourced 3D-printing

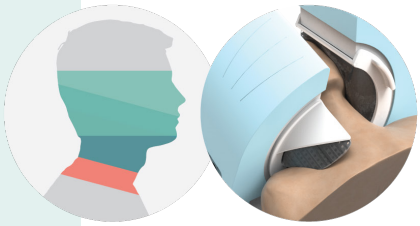
	Part	Material	Firm	Units	Cost
HoneyGrid 	HoneyGrid Larynx	Flex 45 filament	MTB 3D	2x spool 500g	€40
	HoneyGrid Head				
HoneySkin 	HoneySkin Front	SEBS-film	Vreeberg	4x	€0,50
	HoneySkin Back	PP-foil	Vink Kunststoffen	4x	€0,50
HoneyShell 	Slide Panel Extended	PLA + PVA	123 3D + Ultimaker	1x spool 1000g + 1x spool 350g	€25 + €40
	Slide Panel Basic	PLA filament			
	Support Panel				
	Handle				
	Tube Guider				
	Tube Turn	PLA + PVA			
HoneyPad					€149
	+ Ultimaker 3 Extended				€4470

Figure 193 - HoneyPad costs for in-house 3D-printing

For in-house printing an Ultimaker 3 Extended (or combination of other printers) has to be purchased. In-house production will become more advantageous than outsourcing for batch sizes of eight HoneyPad head and neck modules and higher. This is equal to two head modules and two neck modules (eight water boluses in total) for the HyperCollar3D and the same quantity for the MRcollar.

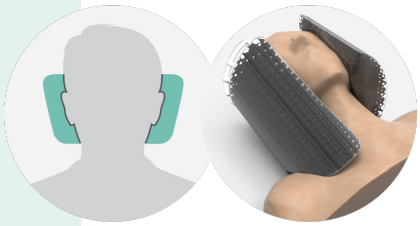
8 Conclusions

The final design of the HoneyPad improves the patient- and operator comfort regarding the different aspects of the six design challenges that have been set-up at the start of this master thesis.



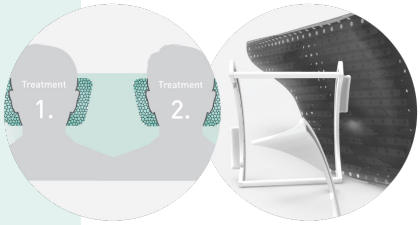
Larynx Fit

The 4D anthropometric analysis has led to the design of a water bolus- and frame extension with a universal larynx fit. CAD-models, experiments and user tests showed that the larynx extension fits patients with varying anthropometrics.



Ergonomic Fit

Based on the representative patient model, a water bolus with an anatomical shape was developed. This design increases patient comfort and treatment effectiveness by closely following the patient's contours. User tests indicated that the HoneyPad was considered more comfortable than the regular water bolus. CAD-models and experiments proved the universal fit of the HoneyPad.

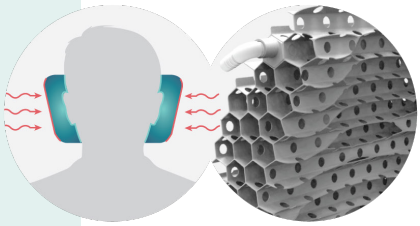


Reproducible Fit

A 3D-printed honeycomb grid and frame around the water bolus provide shape stability to increase the reproducibility of the treatment set-up. The fixed grid geometry enables more accurate treatment planning. The HoneyPad was tested to be more stable than the regular water bolus.

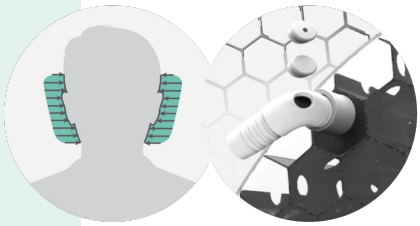
Stable Fit

A sliding mechanism to connect the HoneyPad to the DHT equipment was designed to increase operator comfort, reduce installation time and increase connection durability. A user evaluation confirmed that the slides are considered more convenient and durable compared to the regular water bolus.



Uniform Cooling

Circulating water is guided through the entire volume of the water bolus by a honeycomb grid with a strategic perforation pattern. This design was proven capable of uniform skin cooling by simulations and experiments. Honeycombs ensure an optimal water/material ratio for optimal cooling and transfer of EM energy.



Pressure Control

The honeycomb grid provides stability in the direction that is pressed during installation, whereas it provides flexibility on the sides that are in contact with the patient's skin. A lid in the water tube connector provides a secure place for a fibre optic pressure sensor. Increased comfort regarding pressure points was concluded from the user test.

9 Recommendations

The outcomes of this master thesis have revealed several aspects for further improvement of the HoneyPad that can be investigated in the future.

First of all, it was found that the used TPU foil for the HoneySkin was not the optimal material choice. The SEBS-film and PP-foil that are applied in the regular DHT water bolus were considered more comfortable and better at following the human contour. It has to be tested how these materials will behave in combination with the HoneyGrid and HoneyShell to verify if this is really an improvement.

To prevent the formation of folds and holes in the sealed seams of the HoneyPad, it would be beneficial to use a building plate like the ones that are used for regular water boluses. Because the HoneyPad has a more complicated, organic shape, a customized building plan will have to be developed.

In the HoneyPad the HoneySkin was attached to the HoneyShell with silicone glue. This glue has a long curing time and it is a precise task to correctly align the components. It would therefore be an improvement to develop a mechanical connection between the HoneySkin and HoneyShell instead.

The user test showed that the designed handles were not always used when connecting the HoneyPad to the applicator. Instead, users tended to push and pull on the support panels at the top and bottom. In the current design, these panels are not strong enough to serve this function. In the future these panels could therefore be optimised for use as handles.

As the material of the HoneySkin was adjusted late in the project, the components that connect the HoneyGrid through the HoneySkin to the water tubes were not optimized for this set-up. Secure, water tight connectors that fit the grid therefore have to be designed. Furthermore, the tube turns have to be adjusted in a way that the inner diameter is larger to enable faster filling and draining and minimize air build-up inside the water bolus. Also, a solution has to be found to place the water/air outlet higher in the water bolus to prevent air build-up in the water bolus volume above the outlet.

In the Product Design phase research was conducted regarding materials that can be reformed when exposed to hot water. Within the scope of the master thesis it was not possible to integrate reformable material into the HoneyPad and ensure that the shape can be recovered correctly after impact. Because reformability on top of flexibility is possibly an added benefit to compensate for large deviations in the anthropometrics of the larynx region, research regarding the applicability of such materials is recommended.

Finally, it is advised to conduct more research in the area of stress experience during hyperthermia treatment. This is important because the effectiveness of hyperthermia is dependent on the stress that is experienced by the patient. In this master thesis this challenge is addressed by providing optimal comfort with the HoneyPad. However, more solutions can be sought to increase relaxation during the treatment procedure.

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11 Appendices

A Magnetic Resonance

Designing a water bolus intended for use inside an MRI-scanner has several boundary conditions as a consequence. All materials that are used inside or near the MRI-scanner need to have non-ferromagnetic and non-conductive properties to prevent attraction to the MRI-bore and distortions of the magnetic field respectively. To prevent distortions, water flow also needs to be minimized during imaging. To understand the boundary conditions, the basic working principle of MRI-imaging is explained.

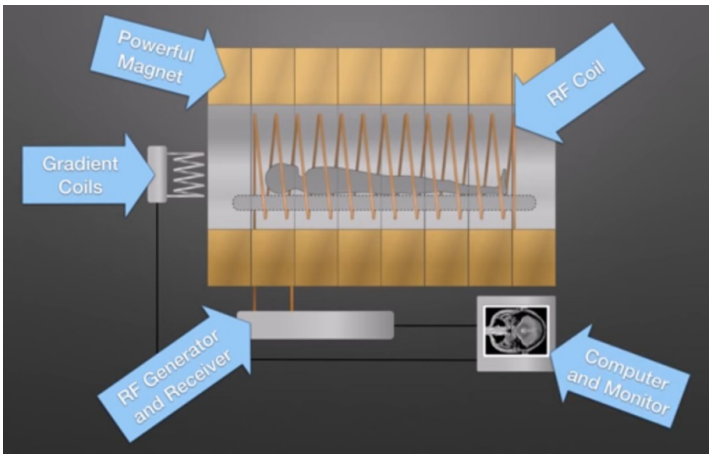

Figure A1 - Components of an MRI-scanner

In Figure A1 can be seen that an MRI-scanner consists of a powerful circular magnet that is positioned around the bore of the system. This magnet forms a strong magnetic field around the patient. A series of gradient electrical coils enables altering the strength of the magnetic field from head to toe of the patient, which makes it possible to image different slices of the body. The generated magnetic field triggers the hydrogen protons inside the tissue to align their axes with the axis of the magnetic field, as Figure A2a depicts. A radiofrequency coil around the bore and a radiofrequency generator together add additional energy to the magnetic field in the form of radiowaves. As is depicted in Figure A2b, these radio pulses cause the protons to absorb energy, resonate and flip into a higher energy state in which their magnetic polarity is reversed. Figure A2c shows that the orientation of the protons' axes also reverses in this state. When the source of radiowaves is switched off, the protons return to their resting state after a specific time which is called the relaxation. In this relaxation state the protons send out a radiowave which is received by the radiofrequency receiver, as is shown in Figure A2d. The time it takes for the magnetic axes of the protons to return to their resting state and the time for their resonance to return to the resting state are measured. These signals are characteristic for a specific tissue, which enables a computer to translate the signals into an MRI-image (Berger, 2002).

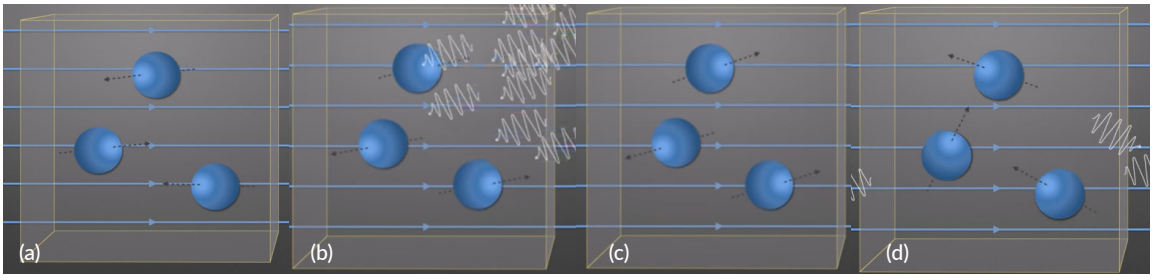

Figure A2 - (a) alignment of hydrogen protons, (b) radiowaves transmitted by the MRI-scanner, (c) flipping of hydrogen protons, (d) radio signals transmitted by hydrogen protons after relaxation.

B Interview Template Patients

Procedure

- How many hyperthermia treatments did you undergo already and how many do you stil have to go?
- What can be improved on the current treatment procedure according to you?

Comfort

- How would you rate your comfort during treatment?
- What aspects make the treatment uncomfortable for you? Where do you experience pain or discomfort?
- Are the uncomfortable aspects the same in every treatment or do they vary over different treatments? How does this vary?
- When do you indicate that you experience discomfort or pain? How is the solved afterwards?
- How comfortable do you think is the contact between your skin and the water bolus?
- How comfortable do you think is the temperature of the parts that touch your skin? Does this feel equal or do you experience cooler or warmer spots?
- How comfortable would you rate the pressure that is applied on your head?
- How comfortable would you rate your posture during treatment?
- Do you experience stress before, during or after the treatment and what are the causes for this stress?
- In which way do you think your comfort can be increased during treatment?
- Hoe zou u uw comfort tijdens de behandeling beoordelen?

Aesthetics

- What is your opinion on the appearance of the hyperthermia equipment? What do you think looks friendly and unfriendly?
- How would you improve the unfriendly aspects?

C Interview Template Clinicians and Technicians

Introduction

- Please introduce yourself, what are your responsibilities at the Hyperthermia Unit?
- What is your opinion about the current water bolus for the HC3D, what are pros and cons?

Construction water bolus

- Could you explain how the current water bolus is assembled, what are the functions of the different components?
- The foam of the current water bolus is cut in a specific shape. What is the function of this?
- What are difficulties regarding the manufcaturing of the water bolus?

Functionality water bolus

- How functional is the cooling function of the water bolus currently (equal or hotspots)?
- How well is the current water bolus capable of following the patient contours?
- How well is the current water bolus capable of supporting the patient and letting the patient lay still?
- The current water bolus design cannot reach the larynx region. What requires attention according to you when a larynx extension will be developed?
- Is there a maximum (for breaking) and minimum (for skin contact) water pressure in the water bolus?

Usability water bolus

- How convenient would you say is the installation of the water bolus in the HC3D?
- How convenient is the filling and draining of the water bolus?
- What exactly happens during the intake, when all settings are defined?
- What is measured exactly with the ruler and level, how is this data saved and reproduced?
- Why is the current water bolus drained after treatment? What would happen when the water stays inside the water bolus?
- The top of the water bolus often remains filled with air. Why is the transparent foil then still needed to check for air bubbles? Is transparency also required for the outer water bolus?

Lifespan water bolus

- What factors are indications that the water bolus should be replaced?
- What are the points that often fail in the water bolus and what is this caused by?

Comfort water bolus

- What are the most common irritations of patients regarding the comfort of the water bolus and the treatment in general?
- How are discomfort complaints expressed and solved?
- Is the water pressure of the bolus varied per patient, and if yes, how is the optimal pressure defined?
- To prevent EM reflection and discomfort of the patient sometimes a salt bag is used to extend the water bolus towards the equipment table. Can this be integrated with the water bolus? Why is the current water bolus not reaching until the bed?

D Idea Evaluation Results

During the evaluation of ideas with the staff from the Hyperthermia Unit of the Erasmus MC, the sheets with ideation drawings were shown to the participants and the different ideas were explained. After an explanation for each sheet, the participants were asked to express their opinions. The feedback from the participants is shown below and has been used in the translation of ideas to concepts.

Extend

- Folded material is vulnerable for leakages. Furthermore it will be a challenge to design something where the folded material can go. When folded out, the mechanism might be unstable.
- When sliding an extension out you have to mind the same challenges. Furthermore, fungi can grow in the sliding grooves.
- An add-on will cause air to be entrapped between two components, which affects the transfer of EM energy. Different water bolus variants are therefore preferred over extension add-ons.

Fit

- Thick filling materials to achieve deformation affect the conduction of the EM energy, the filling material has to be as thin as possible. Deformation with an average human shape looks promising. Flexible honeycombs also look interesting. When flowing water through small pipes the water movement inside the MRI will be suppressed a bit. Foam and silicone should provide enough flexibility, preferrably as flexible as the current foam.
- With reformable material it is important to consider the durability. Hard materials cannot be used in the water bolus because they always form pressure points. A granulate bag that is made vacuum has been used in the hospital ofr other applications already, but this is too stiff and uncomfortable, especially when the patient has to lay still for 75 minutes.
- Customizing for every patient is too expensive and it takes too much time for production. Five minutes extra installation time in the treatment room are already an issue. Preshaped sizes or variants are convenient to fit different patients.

Copy

- Projecting with lasers is already done in the HC3D and will probably also be used in the MRcollar
- Patterns for positioning and repositioning are not really necessary in the Mrcollar, because here you can already copy the position based on the MRI-images. MR-visible patterns would disturb the MRI-images.
- Customizing is again too expensive. The rigid sides for the water bolus are a more promising idea. However, attention should be paid to the shape to prevent hampering of the patient.

Connect

- It would be convenient to clamp the bolus at the top, because in the current set-up there is air between the bolus and applicator at the top.
- The slides are convenient and quick but they might require more precision.
- The vacuum suction method looks convenient, but test if this is strong enough and if the air inside the suction cups does not affect the EM energy transfer. Having multiple suction cups is better to prevent failure when one of them is broken.

Cool

- It has to be tested whether circulating water along the sides of the bolus will be enough for cooling the entire bolus. When deuterium will be used in future set-ups, the liquid flow might not be an issue in the MRI anymore.
- With all the guiding material inside the bolus, the volume might warm up faster which affects cooling. Make sure to minimze the material volume.
- Different compartments require a lot of water tubes. The rotor looks nice, but will require adaptation of the already existing circulator devices. Furthermore, the flow is not that turbulent due to a low flowing speed. A rotor for laminar flow would therefore be unnecessary.

Press

- It is inconvenient to remove the surface pressure mat, the pressure will change after removal. An MR compatible sensor would be a valuable addition.
- In a structure with small openings the water flow might become more turbulent or the flow speed will reduce. This should be tested.
- From the outside you cannot see where the ear is positioned. Therefore it has to be made clear how to correctly position the applicator related to the patient. Due to the asymmetry of the compartments it is not visible if the water bolus is filled and what the water level is. A symmetrical pattern would be better.

E Landmark Descriptions

Number	Landmark	Description
11/12	Neck Extremity R/L	The thinnest part (seen from the front or back) on the side of the neck, located in the length of the ear attachment.
13	Os Thyreoid	The most anterior midsagittal point on the protrusion of the thyroid cartilage.
14/15	Os Thyreoid R/L	The most lateral point on the protrusion of the thyroid cartilage.
16	Jugulum	The midsagittal point on the top of the sternum, right below the pit in between the collar bones.
21/22	Exterior Auricle R/L	The most posterior point on the ear pinna, seen from side view of the head.
27/28	Auricular Sulcus R/L	The most medial point in the pit behind the ear lobe.
33/34	Cheekbone R/L	Midpoint on the surface curve connecting the nasalala and tragion, on the arc of the cheekbone.
35/36	Musculus Masseter R/L	Midpoint on the surface curve connecting the ectocanthus and gonion, at the center of the chewing muscle
37/38	Carotid R/L	Midpoint on the surface curve connecting tragion and jugulum, located at the carotid artery.
39/40	Shoulder Superior R/L	Highest point of the shoulder.
41/42	Shoulder Anterior R/L	Most anterior part of the shoulder.

F Landmark Functions

Landmark	*Waterbolus Fit Function*	*Applicator Fit Function*
Auricular Sulcus Left	Average, mean of left and right	-
Auricular Sulcus Right	Average, mean of left and right	-
Carotid Left	Average, mean of left and right	-
Carotid Right	Average, mean of left and right	-
Cheekbone Left	Average, mean of left and right	-
Cheekbone Right	Average, mean of left and right	-
Cheilion Left	Maximum X, highest of left and right, average Y, Z, mean of left and right	-
Cheilion Right	Maximum X, highest of left and right, average Y, Z, mean of left and right	-
Ectocanthus Left	Maximum X, highest of left and right, average Y, Z, mean of left and right	-
Ectocanthus Right	Maximum X, highest of left and right, average Y, Z, mean of left and right	-
Exterior Auricle Left	Average, mean of left and right	-
Exterior Auricle Right	Average, mean of left and right	-
Glabella	Average	-
Gonion Left	Average, mean of left and right	-
Gonion Right	Average, mean of left and right	-
Inferior Auricle Left	Average, mean of left and right	-
Inferior Auricle Right	Average, mean of left and right	-
Inion	Average	-
Jugulum	Maximum Y, average X, Z	Maximum Y, maximum Z
Menton	Average	-
Musculus Masseter Left	Average, mean of left and right	-
Musculus Masseter Right	Average, mean of left and right	-
Nasalala Left	Maximum X, highest of left and right, average Y, Z, mean of left and right	-
Nasalala Right	Maximum X, highest of left and right, average Y, Z, mean of left and right	-
Neck Extremity Left	Average, mean of left and right	-
Neck Extremity Right	Average, mean of left and right	-
Occiput	-	-
Os Thyreoid	Average	-
Os Thyreoid Left	Maximum X, highest of left and right, average Y, Z, mean of left and right	-
Os Thyreoid Right	Maximum X, highest of left and right, average Y, Z, mean of left and right	-
Posterior Auricle Left	Average, mean of left and right	-
Posterior Auricle Right	Average, mean of left and right	-
Shoulder Anterior Left	Average, mean of left and right	Average Y+standard deviation, highest of left and right, maximum Z, highest of left and right
Shoulder Anterior Right	Average, mean of left and right	Average Y+standard deviation, highest of left and right, maximum Z, highest of left and right
Shoulder Superior Left	Average Y-standard deviation, average X, Z, mean of left and right	Average Y-standard deviation, lowest of left and right, maximum Z, highest of left and right
Shoulder Superior Right	Average Y-standard deviation, average X, Z, mean of left and right	Average Y-standard deviation, lowest of left and right, maximum Z, highest of left and right
Superior Auricle Left	Average, mean of left and right	-
Superior Auricle Right	Average, mean of left and right	-
Tragion Left	Average, mean of left and right	-
Tragion Right	Average, mean of left and right	-
Zygion Left	Average, mean of left and right	-
Zygion Right	Average, mean of left and right	-

G User Evaluation Form

HoneyPad Evaluation Form

Name:

Function:

Comfort	--	-	-+	+	++
How would you rate the overall comfort of the HyperCollar3D (regular) water bolus?	○	○	○	○	○
How would you rate the overall comfort of the HoneyPad (redesigned) head water bolus?	○	○	○	○	○
How would you rate the overall comfort of the HoneyPad (redesigned) larynx water bolus?	○	○	○	○	○

Pressure Points	--	-	-+	+	++
How would you rate the comfort regarding pressure points on your skin in the HyperCollar3D water bolus?	○	○	○	○	○
How would you rate the comfort regarding pressure points on your skin in the HoneyPad head water bolus?	○	○	○	○	○
How would you rate the comfort regarding pressure points on your skin in the HoneyPad larynx water bolus?	○	○	○	○	○

Breathing	--	-	-+	+	++
How would you rate the comfort of breathing in the HyperCollar3D water bolus?	○	○	○	○	○
How would you rate the comfort of breathing in the HoneyPad head water bolus?	○	○	○	○	○
How would you rate the comfort of breathing in the HoneyPad larynx water bolus?	○	○	○	○	○

Material	--	-	-+	+	++
How comfortable feels the contact between the material of the HyperCollar3D water bolus and your skin?	○	○	○	○	○
How comfortable feels the contact between the material of the HoneyPad head water bolus and your skin?	○	○	○	○	○
How comfortable feels the contact between the material of the HoneyPad larynx water bolus and your skin?	○	○	○	○	○

	--	-	-+	+	++
Shape Stability					
How would you rate the stability of the HyperCollar3D water bolus shape during handling?	○	○	○	○	○
How would you rate the stability of the HoneyPad water bolus shape during handling?	○	○	○	○	○
Connecting Effort	--	-	-+	+	++
How convenient is the velcro connection between the HyperCollar3D water bolus and the equipment?	○	○	○	○	○
How convenient is the sliding connection between the HoneyPad water bolus and the equipment?	○	○	○	○	○
Connection Durability	--	-	-+	+	++
How durable is in your opinion the velcro connection between the HyperCollar3D water bolus and the equipment?	○	○	○	○	○
How durable is in your opinion the sliding connection between the HoneyPad water bolus and the equipment?	○	○	○	○	○
Appearance	--	-	-+	+	++
How friendly and reliable does the HyperCollar3D water bolus appear to you?	○	○	○	○	○
How friendly and reliable does the HoneyPad water bolus appear to you?	○	○	○	○	○

Remarks:

H | User Evaluation Results

Name: Daniël de Jong

Function: Klinisch Fysisch Medewerker

	--	-	-+	+	++
Comfort					
How would you rate the overall comfort of the HyperCollar3D (regular) water bolus?	○	○	○	◉	○
How would you rate the overall comfort of the HoneyPad (redesigned) head water bolus?	○	○	○	◉	○
How would you rate the overall comfort of the HoneyPad (redesigned) larynx water bolus?	○	○	○	◉	○
Pressure Points					
How would you rate the comfort regarding pressure points on your skin in the HyperCollar3D water bolus?	○	○	○	◉	○
How would you rate the comfort regarding pressure points on your skin in the HoneyPad head water bolus?	○	○	○	◉	○
How would you rate the comfort regarding pressure points on your skin in the HoneyPad larynx water bolus?	○	○	○	◉	○
Breathing					
How would you rate the comfort of breathing in the HyperCollar3D water bolus?	○	◉	○	○	○
How would you rate the comfort of breathing in the HoneyPad head water bolus?	○	○	◉	○	○
How would you rate the comfort of breathing in the HoneyPad larynx water bolus?	○	○	◉	○	○
Material					
How comfortable feels the contact between the material of the HyperCollar3D water bolus and your skin?	○	○	○	◉	○
How comfortable feels the contact between the material of the HoneyPad head water bolus and your skin?	○	○	○	◉	○
How comfortable feels the contact between the material of the HoneyPad larynx water bolus and your skin?	○	○	○	◉	○

Shape Stability

	--	-	-+	+	++
How would you rate the stability of the HyperCollar3D water bolus shape during handling?	○	○	◉	○	○
How would you rate the stability of the HoneyPad water bolus shape during handling?	○	○	○	○	○

n.v.t.

Connecting Effort

	--	-	-+	+	++
How convenient is the velcro connection between the HyperCollar3D water bolus and the equipment?	○	◉	○	○	○
How convenient is the sliding connection between the HoneyPad water bolus and the equipment?	○	○	◉	○	○

Connection Durability

	--	-	-+	+	++
How durable is in your opinion the velcro connection between the HyperCollar3D water bolus and the equipment?	◉	○	○	○	○
How durable is in your opinion the sliding connection between the HoneyPad water bolus and the equipment?	○	○	○	◉	○

Appearance

	--	-	-+	+	++
How friendly and reliable does the HyperCollar3D water bolus appear to you?	○	○	○	◉	○
How friendly and reliable does the HoneyPad water bolus appear to you?	○	○	○	◉	○

Remarks:

put a sign/marker to see what is bottom/top and left/right.

HoneyPad Evaluation Form

Name: Ali

Function: KFM

	--	-	-+	+	++
Comfort					
How would you rate the overall comfort of the HyperCollar3D (regular) water bolus?	○	○	○	⊗	○
How would you rate the overall comfort of the HoneyPad (redesigned) head water bolus?	○	○	○	⊗	○
How would you rate the overall comfort of the HoneyPad (redesigned) larynx water bolus?	○	○	○	⊗	○
Pressure Points	--	-	-+	+	++
How would you rate the comfort regarding pressure points on your skin in the HyperCollar3D water bolus?	○	○	○	⊗	○
How would you rate the comfort regarding pressure points on your skin in the HoneyPad head water bolus?	○	○	○	⊗	○
How would you rate the comfort regarding pressure points on your skin in the HoneyPad larynx water bolus?	○	○	○	⊗	○
Breathing	--	-	-+	+	++
How would you rate the comfort of breathing in the HyperCollar3D water bolus?	○	○	⊗	○	○
How would you rate the comfort of breathing in the HoneyPad head water bolus?	○	○	○	⊗	○
How would you rate the comfort of breathing in the HoneyPad larynx water bolus?	○	○	○	⊗	○
Material	--	-	-+	+	++
How comfortable feels the contact between the material of the HyperCollar3D water bolus and your skin?	○	○	○	⊗	○
How comfortable feels the contact between the material of the HoneyPad head water bolus and your skin?	○	○	○	⊗	○
How comfortable feels the contact between the material of the HoneyPad larynx water bolus and your skin?	○	○	○	⊗	○

Shape Stability

	--	-	-+	+	++
How would you rate the stability of the HyperCollar3D water bolus shape during handling?	○	○	⊗	○	○
How would you rate the stability of the HoneyPad water bolus shape during handling?	○	○	○	○	⊗

Connecting Effort

	--	-	-+	+	++
How convenient is the velcro connection between the HyperCollar3D water bolus and the equipment?	○	○	○	⊗	○
How convenient is the sliding connection between the HoneyPad water bolus and the equipment?	○	○	○	○	⊗

Connection Durability

	--	-	-+	+	++
How durable is in your opinion the velcro connection between the HyperCollar3D water bolus and the equipment?	○	⊗	○	○	○
How durable is in your opinion the sliding connection between the HoneyPad water bolus and the equipment?	○	○	○	○	⊗

Appearance

	--	-	-+	+	++
How friendly and reliable does the HyperCollar3D water bolus appear to you?	⊗	○	○	○	○
How friendly and reliable does the HoneyPad water bolus appear to you?	○	○	○	○	⊗

Remarks:

The impression about Comfort, Pressure, Breathing and material is based on using only one boulus. It may change when the head is completely in the applicator.

HoneyPad Evaluation Form

Name: Kemal Stimser

Function: Researcher in Training

	--	-	-+	+	++
Comfort					
How would you rate the overall comfort of the HyperCollar3D (regular) water bolus?	○	(X)	○	○	○
How would you rate the overall comfort of the HoneyPad (redesigned) head water bolus?	○	○	(X)	○	○
How would you rate the overall comfort of the HoneyPad (redesigned) larynx water bolus?	○	○	○	(X)	○
Pressure Points	--	-	-+	+	++
How would you rate the comfort regarding pressure points on your skin in the HyperCollar3D water bolus?	○	(X)	○	○	○
How would you rate the comfort regarding pressure points on your skin in the HoneyPad head water bolus?	○	○	○	(X)	○
How would you rate the comfort regarding pressure points on your skin in the HoneyPad larynx water bolus?	○	○	○	(X)	○
Breathing	--	-	-+	+	++
How would you rate the comfort of breathing in the HyperCollar3D water bolus?	○	(X)	○	○	○
How would you rate the comfort of breathing in the HoneyPad head water bolus?	○	○	○	(X)	○
How would you rate the comfort of breathing in the HoneyPad larynx water bolus?	○	○	○	(X)	○
Material	--	-	-+	+	++
How comfortable feels the contact between the material of the HyperCollar3D water bolus and your skin?	○	○	(X)	○	○
How comfortable feels the contact between the material of the HoneyPad head water bolus and your skin?	○	○	(X)	○	○
How comfortable feels the contact between the material of the HoneyPad larynx water bolus and your skin?	○	○	(X)	○	○

Shape Stability

	--	-	-+	+	++
How would you rate the stability of the HyperCollar3D water bolus shape during handling?	○	⊗	○	○	○
How would you rate the stability of the HoneyPad water bolus shape during handling?	○	○	○	○	⊗

Connecting Effort

	--	-	-+	+	++
How convenient is the velcro connection between the HyperCollar3D water bolus and the equipment?	○	○	⊗	○	○
How convenient is the sliding connection between the HoneyPad water bolus and the equipment?	○	○	○	○	⊗

Connection Durability

	--	-	-+	+	++
How durable is in your opinion the velcro connection between the HyperCollar3D water bolus and the equipment?	○	○	⊗	○	○
How durable is in your opinion the sliding connection between the HoneyPad water bolus and the equipment?	○	○	○	⊗	○

Appearance

	--	-	-+	+	++
How friendly and reliable does the HyperCollar3D water bolus appear to you?	○	⊗	○	○	○
How friendly and reliable does the HoneyPad water bolus appear to you?	○	○	○	⊗	○

Remarks:

HoneyPad Evaluation Form

Name: Audrey

Function: KFM

	--	-	-+	+	++
Comfort					
How would you rate the overall comfort of the HyperCollar3D (regular) water bolus?	○	○	○	⊗	○
How would you rate the overall comfort of the HoneyPad (redesigned) head water bolus?	○	○	○	⊕	○
How would you rate the overall comfort of the HoneyPad (redesigned) larynx water bolus?	○	○	⊕	⊕	○
Pressure Points	--	-	-+	+	++
How would you rate the comfort regarding pressure points on your skin in the HyperCollar3D water bolus?	○	○	○	⊕	○
How would you rate the comfort regarding pressure points on your skin in the HoneyPad head water bolus?	○	○	⊕	○	○
How would you rate the comfort regarding pressure points on your skin in the HoneyPad larynx water bolus?	○	○	⊕	○	○
Breathing	--	-	-+	+	++
How would you rate the comfort of breathing in the HyperCollar3D water bolus?	○	○	○	○	⊕
How would you rate the comfort of breathing in the HoneyPad head water bolus?	○	○	○	○	⊕
How would you rate the comfort of breathing in the HoneyPad larynx water bolus?	○	○	○	○	⊗
Material	--	-	-+	+	++
How comfortable feels the contact between the material of the HyperCollar3D water bolus and your skin?	○	○	○	○	⊕
How comfortable feels the contact between the material of the HoneyPad head water bolus and your skin?	○	○	○	⊕	○
How comfortable feels the contact between the material of the HoneyPad larynx water bolus and your skin?	○	○	○	⊕	○

Shape Stability

	--	-	-+	+	++
How would you rate the stability of the HyperCollar3D water bolus shape during handling?	○	○	⊕	○	○
How would you rate the stability of the HoneyPad water bolus shape during handling?	○	○	○	○	⊕

Connecting Effort

	--	-	-+	+	++
How convenient is the velcro connection between the HyperCollar3D water bolus and the equipment?	○	○	○	○	⊕
How convenient is the sliding connection between the HoneyPad water bolus and the equipment?	○	○	○	○	⊕

Connection Durability

	--	-	-+	+	++
How durable is in your opinion the velcro connection between the HyperCollar3D water bolus and the equipment?	○	○	○	⊕	○
How durable is in your opinion the sliding connection between the HoneyPad water bolus and the equipment?	○	○	○	○	⊗

Appearance

	--	-	-+	+	++
How friendly and reliable does the HyperCollar3D water bolus appear to you?	○	○	⊕	○	○
How friendly and reliable does the HoneyPad water bolus appear to you?	○	○	○	⊕	○

Remarks:

HoneyPad Evaluation Form

Name: Tomas Drizdal

Function: PhD student

Comfort

	--	-	-+	+	++
How would you rate the overall comfort of the HyperCollar3D (regular) water bolus?	○	○	⊗	○	○
How would you rate the overall comfort of the HoneyPad (redesigned) head water bolus?	○	○	○	⊗	○
How would you rate the overall comfort of the HoneyPad (redesigned) larynx water bolus?	○	○	○	⊗	○

Pressure Points

	--	-	-+	+	++
How would you rate the comfort regarding pressure points on your skin in the HyperCollar3D water bolus?	○	⊗	○	○	○
How would you rate the comfort regarding pressure points on your skin in the HoneyPad head water bolus?	○	○	○	⊗	○
How would you rate the comfort regarding pressure points on your skin in the HoneyPad larynx water bolus?	○	○	○	⊗	○

Breathing

no idea from ~~the~~ just attached empty bolus

	--	-	-+	+	++
How would you rate the comfort of breathing in the HyperCollar3D water bolus?	○	○	○	○	○
How would you rate the comfort of breathing in the HoneyPad head water bolus?	○	○	○	○	○
How would you rate the comfort of breathing in the HoneyPad larynx water bolus?	○	○	○	○	○

Material

	--	-	-+	+	++
How comfortable feels the contact between the material of the HyperCollar3D water bolus and your skin?	○	○	○	⊗	○
How comfortable feels the contact between the material of the HoneyPad head water bolus and your skin?	○	○	⊗	○	○
How comfortable feels the contact between the material of the HoneyPad larynx water bolus and your skin?	○	○	⊗	○	○

Shape Stability

	--	-	-+	+	++
How would you rate the stability of the HyperCollar3D water bolus shape during handling?	○	⊗	○	○	○
How would you rate the stability of the HoneyPad water bolus shape during handling?	○	○	○	⊗	○

Connecting Effort

	--	-	-+	+	++
How convenient is the velcro connection between the HyperCollar3D water bolus and the equipment?	○	○	⊗	○	○
How convenient is the sliding connection between the HoneyPad water bolus and the equipment?	○	○	⊗	○	○

Connection Durability

	--	-	-+	+	++
How durable is in your opinion the velcro connection between the HyperCollar3D water bolus and the equipment?	○	○	⊗	○	○
How durable is in your opinion the sliding connection between the HoneyPad water bolus and the equipment?	○	○	○	⊗	○

Appearance

again don't know how to judge this without connecting it to the real device

	--	-	-+	+	++
How friendly and reliable does the HyperCollar3D water bolus appear to you?	○	○	○	○	○
How friendly and reliable does the HoneyPad water bolus appear to you?	○	○	○	○	○

Remarks: