# ERGONOMIC WATER BOLUS DESIGN

For Hyperthermia Treatment of Head and Neck Cancer Patients

Master thesis by Marie Beljaars
Delft University of Technology - 2021

Erasmus MC
University Medical Center Rotterdam

TU Delft

# ERGONOMIC WATER BOLUS DESIGN

## For Hyperthermia Treatment of Head and Neck Cancer Patients

### Master thesis

July 2021
Master Integrated Product Design
Industrial Design Engineering
Delft University of technology


### Author

Marie Beljaars

### Erasmus MC Cancer institute

Hyperthermia Unit, Radiation Oncology Department
Zimmermanweg 11
3015 CP Rotterdam
+31 10 704 0704

Project coach: Dr. K. Sumser
Unit Hyperthermia, Radiotherapy Department

### Delft University of Technology

Faculty of Industrial Design Engineering
Landbergstraat 15
2628 CE Delft
+31 15 278 9807

Project chair: Prof. dr. ir. K.M.B. Jansen
Department of Sustainable Design Engineering
Emerging Materials

Project mentor: Dr. T. Huysmans
Department of Human-Centered Design
Applied Ergonomics & Design

# ACKNOWLEDGEMENTS

By finalizing this master thesis I have reached the end of two inspiring years at TUDelft. During this thesis I got a lot of support and encouragement from people around me. I would like to take this opportunity  to thank everyone who helped me in the process..

First of all, I want to thank my supervisory team: Kaspar, I would like to thank you for your advice, input and regular check-ins at applied labs. Your expertise on materials and cooling really helped me to achieve better results. Toon, I want to thank you for giving advice, for sharing your knowledge on ergonomics and anthropometrics, giving lots of input on delivered work and directing me towards interesting software and approaches for ergonomic research.

I would also like to thank the team from Erasmus MC, for giving me the opportunity and a lot of freedom to work on this project. Thank you Kemal, for always being ready to help me out. Thanks to you I was able to do a lot of different tests at the hospital and to get a better understanding of all factors at play during hyperthermia treatment. Gerard, thank you for your input, giving me valuable insights and connecting me to the right people when needed.
In addition, I would like to thank the technical staff, especially Arjan and  Melanie for giving me a more practical view on the water bolus production and its issues and helping me out with materials, equipment and practical tips to make the bolus watertight.

Lastly, I want to thank my friends and family for showing interest in the project, offering advice or just listening whenever needed.

# EXECUTIVE SUMMARY

Hyperthermia (HT) is a cancer treatment that is generally used in combination with chemotherapy or radiotherapy. During this therapy, electromagnetic energy is used to elevate the temperature of a tumour to 40–44 °C for 60–90 minutes. This process makes the tumorous cells more sensitive to radiation and chemotherapy.

Deep hyperthermia treatment of head and neck cancers is usually administered for recurring tumours. Patients with recurrent head and neck cancer have a 2-year survival rate of only 10-20 % when retreated with chemotherapy and radiotherapy. Furthermore, toxic side-effects of these therapies are even more severe after re-treatment. Hyperthermia treatment can be a good solution for these problems, but currently, there is a lack of deep heating equipment for neck and head.

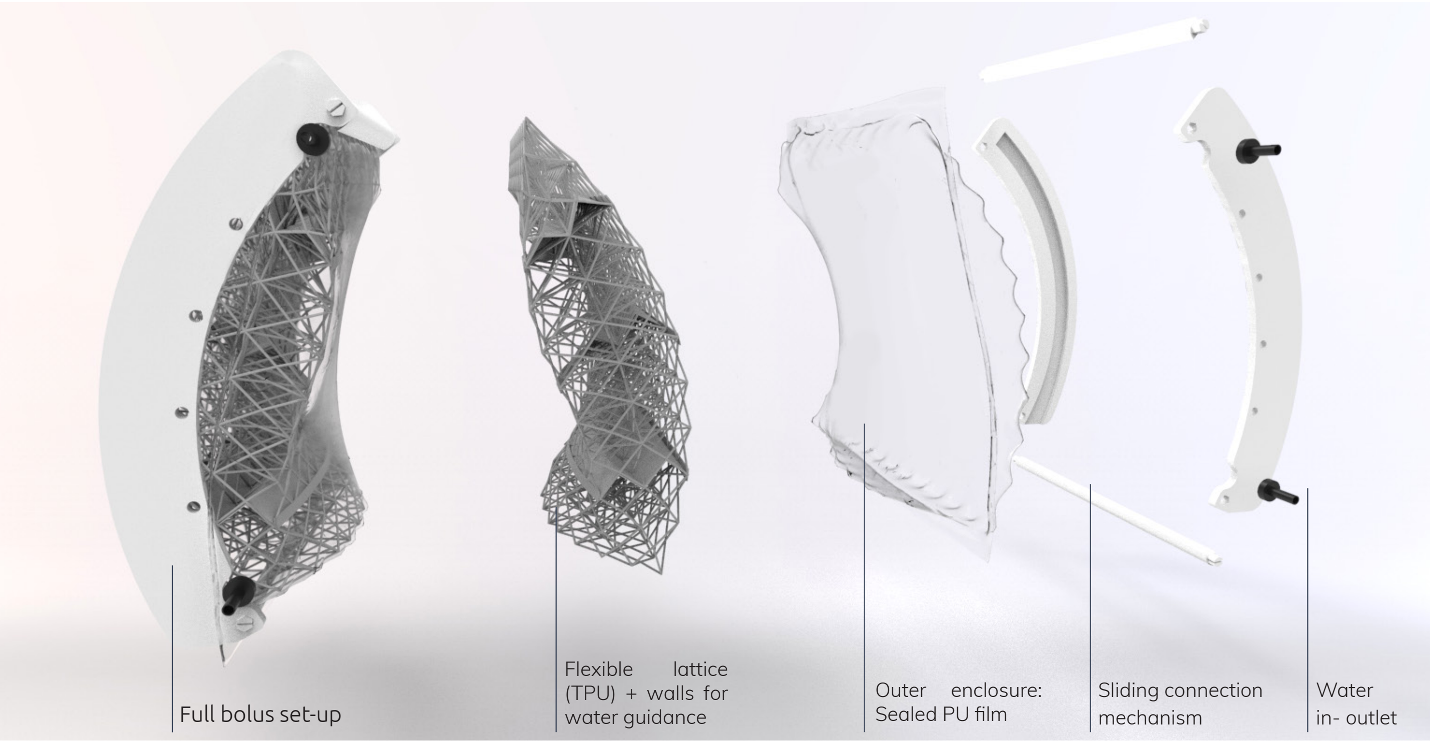
After two iterations, Erasmus MC has recently developed a novel MR compatible head and neck hyperthermia applicator (MRcollar). A water bolus needs to be placed between the applicator and the patient's skin to act as a cooling agent to prevent skin burns and as a transferring agent to conduct the electromagnetic energy to the internal tumour tissue. However, there is no water bolus developed yet to be used in this applicator. Therefore, this thesis project is focused on developing a bolus for the MRcollar.

By analysing the treatment context, the previous applicators and boli and talking to stakeholders, the main challenges for this project could be defined. The bolus should be comfortable for the patients. For example, the pressure on the skin should be minimized, there should be enough space for breathing and seeing in order to reduce any claustrophobic sensations. The cooling must be effective and uniform throughout the bolus volume. Furthermore, the shape of the bolus should be stable, predictable and reproducible to efficiently simulate the treatment. The bolus should function in the MRcollar, not disrupting electromagnetic waves or MR imaging and being watertight. Lastly, the bolus should be easy to install by the clinicians.

Different ideas and concepts were generated based on these challenges, after which it was decided to make the bolus out of a flexible 3D printed inner structure, surrounded by a plastic film. This concept was further detailed, tested and improved during the embodiment phase with a main focus on creating an anthropometric fit, good water flow, flexibility and stability and creating a watertight enclosure.

The final design, which can be seen below, is a flexible, 3d printed lattice structure with implemented water channels to guide the water flow that is designed to follow the shape of the head. The bolus is made watertight by gluing and sealing a plastic film around the structure.

This design was validated and found to be successful on all the previously mentioned challenges. However, there are still opportunities for improvement, which are stated in the recommendations section.



# TABLE OF CONTENTS

# INTRODUCTION

## Context

In the Erasmus MC – Cancer Institute Hyperthermia unit, patients with cancer are being treated by raising tumour temperatures to the range of 40 - 44°C for 60-90 minutes. This process, named hyperthermia treatment, aims to improve sensitivity to radio- or chemotherapy and is used to treat around 150 new patients each year. Recently within the hyperthermia unit, a novel MR compatible head and neck hyperthermia applicator (MRcollar) was designed and developed. Electromagnetic energy is applied from this applicator that is placed around the patient's head or neck. A water bolus needs to be 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. In this thesis a water bolus for this new applicator will be designed to optimize cooling and patient comfort.

## Problem definition

An ergonomic and effective water bolus is crucial for successful hyperthermia treatment. However, currently there is no water bolus developed yet to be used in the new applicator.
For effective treatment, we rely on an accurate, reproducible and stable positioning of the water bolus that provides cooling on the patient skin and energy conduction between the MRcollar applicator and the patient. The water bolus should ergonomically follow the patient's contours to ensure good contact with the skin of the patient for adequate cooling and power transfer. Further, the water flow should reach the full volume of the bolus to ensure proper cooling in all areas. Furthermore, the design 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.

## Assignment

The aim of this thesis is to develop, prototype and test an ergonomic water bolus for hyperthermia treatment of head and neck. The end goal is to have a working prototype which could be used for research purposes. This will be approached by analysing the context and formulating needs and constraints, developing a conceptual design of a water bolus, manufacturing and testing of proof-of-concept set-ups and finally evaluating the new design by volunteer experiments.

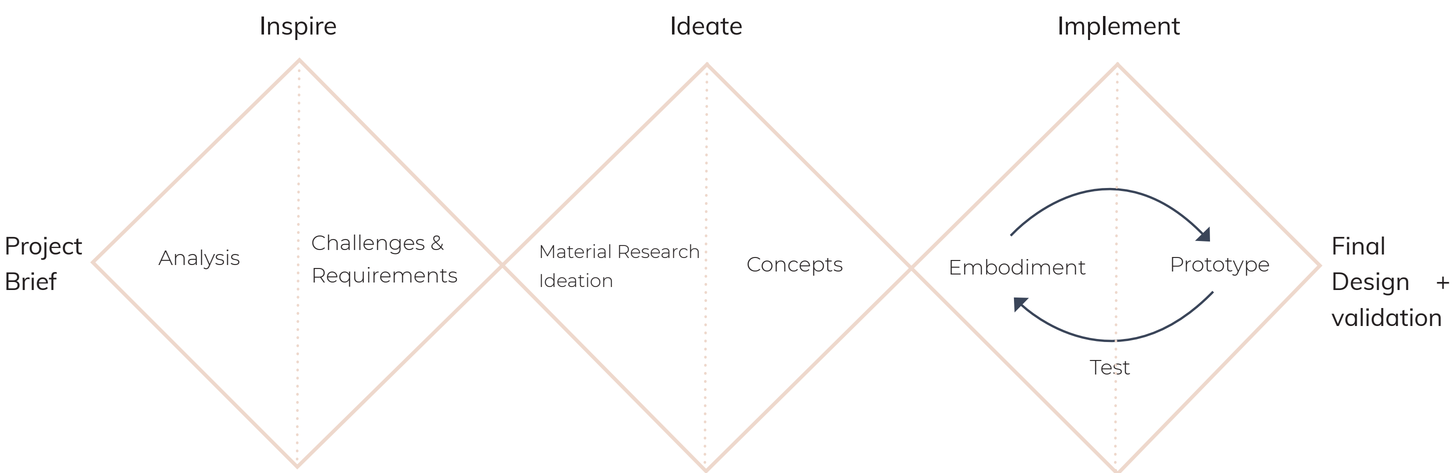
# APPROACH

Throughout this project, a triple diamond approach was used consisting out of three main phases: Inspire, Ideate and Implement. In the first phase, an analysis of the context, hyperthermia treatment, equipment and stakeholders was made. The findings of this analysis could be converged into challenges and requirements for the project.

With these challenges in mind the ideate phase could start, where research to possible solutions was done and different ideas were generated. A selection of these ideas was made and transformed into three and later two concepts.

In the last, implementation phase the concepts were developed in more detail. Different prototypes were made, tested and improved before arriving to a final design iteration.

At the end of this thesis the final design is presented and validated after which recommendations for future development are made.



# 1 ANALYSIS

To get a deeper understanding of all factors at play regarding deep hyperthermia of head and neck, and to be able to define the main goals for this project, an analysis of the context around hyperthermia treatment at Erasmus MC was carried out. The main focus points of this analysis were the basic working principles of hyperthermia, the treatment procedure for patients with head and neck tumours, the equipment and boli that were used throughout the development process and the stakeholder concerns. The insights gained during the analysis phase could then be translate into challenges and requirements which will serve as a guideline throughout the project.

# 1.1 HYPERTHERMIA

## What is hyperthermia?

Hyperthermia (HT) is a cancer treatment that is generally used in combination with chemotherapy or radiotherapy. During this therapy, the temperature of a tumour is elevated to 40–44 °C for 60–90 minutes to make its cells more sensitive to radiation and chemotherapy.

Because of the physiological difference between healthy and tumour tissue, only the tumour cells are being sensitized at this temperature, while surrounding healthy cells remain mostly undamaged (van der Zee, 2002). Usually, HT is applied 60 minutes before or after radiotherapy, while it is applied simultaneously with or briefly after chemotherapy. (Paulides et al., 2020)

Hyperthermia improves blood flow in the treatment area. As a result, the cancer cells receive more oxygen. It also prevents damaged cancer cells from regenerating after chemotherapy or radiotherapy. Lastly, it makes it easier for the immune system to recognise and clear away cancer cells. All these factors combined make the tumour more susceptible to treatment with radiation or chemotherapy. (Hyperthermie Bij Kanker, 2018; Paulides et al., 2020)

Various clinical trials have proved that the addition of hyperthermia to radiotherapy results in remarkably higher tumour control rates which translates into enhanced overall survival (Horsman & Overgaard, 2007). Additionally, hyperthermia positively influences the effectiveness of chemotherapy. No studies have found an increase in late toxicity, thus no long-term side-effects have been found caused by hyperthermia treatment. (M. Paulides et al., 2020).

Currently, three Dutch hospitals are offering hyperthermia treatment: Amsterdam UMC, Erasmus MC and Instituut Verbeeten. It is applied for the following tumour types:

- recurrent breast cancer in the previously radiated area
- cervical cancer
- melanoma
- soft tissue tumours
- recurrence of cancer in the small pelvis: rectal cancer, bladder cancer
- superficial bladder cancer
- ovarian cancer: in case of metastases in the peritoneum
- colorectal cancer: in case of metastases in the peritoneum
- head and neck cancer

(Hyperthermie Bij Kanker, 2018).

## Types of hyperthermia treatment

### Heating regions:

Hyperthermia can be applied locally, regionally or on the whole body.

#### Local hyperthermia

When the heat is applied to a small area of the body, containing only the tumour and the surrounding tissue, it is referred to as local hyperthermia. Local hyperthermia can be applied externally, by using applicators outside the body (see figure 1-2), or internally by positioning the applicators in a body cavity like the oesophagus or rectum (=Intracavitary, see figure 4) or by inserting a probe into the tumorous body tissue (=interstitial, see figure 3).

#### Regional hyperthermia

In the case of regional hyperthermia, the heat is applied to a larger body area such as an organ, a limb or a body cavity (see figure 5). A variety of different antennas and applicators can be used for generating the heat.

#### Whole-body hyperthermia

Whole-body hyperthermia can be used to treat metastatic cancer which has spread throughout the body. In this case the whole body is heated up to 39-40 °C for multiple hours (see figure 6). This treatment is currently only tested in clinical trials and not applied in The Netherlands.
(Paulides et al., 2020; Vormen van Hyperthermie, 2018)

## Heating approach

The tissue is heated to the desired temperature by exposing it to electromagnetic waves. Electromagnetic fields are a combination of electric and magnetic fields of force. When the electromagnetic waves reach the body tissue, they cause the polar molecules to rotate to keep up with the fast-changing field. This causes friction between the adjacent molecules which results in heating. (Technology – Sensius, n.d.)

To direct the electromagnetic (EM) energy to the tumour area, applicators are used. A water bolus is positioned between the applicators and the skin, to provide EM coupling between the antennas and the body and to avoid skin burns. Each antenna is then programmed to the optimal phase, frequency and amplitude to provide constructive wave interference and selectively heat the target area.

Higher frequencies will generally reach superficial areas, while lower frequencies can penetrate deeper into the body. By increasing the number of antennas, the waves can reach deeper located areas and the steering capabilities of the antennas are improved.

### Superficial hyperthermia

The type of hyperthermia treatment that is mostly used in clinical practice is localized heating of superficial tumours. This technique can be used for tumours of limited volume, which are located up to 4 cm underneath the skin. Higher microwave frequencies (400-1000Mhz) are used to generate local heating of the skin and superficial tissues. Large tumours can be heated by combining multiple antennas where each element can be controlled independently.

### Deep hyperthermia

The goal of deep hyperthermia is to concentrate heat in the tumour area, without raising the temperature of the surrounding healthy tissue to high levels. This treatment is used for tumours that are positioned more than 4 cm under the skin. The aimed temperature is mostly best achieved with a phased approach, where a set of antennas is placed circumferential around the patient. Each antenna can then be adapted independently to the desired amplitude, phase and frequency to selectively heat the target area (M. Paulides et al., 2020).

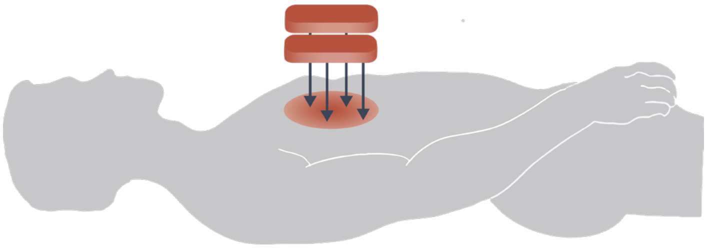


*Fig. 1: Superficial - Local hyperthermia treatment*

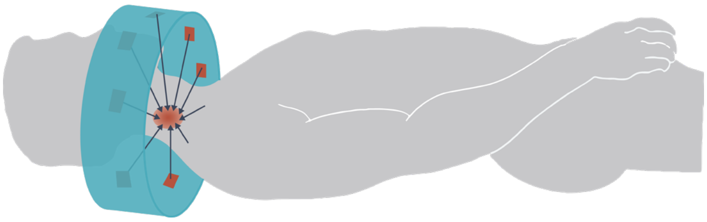


*Fig. 2: Deep - Local hyperthermia treatment*

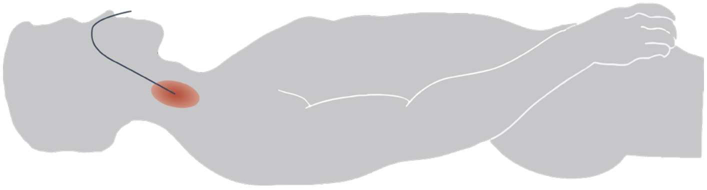


*Fig. 3: Deep - Interstitial hyperthermia treatment*

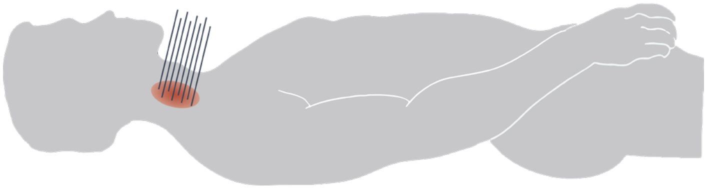


*Fig. 4: Deep - Intracavitary hyperthermia treatment*

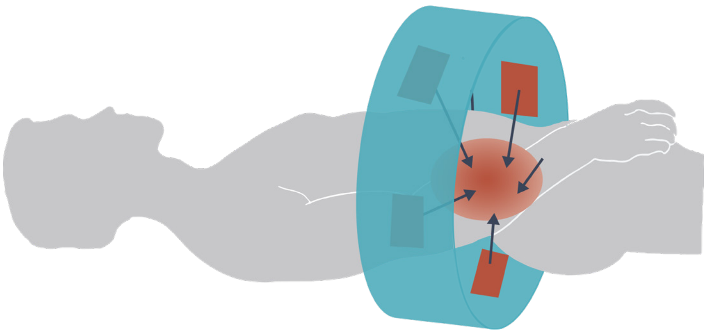


*Fig. 5: Deep - Regional hyperthermia treatment*

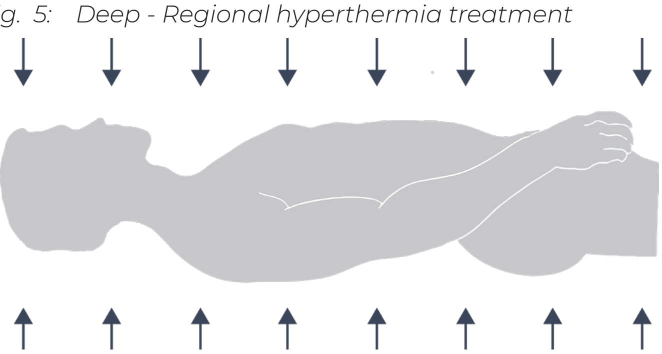


*Fig. 6: Whole-body hyperthermia treatment*

# Hyperthermia of head and neck tumours

In this project, the focus is on hyperthermia treatment of head and neck tumours which can be categorized within deep, local Hyperthermia.

Patients with recurrent head and neck cancer have a 2-year survival rate of only 10-20 % when retreated with chemotherapy and radiotherapy. Furthermore, toxic side-effects of these therapies are even more severe after re-treatment, causing life-threatening events and death in more than 30 per cent of cases. (Common Toxicity Criteria Manual, 1999; Paulides et al., 2016). Thus, there is a need for new, optimized treatment options. Hyperthermia treatment can be a good solution for these problems, but currently, there is a lack of deep heating equipment for neck and head. That is why Erasmus MC is developing an applicator for deep, targeted heating of these areas. (Paulides et al., 2007)

## Head and neck cancer

With 51 540 new cases and 10 030 deaths in the US, head and neck cancer was the seventh most diagnosed type of cancer worldwide in 2018. Typically, head and neck cancer is diagnosed in older patients and associated with heavy tobacco and alcohol use. Partially because of decreasing tobacco use, neck cancers are slowly declining globally (Chow, 2020). Men are three times more likely to suffer from head and neck cancer than women (Marur & Forastiere, 2008).

Most head and neck cancers (>90%) are of squamous cell histology and are found in the lip/oral cavity, nasopharynx, oropharynx, hypopharynx, and the larynx (See figure 7).
About 30-40 pe rcent of patients are diagnosed with stage I or II disease: smaller tumours without lymph node involvement. These tumours can be cured by radiotherapy or surgery alone and are associated with survival rates of 70 to 90 per cent.

More than 60 per cent of head and neck cancer patients are diagnosed with stage III or IV disease: larger tumours with local invasion and/or metastases to regional nodes. These types of cancers have a recurrence-rate of 15-40 per cent and an overall 5-year survival rate of less than 50 per cent. (Chow, 2020).

## Deep hyperthermia treatment of head and neck tumours

Deep Hyperthermia treatment can be administered for tumours in all areas displayed in figure 7. Usually this treatment is used for patients with stage III and IV disease who became unresponsive to chemo- and radiotherapy. Clinical trials show that a significantly better tumour control can be achieved after a combination of hyperthermia-treatment and chemo- or radiotherapy (Paulides et al., 2016).

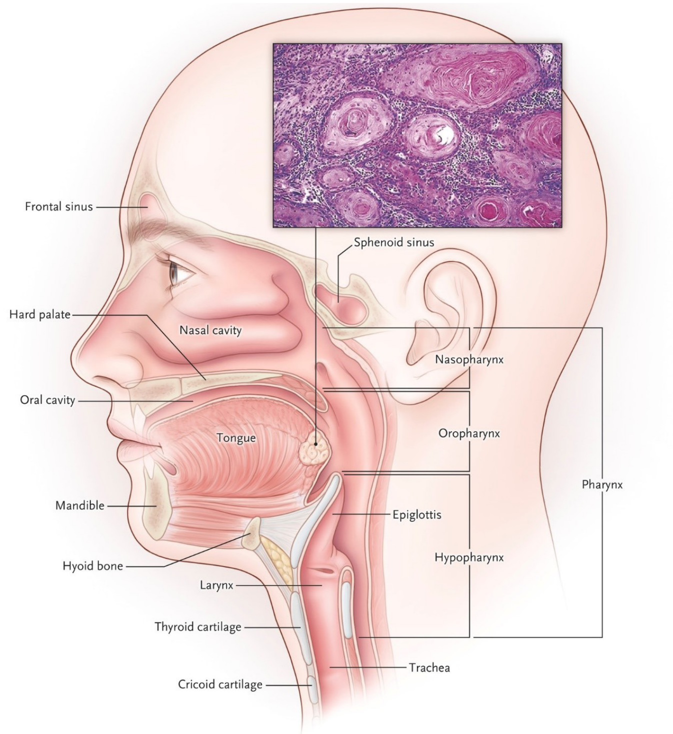



*Fig. 7: Major Anatomical Sites of Squamous-Cell Carcinoma of the Head and Neck. (Chow, 2020)*

# 1.2 TREATMENT PROCEDURE

## Patient's perspective

### Intake

Before the hyperthermia treatment can take place, the patient comes to the hospital for an intake appointment. During this appointment, the technician positions the patient in the applicator. The applicator can be translated in X-,Y- and Z- direction and can be rotated forwards and backwards (see figure 8). Also, the position of the headrest can be adapted to optimize patient comfort. The values of these different parameters are usually chosen based on eyesight and previous experience of the technician and are registered for later use in the treatment planning (see next page). Because all head and neck hyperthermia patients are also undergoing radiotherapy sessions, CT scans of the patient will already be available for the clinicians and technicians.

### Treatment preparation

The treatment will take place within 2-4 hours after radiotherapy. The patient is positioned in the applicator in the same way as during the intake appointment. In some cases, catheters for temperature monitoring are inserted into the patient's tissue. The patient stays awake during treatment and can communicate with the technician. (Bijwerkingen En Klachten van Oppervlakkige Hyperthermie, 2018; Erasmus MC - Patiëntfolder: Diepe Hyperthermie, n.d.; Vormen van Hyperthermie, 2018)

### Treatment

The target area will be heated to 40-44 degrees Celsius using electromagnetic energy, this will cause the overall body temperature to rise 0,2-0,3 degrees Celsius. The patient will react to this rise in temperature by an increased heartbeat, sweating and turning red. The clinician can provide cooling in terms of air-conditioning, cold towels or cold packs. It takes a maximum of 30 minutes to heat the target area to the desired temperature, afterwards it is aimed to keep this temperature level for 60 minutes (see figure 9).

During the treatment, the temperature distribution is closely monitored by the thermometers inserted in the tissue (HYPERcollar3D) or by using MR imaging for temperature readings (MRcollar). Additionally, the patient will be asked for feedback on possible uncomfortable areas. If a certain area becomes too hot or uncomfortable, the simulation will be re-optimized and treatment properties will be adjusted to avoid hotspots.

After the treatment, the thermometers will be removed, the patient can take a shower and can go home. Usually hyperthermia sessions are administered once a week for 3-6 weeks. (Bijwerkingen En Klachten van Oppervlakkige Hyperthermie, 2018; Erasmus MC - Patiëntfolder: Diepe Hyperthermie, n.d.; Vormen van Hyperthermie, 2018)

### Possible side effects

Hyperthermia treatment can cause skin burns, this is tried to be avoided by the water bolus cooling. The heat can also cause burns in deeper fat tissue when the temperature during treatment is too high. This happens to 1 in 10 patients at most. These areas can feel sensitive or painful for a few months. Occasionally a burn occurs in muscle tissue, this causes muscle aches. In case of HT in head and neck, these aches usually occur in the jaw muscle. The pain will disappear after a few days to weeks. After the treatment, the patient can feel tired and lifeless. This feeling occurs mainly on the day of treatment and the day after. Lastly, sometimes the catheters inserted in the tissue are not removed in between treatments. This can cause redness, inflammation, loss of fluid past the catheters and an overall uncomfortable feeling. The catheters can be removed if these complaints arise. (Bijwerkingen En Klachten van Oppervlakkige Hyperthermie, 2018)

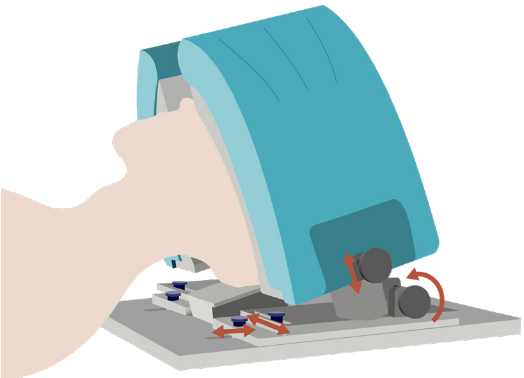


*Fig. 8: Positioning of patient in Applicator*

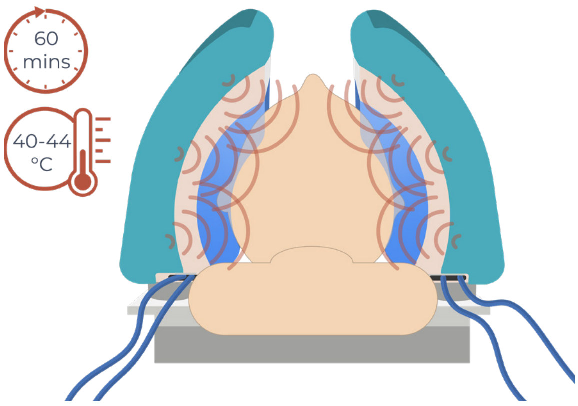



*Fig. 9: Hyperthermia of head and neck treatment*

# Technician's perspective

## Pre treatment: Hyperthermia treatment planning

Before the Hyperthermia treatment can be applied, patient-specific hyperthermia treatment planning (HTP) is performed to predict and optimize the treatment performance.

By using HTP, an optimal treatment plan can be created for every single patient, maximizing the thermal dose in the tumour but minimizing possible hotspots. HTP is a powerful decision-making tool for clinicians, which allows them to evaluate the (in)ability to heat the tumour and to make real-time adaptions during treatment, responding to patients complaints (Paulides et al., 2020).

The treatment planning works as follows:

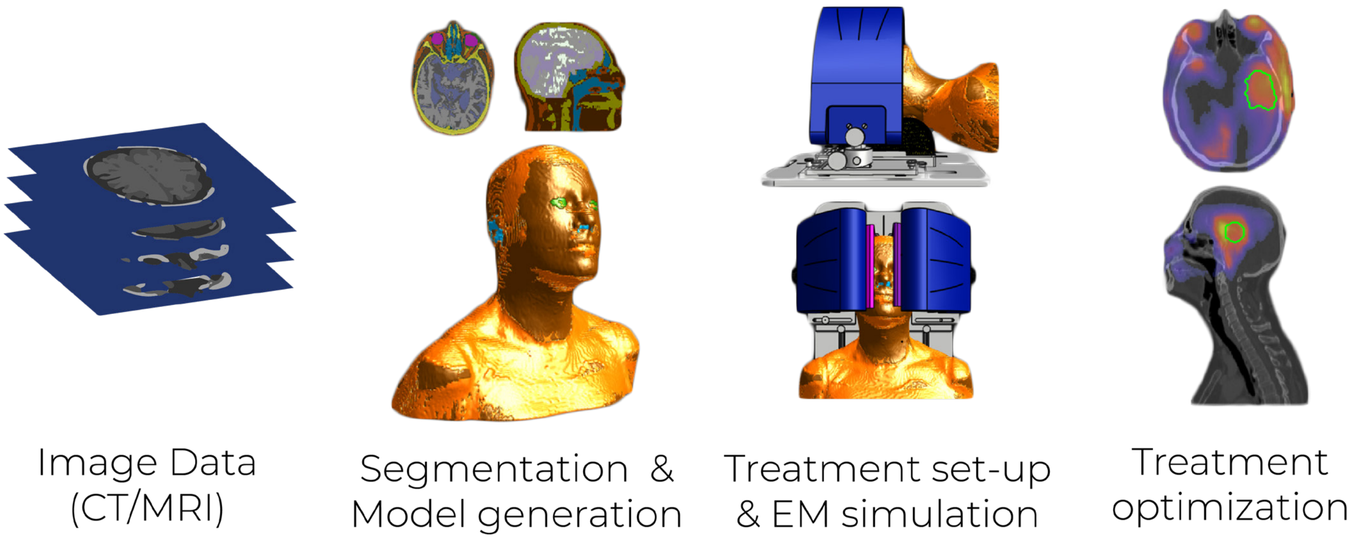



*Fig. 10: Hyperthermia treatment planning*

### Image Data (CT/MRI)

CT scans of the patient are already available for use in the treatment planning since the patient is also undergoing radiotherapy. These CT scans give sufficient information to use in the simulation software. In case of treatment with the MRcollar, MR images can also be used to import in the software.

### Segmentation and Model Generation

Segmentation algorithms are used to delineate different tissues. E.g. for deep HT, tissues can be classified as muscle, fat, bone, air and many more. After this, the model is discretised in voxels to prepare it for simulation.

### Treatment Setup & EM simulation

A digitized patient model, including the collar and water bolus, is created. The pre-defined X-, Y- Z- and rotation parameters are inserted in the model to replicate the real setting as closely as possible, dielectric and thermal properties are allocated to the different tissues. This includes physiological parameters like blood perfusion rate and metabolic heat generation rate. Additionally, the material properties of the applicator and the water bolus are assigned in the model.

Based on specific absorption rate (SAR), or more generally power density simulations, the temperature distribution can be predicted.

### Treatment optimization

The electrical field (power and phase) generated by each antenna is calculated as well as the distribution of energy disposition to maximize power delivery in the tumour while minimizing hotspots in the healthy tissue.

Usually, the same model is used for each session of the hyperthermia treatment. With the MRcollar it would be possible to recalculate the new optimized antenna settings based on the obtained images during treatment. This would provide the best possible scenario for each treatment day, the target areas would stay the same, but the field may need optimization. However, this technique is currently not yet developed well enough to be used in practice. (Paulides et al., 2020)

## During treatment: Temperature monitoring

Currently, two techniques are being explored for temperature monitoring: Simulation adaptive HT and MR adaptive HT:

### Simulation adaptive

The simulation adaptive approach (see fig. 11) is relatively cheap and is already being used in treatments with HYPERcollar3D. This technique is strongly relying on advanced planning software to carry out the hyperthermia treatment planning and perform guidance during treatment. Temperature can be monitored during treatment by a combination of on-skin, interstitial, intraluminal and/or intracavitary thermometry with the insights from the treatment planning. To place the thermometers inside the tissue, catheters are first inserted in which the thin, flexible temperature sensors can be positioned (Paulides et al., 2020). Current invasive thermometry techniques are limited to localized temperature monitoring and can cause serious discomfort to the patients. Therefore, 70 per cent of cases fully rely on treatment planning. (Rijnen et al., 2015)

### MR adaptive

The MR adaptive approach (see fig. 12) is a more advanced and precise technique, but is still in an early development stage and will most likely remain an approach for academic settings in the next decade. This approach will be used in combination with the MR collar. MR adaptive HT uses magnetic resonance thermometry (MRT) to monitor the temperature distribution during treatment. By using this approach; the patient positioning in the applicator can be verified, the evolution of the tumour during the course of the treatment can be monitored and physiological properties like blood perfusion can be visualized during therapy. All these factors are beneficial to avoid hotspots and for real-time adaptation of the treatment planning. However, currently, MR thermometry can not yet generate accurate enough temperature measurements to make the use of catheters redundant. (Paulides et al., 2020)

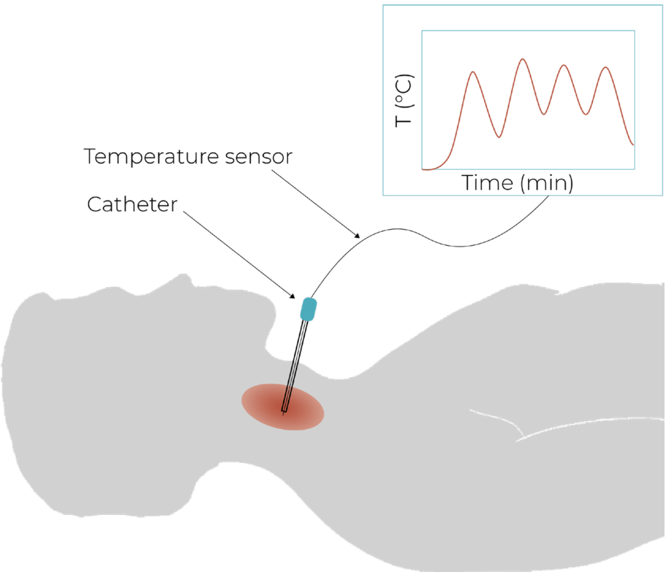



*Fig. 11: Simulation adaptive HT*

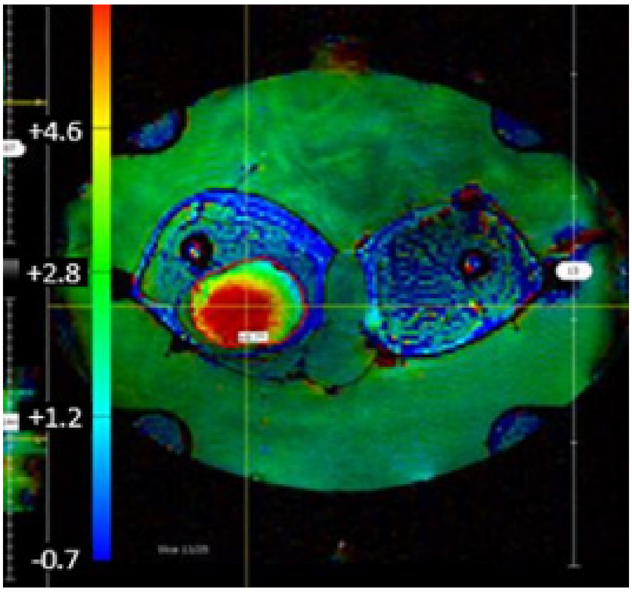



*Fig. 12: MR adaptive HT (Paulides et al., 2020)*

# 1.3 EQUIPMENT

The development of a Hyperthermia applicator for head and neck tumours by Erasmus MC has already gone through three iterations: HYPERcollar, HYPERcollar3D and MRcollar. However, the main components have remained the same. Each applicator consists out of an outer stiff shell, containing several antennas which will generate the EM energy and one or more water boli, through which water can circulate. The boli are needed to conduct the energy from applicator to skin as ell as to cool the antennas and the skin.

The working principles and issues of each iteration will be explained in more detail below.
In this thesis, the focus lays on designing the inner water bolus for implementation in the MRcollar. If the bolus design is working well, it can later also be applied in the HYPERcollar3D

## HYPERcollar

The first applicator developed by Erasmus MC for deep hyperthermia treatment of head and neck tumours was the HYPERcollar (see fig. 13). To design the HYPERcollar, an inversed approach was used: first, the target volume was defined and then theoretical modelling was used to design an applicator that would be able to heat this volume. The HYPERcollar consists out of one fully cylindrical device consisting of two rings (r = 20cm) of six antennas and 6 cm spacing between these rings. (Paulides et al., 2016)

One large water bolus is used to fill the space between the antennas and the patient's skin to guarantee transport of EM energy and to cool the skin. The water bolus is made out of inelastic polyurethane. The patient is positioned by sliding him into the cylindrical set-up. (Rijnen et al., 2015)

### Issues

The main problem of the HYPERcollar was that the water bolus properties and positioning of the patient were unstable and inaccurate over time, because of the large water volume and formation of folds. Additionally, the pressure of the bolus caused the head to be lifted upwards or to move. If the patient is not positioned in the same way as simulated in the treatment planning, a mismatch between HTP and clinical practice takes place. This can affect the quality of the treatment, since the target area won't be sufficiently covered as well as patient comfort, since hotspots might occur.

Additionally, completely surrounding the patient's face with the water bolus made it difficult for the patient to breath. A piece of tape was used to create breathing cavities, but these cavities were difficult to remain in shape and to reproduce in the following treatments.

Lastly, the temperature in the high water volume was difficult to control. During the filling of the bolus, big folds would form (see fig. 14), dividing the bolus into different sections, blocking water circulation and causing inhomogeneous cooling of both the skin and the antennas. (Rijnen et al., 2015)

*Fig. 13: HYPERcollar (Paulides et al., 2016)*

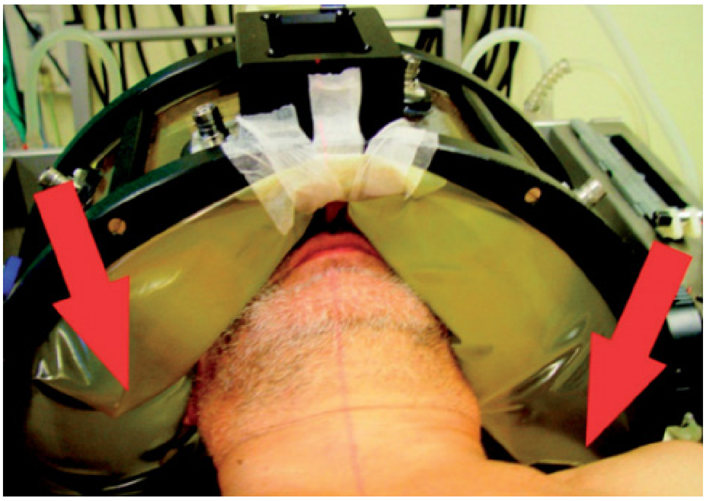


*Fig. 14: Folds in HYPERcollar (Rijnen et al., 2015)*

# HYPERcollar3D

The redesign of the HYPERcollar mainly focused on controllable and reproducible positioning of the patient. This new applicator, HYPERcollar3D (see fig. 15), consists out of two half rings that can be rotated independently to open or close the applicator after positioning the patient. Each half-ring contains an inner, flexible water bolus and an outer, rigid water bolus.

The outer bolus is a thick, rigid, transparent PMMA shell around the antennas. This shell will protect the antennas and a circulating water flow will provide cooling and allow for stable antenna behaviour.

The inner bolus is used to connect the outer shell and the skin. It consists out of open-cell, water-permeable polyether foam surrounded by a soft, elastic SEBS film on the skin side and a more stiff PP film on the applicator side. The inserted foam allows for more stable positioning of the head and avoids folds to occur while water can still circulate through the bolus.

To achieve more predictable and reproducible positioning of the head, the patient can be positioned on an adjustable headrest. Assisted by a sagittal and coronal laser set-up, this headrest can be used to fine-tune head position and rotation.

Lastly, an improved antenna arrangement was implemented in the new applicator to reduce hot spots. The HYPERcollar3D has 20 antennas, of which the 12 antennas that result in the most effective way of heating the target area are used during the treatment.
(Paulides et al., 2016; Rijnen et al., 2015)

## Improvements

By dividing the bolus into an outer and inner component, the inner, flexible bolus can be kept rather thin. The lower water volume provides more predictable and homogeneous cooling and reduces pressure on the patient's skin.

Because the applicator is now consisting out of two half rings, it is easier and comfortable to position the head for both the patient and the operator. Furthermore, a predictable and reproducible breathing gap can be provided between the two halves.
To conclude, the new water bolus design substantially improves the match between HTP and clinical practice.
(Rijnen et al., 2015)

## Issues

Even though this applicator is a big improvement since the HYPERcollar, it could still perform better in accurate and reproducible positioning of the patient. Additionally, because of the metal components, this applicator would not be suitable for use in an MRI.

One of the biggest problems of the water bolus used in this applicator, is that it leaks easily. The SEBS film is very thin and tears quickly. Furthermore, it does not seal well in combination with the PP film, often causing small gaps between the two layers. According to the technicians that make the bolus and supervise the treatments, the bolus usually needs to be replaced about three times within the 6 sessions of one patient. The leaks, and thus replacement of the bolus, often occur during the treatment sessions. This causes interruptions in the treatment which can influence its effectiveness.

Another issue is that the bolus is produced in a flat beam shape but used in a curved shape during treatment. This causes folds to occur in the SEBS film and makes it difficult to connect the bolus to the applicator.

Lastly, the elastic SEBS film inflates like a balloon when filled with water. The technicians need to use tape to avoid the bolus to inflate and cover the patient's eyes and mouth.

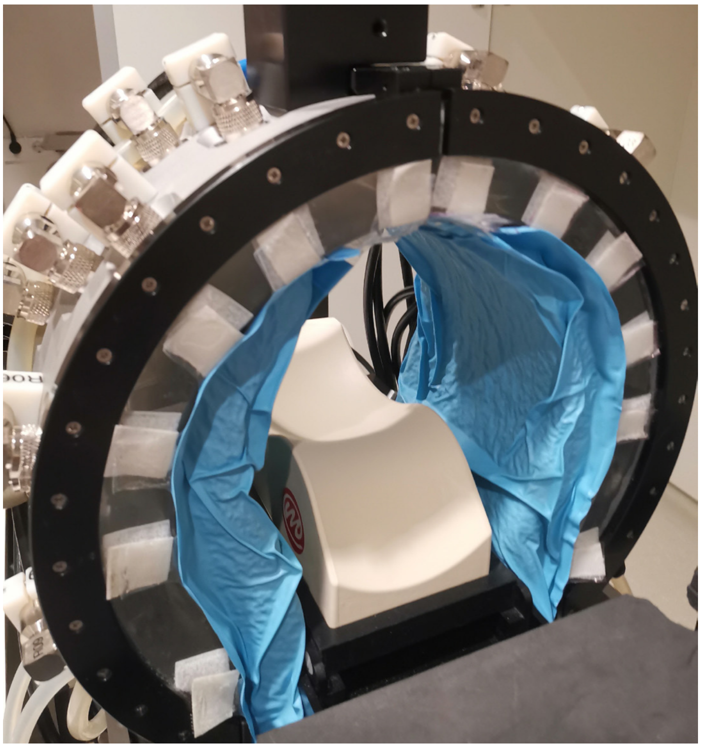


*Fig. 15: HYPERcollar3D*

## MRcollar

ErasmusMC is currently developing a third iteration of the applicator which is adapted for use in an MRI-scanner (see figure 16-19), this applicator is not yet used for treatment of patients. As explained in chapter 1.2, research is being conducted to use MRI as a tool for real-time temperature monitoring of the target area and surrounding tissues, which can be used to evaluate hotspots during treatment. Additionally, the use of MR imaging to capture electrical tissue properties, diffusion and blood perfusion is being explored (Paulides et al., 2020).

The MRcollar has the same working principles as the HYPERcollar3D, but is adapted for MRI use; All metals used in the HYPERcollar3D are replaced by plastics, non-ferrous, non conductive materials need to be used to avoid attraction to the magnetic field and to allow for better imaging.

To reduce the complexity of the system, the 12 most relevant antennas are selected instead of using 20. But it is planned to include 20 antennas again in a later phase of the trial to improve heat control. The two halves open in a translating movement instead of a rotating movement, which makes it easier for the patient to come out of the device. Lastly, each antenna now has its own cooling cell, which reduces the amount of needed water (see fig. 17).

### Issues

There is currently no design yet for a water bolus to use in the MRcollar. The design still has to be made for use during the treatment and the digital model is needed to be imported into the simulations. If the water bolus cannot be simulated, the treatment cannot be tested on patients.

*Fig. 16: MRcollar*

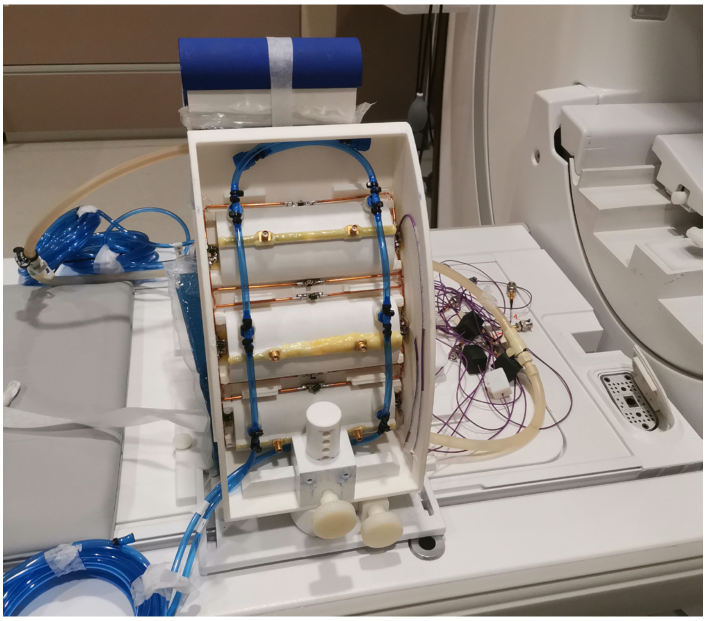


*Fig. 17: Outer water bolus with antennas*

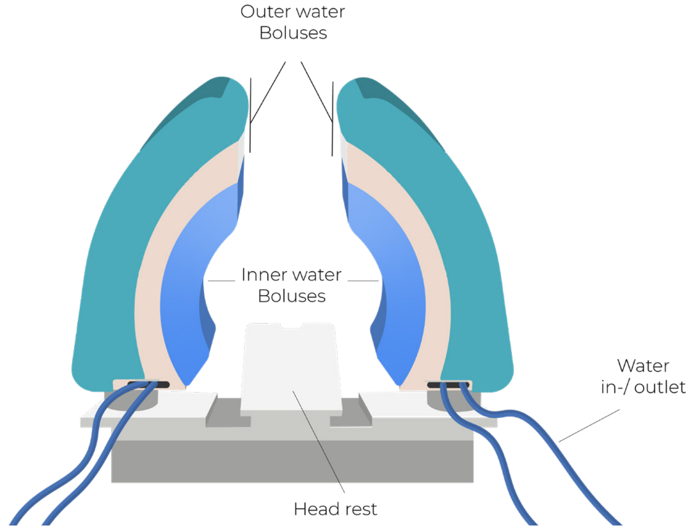
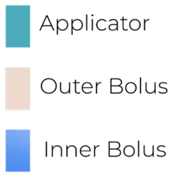
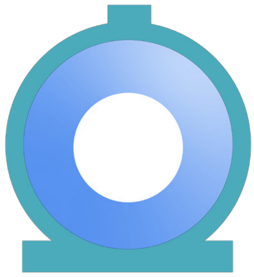
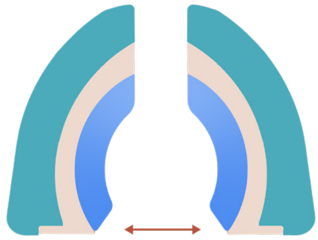



*Fig. 18: MRcollar, components overview*

*Fig. 19: Patient in MRcollar*

# Collar iterations overview

|  | <br>HYPERcollar | <br>HYPERcollar3D | <br>MRcollar |
|---|---|---|---|
| Applicator | 6 antennas<br>One full ring | 20 antennas<br>Two half rings<br>Rotate to open | 12 antennas<br>Two half rings<br>Slide to open<br>MR compatible |
| Bolus | One bolus, fully surrounding the patient | Two halves with each:<br>· One inner bolus<br>· One outer bolus | Two halves with each:<br>· One inner bolus (yet to be developed)<br>· One outer bolus |
| Main bolus issues | Unstable<br>Inaccurate patient positioning<br>Folds<br>Breathing difficulties<br>Poor temperature control | Leaks<br>Fragile outer film<br>Folds<br>Inflation<br>Breathing difficulties<br>(See also next pages) | No inner bolus developed yet |

# Water Bolus

This thesis will focus on developing an inner water bolus for use in the MRcollar. Currently there is no water bolus design yet for this applicator. Therefore, the function, components, working principles and issues of the bolus that is currently used in HYPERcollar3D are analysed. These findings will also be applicable in the development of a new bolus.

## Function

Two water boli are placed between the antennas and the skin of the patient. The boli have three main objectives: (1) To cool the skin and avoid burns, (2) to cool the antennas to ensure proper functionality throughout the treatment and (3) to conduct the electromagnetic waves from antennas to skin. The boli should provide these functions, without disrupting the energy transfer from the antennas as well as the MR imaging.

## Components

The MRcollar will consist of two halves, each containing two boli: an inner water bolus and an outer bolus. The inner and outer bolus together ensure proper conductivity of electromagnetic waves from antenna to skin.

The outer bolus is used to cool the six antennas of each half. Each antenna is positioned in its own water compartment, a water circulation tube is used to connect the different compartments and ensure a continuous water flow along all antennas.

The inner bolus (see fig. 20) will be used to cool the skin. This bolus needs to be flexible to adapt to the shape of the patient and ensure good skin contact. However, it needs to be firm enough to provide comfortable, stable and reproducible positioning of the patient. The inner bolus of the HYPERcollar3D, consists out of an outer SEBS and polypropylene film layer. Inside the film layer, open cell polyether foam is inserted to provide firmness, while still allowing water circulation and deformation of the bolus to the shape of the head. Two tubes are inserted in the film to allow for in- and outflow of water. The bolus can be connected to the applicator by using Velcro strips.

## Water flow

The water circulating through the inner bolus is maintained at a temperature of 20-30 °C. This temperature will provide effective cooling of the skin, without counteracting the heating of the target tissue. The water used to cool the antennas has a temperature of 35°C (Paulides et al., 2016). To make sure the water flows throughout the full bolus volume, a tube first guides the water from the inlet to the back of the bolus, before it can start flowing back to the outlet.

## Issues

The main issues of the HYPERcollar3D inner water bolus are displayed on the next page.

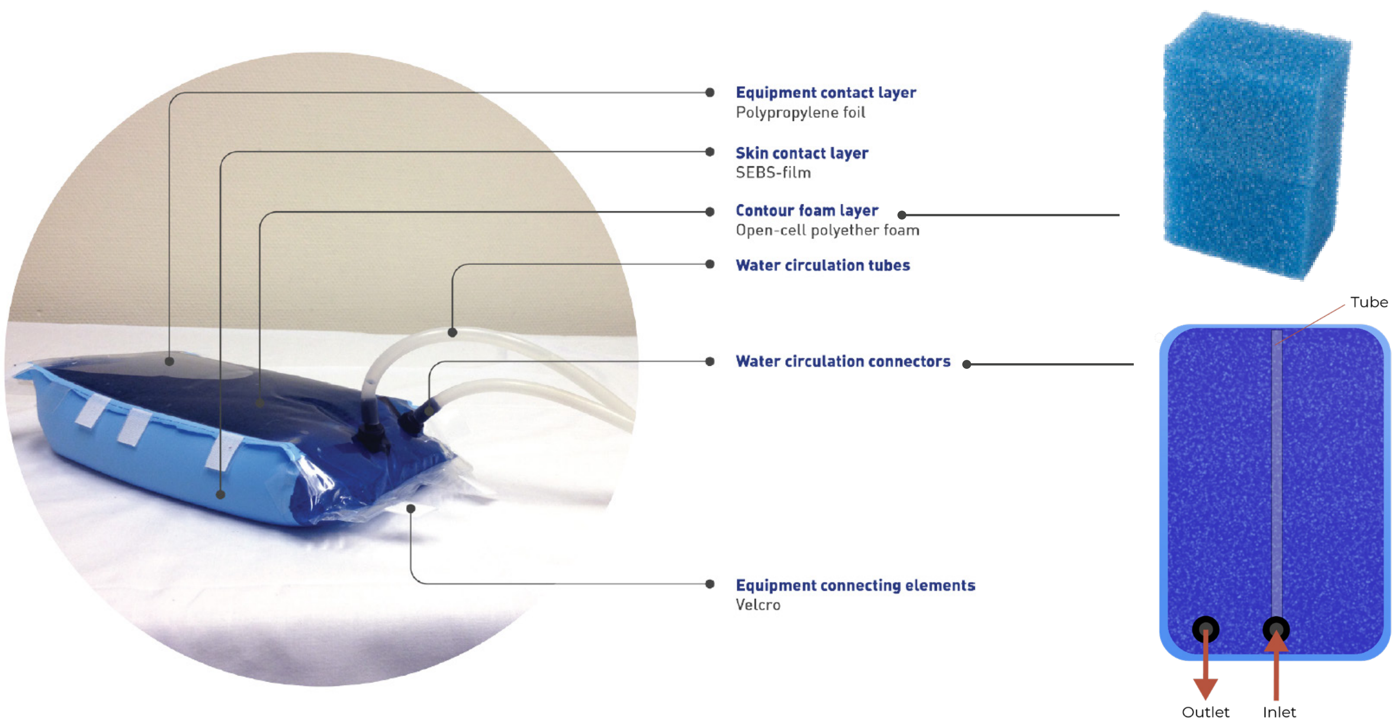



*Fig. 20: HYPERcollar 3D, inner water bolus components and materials (van den Berg, 2017)*

## BOLUS INFLATION

Water in combination with flexible film: Bolus expands outwards

- Uncontrollable shape and flow
- Top of the bolus inflates too much, covering the eyes of the patient

## LEAKS

- 3D shape sealed as 2D shape
  - Multiple layers folded together
  - Difficult to seal
- SEBS film breaks very quickly
- 2 Materials, difficult to seal together

## SHAPE

- Not adapted to head and neck shape
- Lot of compression needed to be in full contact with the skin

## WATER FLOW

- Gravity causes most water to stay at the bottom, creating a balloon
- No guidance of water, no control on water flow

## FOLDS

- Sealing happens when the bolus is flat
  - Excess material when curving it
  - Formation of folds and wrinkles

# 1.4 STAKEHOLDERS

Based on interviews with Erasmus MC employees and desk research, the four main stakeholders of the water bolus were defined. (1) The developers of the equipment, (2) the technicians who are responsible for the treatment planning, simulations and temperature monitoring, (3) the clinicians who prepare and supervise the treatment and (4) the patients being treated with hyperthermia. For each stakeholder, the most important water bolus features and concerns are described below.

## Developer

For the developers of the MRcollar it is important to have a water bolus that works effectively, is manufacturable and has a reasonable price. If the bolus is working effectively in the MR collar, they also want to implement the redesign in the HYPERcollar3D for use in clinical trials. Their end goal is to commercialize the MRcollar under the company name Sensius, and to use the HYPERcollar3D in academic settings.

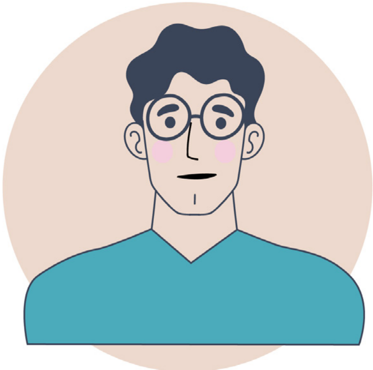
## Technician

The main goal of the technician is to carry out simulations that represent the real setting as closely as possible. To do this, the patient needs to be positioned as accurately and stable as possible in the water bolus. Also the shape, temperature and position of the water bolus during treatment need to be predictable and reproducible. Currently his main concern is to have a MRcollar adapted water bolus to use in the real setting as well as in the simulations, since there is no design yet.

## Clinician

The clinician would benefit from a water bolus that is easy to set-up before the treatment takes place. It should be easy and quick to connect the bolus to the applicator and the water-circulation system, after which it should stay fixed in place. Also the positioning of the patient within the applicator, should be made as easy and efficient as possible.

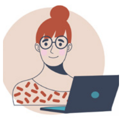
In order to carry out an effective treatment and to do real-time monitoring and adaptations, the water bolus should not leak and not disrupt the EM waves, nor the MR imaging. It's also important that the bolus can withstand multiple treatments without breaking or losing effectiveness.



## Patient

Based on patient interviews carried out by a previous graduate student (van Den Berg, 2017) and a personal test it was concluded that the patient can experience serious discomfort and/or stress during treatment. The current bolus partially covers the eyes, nose and mouth which can lead to breathing difficulties and a claustrophobic feeling. Also, the pressure on the skin caused by the water can become rather high and uncomfortable for the patient. Lastly, during the treatment hotspots can emerge, leading to burns and/or muscle strains. Improving these aspects in the redesign would significantly enhance patient comfort and reduce stress, which is proven to make the treatment more effective.

## Overview

| | Function | Concerns |
|---|---|---|
|  Developer | Develop and commercialize MRcollar | Cost<br><br>Developing a working and manufacturable bolus |
|  Technician | Hyperthermia treatment planning and temperature monitoring | Represent real setting in simulations<br>· Accurate and reproducible patient positioning<br>· Predictable bolus shape and temperature<br>· Digital water bolus model for use in simulations<br>· No EM wave or MRI interruption |
|  Clinician | Prepare and supervise treatment | Easy and quick set-up<br>· Attachment bolus-applicator<br>· Patient positioning<br><br>Effective and efficient treatment<br>· No leaks<br>· Withstand multiple treatment cycles |
|  Patient | Undergoing hyperthermia treatment | Comfort<br>· Minimize stress<br>· Minimize pressure<br>· Breathing: avoid covering mouth and nose<br>· Minimize hotspot occurrence<br><br>Effective treatment |

# 1.5 DESIGN CHALLENGES

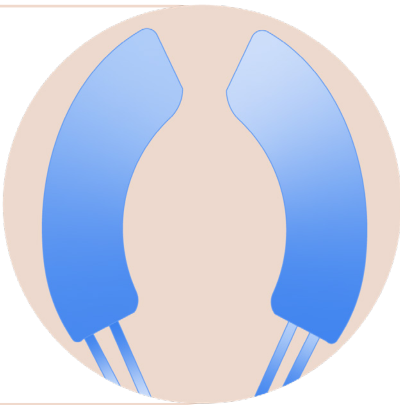
Based on the findings in the analysis phase, six interrelated goals were defined. These challenges will serve as a guideline throughout the design process in order to develop a water bolus that is complying with the needs of every stakeholder.

## Main challenges

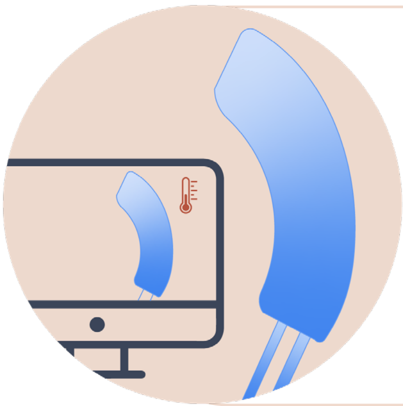
One of the most important aspects to take into account when designing the bolus is patient comfort. This includes reducing the pressure on the skin, making sure there is enough space to breath and avoiding hotspots from occurring. By enhancing patient comfort, stress can be minimized which is proven to enhance the effectiveness of the treatment.

Patient comfort

The main function of the bolus is to provide effective and uniform cooling to the skin, in order to avoid occurrence of hotspots and burns. To achieve effective and uniform cooling, formation of folds and air bubbles should be avoided. Additionally the outer material should efficiently conduct the cooling from water to skin. Lastly, the water should be distributed uniformly throughout the full bolus volume.



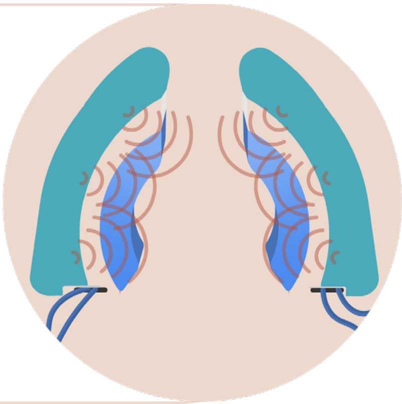
Effective & uniform cooling



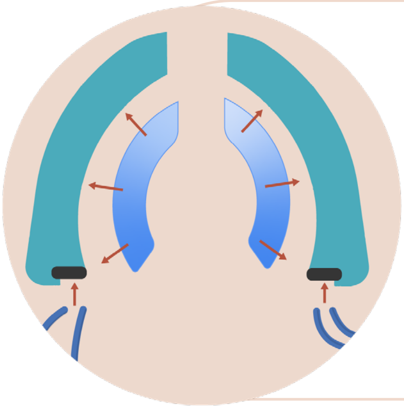
During the hyperthermia treatment planning, the water bolus will be simulated digitally in order to generate the optimal antenna settings for effective treatment. To simulate the bolus as closely as possible to reality, its properties should be predictable and reproducible: the same bolus shape and temperature have to be achieved during multiple treatments.

Shape: stable predictable and reproducible

The new bolus design has to function in the MRcollar design without causing interference with the electro magnetic waves from the antennas as well as the MR imaging. It has to be MR compatible, meaning it has to consist out of non-ferrous, non-conducting materials. To avoid harm to patient and equipment, the bolus should be watertight and not easily punctured.



Functionality in MRcollar



The set-up by the clinician should be easy and efficient. It has to be easy to (dis)connect the bolus to the applicator and water circulation tubes and to position the patient. Once installed, the bolus should stay fixed in place throughout the treatment.

Usability by clinician

# 1.6 LIST OF REQUIREMENTS

## 1. Performance

### 1.1. Cooling & Water flow

- Good skin contact: No gaps between bolus and skin
- Uniform water distribution throughout the bolus volume
- No formation of folds
- No formation of air bubbles
- Watertight, no leaks

### 1.2. MRcollar compatibility

- Fit in MRcollar
- Using existing sliding connection system
- Not interfering MR imaging
- Conducting EM waves

### 1.3. Reproducible in simulations (HTP)

- Predictable behaviour of the bolus shape, temperature and position
- Reproducible: Same shape can be acquired during following treatments
- Optimized water volume
  - Enough for cooling
  - As minimal as possible for predictable and homogeneous temperature distribution
- Stable: Patient position remains the same during the treatment
- Precise and accurate positioning of the head in relation to the antennas

## 2. Economical

### 2.1. Production

- Manufacturable in low volumes (<20 pieces)
- Easily available materials
- Reasonable material and labour costs

### 2.2. Life in service

- Lasting a minimum of one treatment cycle of 6 hyperthermia sessions

## 3. Patient comfort

### 3.1. Ergonomic fit

- Following the contours of head and neck
- Minimize amount of compression needed to be in full skin contact
- Minimize pressure on the skin, equal pressure distribution

### 3.2. Minimize stress

- Avoid claustrophobic feeling
  - Big enough gap for breathing/seeing
- Friendly and reliable appearance
- Avoid hotspots

# 4. Materials

## 4.1. General

- MRI compatible
  - Non-ferrous materials
  - Non-conducting materials
  - Not interfering MR imaging
- Not interfering EM waves
- Bio-compatible
- Easily Available and affordable
- Manufacturable in low volumes

## 4.2. Outer enclosure

- Transfer cooling from water to skin
- Flexible: Able to adapt to shape of the head
- Durable, last multiple cycles
- Waterproof (IP8), no leaks
  - Not easily punctured
- Comfortable skin contact
- Avoid inflation

## 4.3. Inner structure

- Flexible enough to adapt to the contours of head and neck for every patient
- Rigid enough to provide support to the head and neck
  - Patient stays positioned in the same way during the treatment
  - Patient position can be repeated every treatment
- Allow for good water flow
- Shape of the structure can be produced in a way to ergonomically follow the patient contours

# 5. Installation of use

- Easy to set-up by the clinician
  - Easy to connect bolus to applicator,
  - Easy to connect bolus to water circulation
  - Easy replacement
  - Easy to position patient
- Stay fixed in place during treatment

# 2 MATERIAL RESEARCH

In order to come up with feasible ideas in the next phase, research to possible outer materials and inner structures was carried out. First it was explored which solutions could be used to provide structure and rigidity to the bolus while still allowing for water flow. Then, it was determined which materials could be used for these inner structures and which materials could be used to make the bolus watertight. Throughout this chapter it was considered that all materials used in the water bolus have to be: MRI compatible, EM compatible and bio-compatible (see requirement 4.1).

# 2.1 INNER STRUCTURE

The first version of the Hyperthermia applicator was the HYPERcollar. In this applicator, the bolus consisted out of a large bag of water surrounding the neck of the patient without inserting any kind of structure. There were multiple problems with this solution: first of all, it was difficult to position the patient in a stable way in the bolus and to reproduce this exact position during following treatments. Secondly, the large unsupported water volume would cause folds in the surrounding film, which led to disruption of water flow.

In the HYPERcollar3D it was tried to resolve these issues by inserting open cell filter foam in the bolus. This foam still allows for water flow, while providing some more support to the head and neck, allowing for more stable and reproducible positioning of the patient and avoiding folds. This was already a good improvement, however a structure that is adapted to follow the shape of the patients' head and neck better can still improve the positioning, provide better skin contact and enhance patient comfort.

## Requirement 4.3.: Inner structure

- Flexible enough to adapt to the contours of head and neck for every patient
- Rigid enough to provide support to the head and neck
    - Patient stays positioned in the same way during the treatment
    - Patient position can be repeated every treatment
- Allow for good water flow
- Shape of the structure can be produced in a way to ergonomically follow the patient contours

A few ideas to provide structure were explored in this phase: 3D printing a (lattice) structure, trying to adapt the open-cell foams better to the skin and making a combination of a more flexible and a more rigid structure.

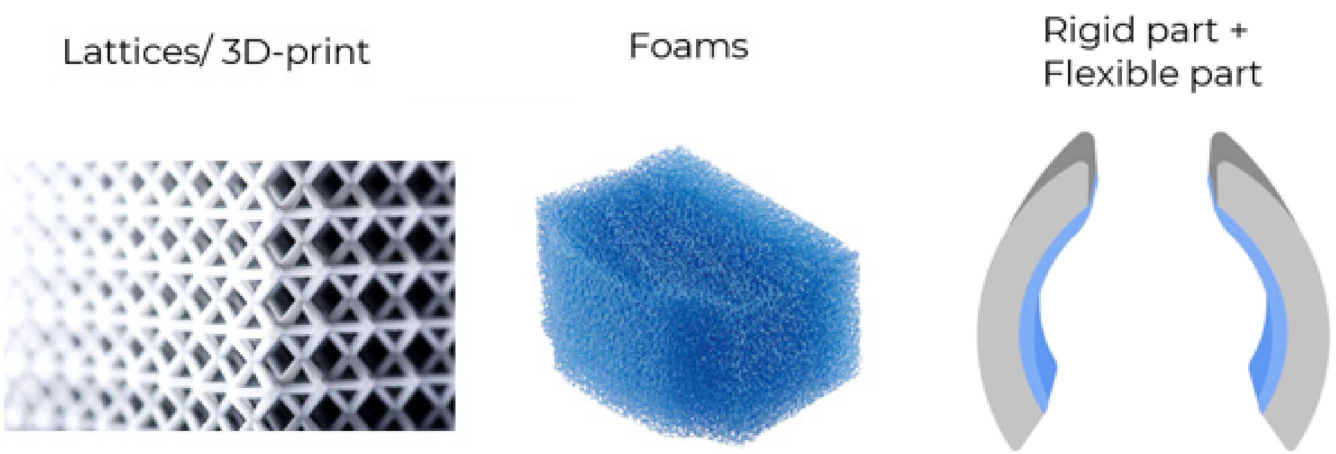



*Fig. 21: Initial inner structure ideas*

# Cellular structures

A cellular structure consists out of a network of interconnected surfaces or beams that allow for very good mechanical properties while keeping the weight low (Wang & Rai, 2016). For this project, cellular structures are very interesting because they can both provide support and flexibility, while the open structure allows for water to flow through. Cellular structures can be classified in three categories: foams (open-cell and closed cell), honeycombs and lattices.
Honeycombs consist out of two-dimensional arrays of polygons. They have a regular shape and every unit cell has the same shape and size.
Foams are three dimensional materials, in which the unit cells are randomly generated with varying sizes, shapes and orientation in space.
A lattice structure can be defined as a three dimensional structure, consisting out of repeating and interconnecting unit cells. This creates an open structure composed of interconnecting beams and/or faces.
In comparison to honeycombs and foams, lattices have better mechanical properties and the possibility to Improve compressive and shear strength.
(Pan et al., 2020; Wang & Rai, 2016).

# Lattice structures

Since lattice structures seemed very promising for the water bolus, a few experiments were carried out, to obtain a better insight in its possibilities and limits.
A lattice can be generated by following the steps as shown in figure 22. First the desired volume which is called the design space has to be defined, then this space is subdivided in voxels with predefined dimensions, next the designer chooses which unit cell will be used to fill every voxel, once every voxel is filled with a unit cell the lattice can still be modified to create a clean structure fitting to the design space and to optimize its mechanical properties if desired. As a last step, the lattice can be thickened and meshed to prepare for production. (Porterfield, 2020)
During this project, the lattices are created using grasshopper with the Crystallon Plug-in or by using the program Ntopology. Grasshopper is slower and more complex in use, but gives you more insight and control in the process. Ntopology is more optimized and user-friendly in use, but gives you a little less control and possibilities in adjusting the lattices.
The different parameters that can influence the mechanical properties such as the strength and flexibility of the lattice are listed below.

- Global shape and dimensions (design space)
- Voxel size (XYZ)
- Type of unit cell (See Appendix XX)
    - Lattice shell
    - Lattice cell
- Thickness/radius
- Used material/filament (see chapter Materials)

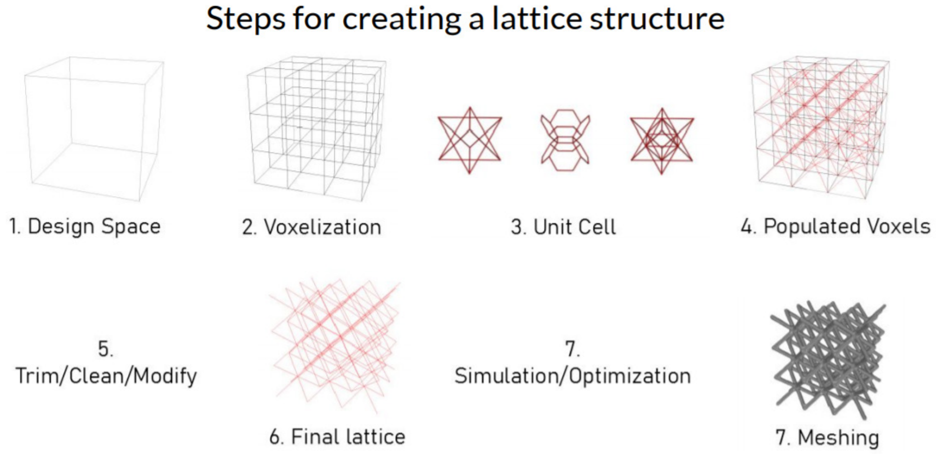



*Fig. 22: Steps for creating a lattice structure (Porterfield, 2020)*

# Manufacturing

## Rigid Lattices

Due to the complex and open structure of lattices, they can only be produced using additive manufacturing techniques.

A few test prints were made to explore the feasibility of 3D printing the lattice structures. The main expected problem was providing support to the lattices when printing them. Printing the structures without support might be challenging since the overhangs can be larger than 45° at certain points and sometimes the printer will need to bridge small distances. However printing with regular (PLA) support is not an option, since it would be impossible to remove them afterwards.

The first samples were created on an Ultimaker FDM printer using PLA filament, without adding any support structure (see fig. 23). This already gave good results and would be a good solution to produce rigid lattices later in the project. It can be concluded that the Ultimaker is capable of handling the overhangs and bridging in the lattice structures. also printing a larger and more organic structure is possible using this technique. However printing the lattices without support, is pushing the printer to its limits which results in a reduced surface quality and the occurrence of stringing.

During the next test, the lattices were still printed in PLA but now a support structure was printed using PVA dissolvable filament (see fig. 24). By putting the prints in lukewarm water for a few hours after printing, the support structure dissolves and only the lattice remains intact. This resulted in a very good surface quality and overall strength, but substantially increased printing and post-processing time.

Using stereo lithography to print the structure will not be possible, since the test print failed even with added support structures (see fig. 25). Adding more support will make removal of it impossible.

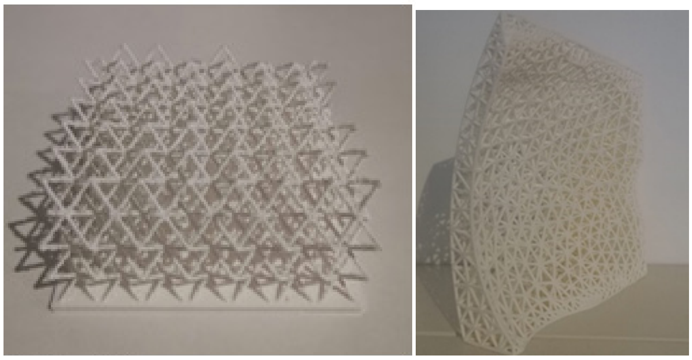


*Fig. 23: FDM - PLA, no support*

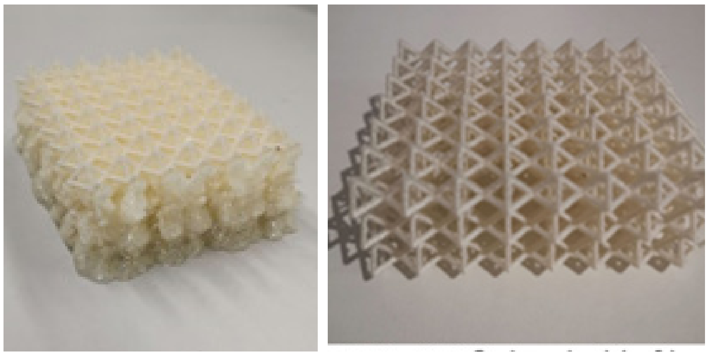


*Fig. 24: FDM - PLA + dissolvable support (PVA)*

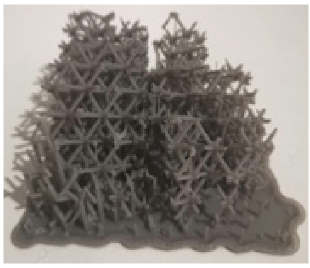


*Fig. 25: SLA*

## Flexible Lattices

When printing the lattices in PLA, they are very rigid and strong. This might be useful as a base shape providing structure in the bolus, but doesn't offer the flexibility needed to adapt to the shape of the patient's head. To obtain this flexibility, flexible filament can be used when printing the lattices.

The most commonly used flexible filament is TPU. When printing the lattices in TPU without support (see fig. 26), the structure can move during print, making it very difficult for the printer to position the following layer on the model and causing the print to fail. This problem increases proportionally with the flexibility of the structure. Thus, it is still possible to print a lattice that has smaller unit cells and therefore is less flexible in TPU without support. But it will not be possible to reach the desired flexibility for this project without using support.

Better results can be achieved when printing in TPU with PVA dissolvable support (see fig 27). The rigid support makes sure the print will not bend during the print process, hence will be less likely to fail. However, this approach will cause extremely long printing times while still not achieving a good surface finish and overall strength of the lattice.

That's why it would be recommendable to outsource the 3d-printing of the flexible parts to an external company that is equipped with Selective Laser Sintering (SLS) or Multi Jet Fusion (MJF) printers. These techniques make use of material powder which is melted together layer by layer to create an object. The powder that is not sintered or fused together can be used as a support material which is blown out by air after print. Possible companies to do this are Oceanz: SLS in flexible TPU or Materialize: MJF in Ultrasint TPU 90A-01 (see fig. 28). The price per bolus would be around 170 euros, which is costly, but not more expensive than it would be to print the rigid lattices at an external company.

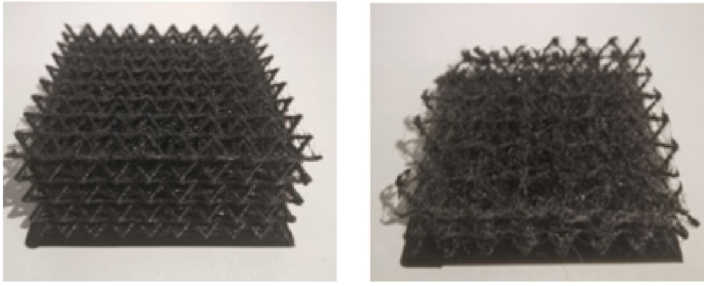


*Fig. 26: FDM - TPU, no support*

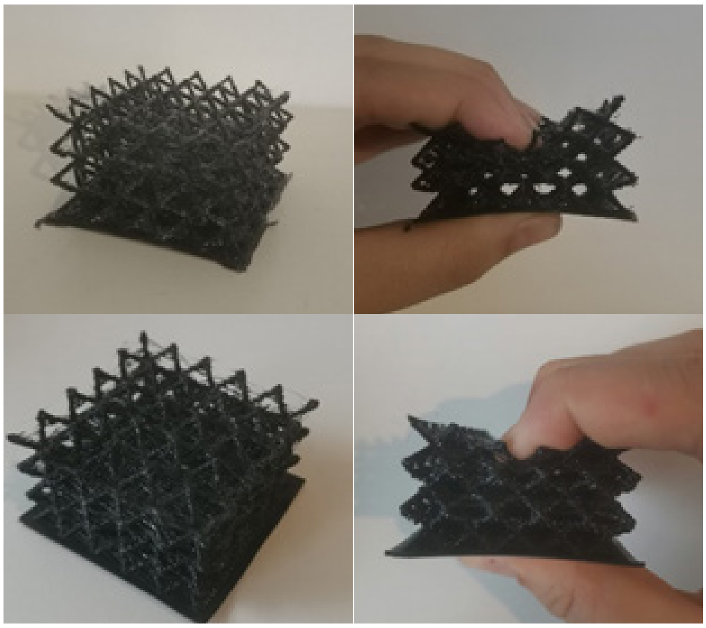


*Fig. 27: FDM - TPU + dissolvable support (PVA)*

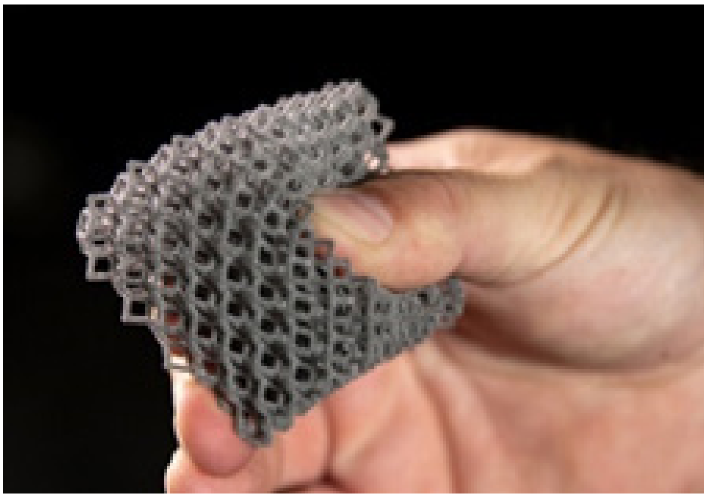


*Fig. 28: Materialise Ultrasint TPU 90A-01*

## Overview 3D printing tests and findings

Explanation printing technologies (Redwood, n.d.)

| | |
|---|---|
| Fused Deposition Modeling (FDM) | A string of thermoplastic material is melted and pushed through a heated nozzle. The nozzle continuously moves over the buildplate, extruding the material layer by layer. When the material cools down, it solidifies. |
| Stereolithography (SLA) | The build platform is submerged upside down into a tank filled with liquid photopolymer resin. The resin is then solidified layer by layer, by using a laser. To improve the mechanical properties of the print, parts are usually post-cured using UV-light |
| Selective Laser Sintering (SLS) | For every layer, powder material is spread onto the build platform and the cross section of the object is sintered together by a laser. As a result, the sintered component will be fully encased in powder by the end of the process, which can be easily removed during post-processing. |
| Multi Jet Fusion (MJF) | For every layer, powder material is spread onto the build platform, after which inkjet nozzles deposit fusing and detailing agent on the cross section of the object. A strong infrared source then passes over the build platform, causing the areas with fusing agent to be sintered together. As a result, the sintered component will be fully encased in powder by the end of the process, which can be easily removed during post-processing. |

Print tests

| | Rigid lattice | | | Flexible lattice | |
|---|---|---|---|---|---|
| **Technique + Material** | FDM PLA | FDM PLA + PVA | SLA Resin | FDM TPU | FDM TPU + PVA |
| **Print successful?** | Yes | Yes | No | No | Yes |
| **Surface quality** | - | + | + | -- | + |
| **Support** | No support | Dissolvable support | Non-dissolvable support | No support | Dissolvable support |
| **Print time** (70 x 70 x 30 mm) | 7h 43min | 21h 1min | 6h 15min | 8h 28min | 22h 6 min |

Possibilities for outsourcing

| **Technique + Material** | SLS Oceanz flexible | MJF Materialise Ultrasint TPU 90A-01 |
|---|---|---|
| **Surface quality** | ++ | ++ |
| **Support** | Powder, easy removal | Powder, easy removal |
| **Print time** | Delivery time: 4 working days | Delivery time: 4 working days |

## Materials

The most common material for FDM 3D printing is PLA, this material was also used for the tests. However, PLA is a biodegradable material that will break down when in constant contact with water. To make the lattice water resistant, it would be better to print it in PET or Nylon or to coat it with a water resistant spray. An overview of rigid printing materials for FDM printing and their properties can be found in Appendix B. If the lattice would be SLS printed at a 3D printing company, the standard used material is PA12, this material is water resistant and an extra sealing layer can be added after print to further increase the water resistance properties.

For flexible printing, usually TPU or TPE is used in FDM printers as well as in other printing methods. These materials are available with different properties and flexibilities. The hardness of flexible materials is usually indicated by using the shore hardness scale. A higher number on the scale means a harder material. Scale A is used for softer materials while scale D is used for harder ones. An overview of available printing materials and their shore hardness can be found in Appendix B.

## Pro's and cons

The biggest benefit of using lattice structures is that the designer is able to tailor the structure to acquire the desired mechanical properties for any specific application. Even a variety of mechanical properties (e.g. strength, flexibility) can be achieved within one structure by locally or regionally adapting the unit cells in size, thickness or orientation. Lastly, any desired lattice shape can be generated in CAD modelling software and 3D-printed, thus the shape could be designed to follow the head shape of the patient in 3 dimensions. However, lattices are rather complex and expensive to manufacture.

# Foams

Foams are produced  by mixing two substances together that cause the foaming reaction. Thus, the direction, size and shape of the cells differ throughout the foam structure. When more than half of the cells are open, the foam is classified as open-cell foam. Other than closed cell foams, open cell foams allow for water to flow through, which makes them interesting as a structure provider in the water bolus.

To make the foams even more porous and open, they can undergo a reticulation process, where only very few cell bubbles remain closed. Reticulated foams are usually classified by pores per inch (PPI), where 10 PPI is the most open and light structure which will allow for most water flow, while 80 PPI is a more dense structure with very small cells which is more restrictive. (see figures 29 and 30) (Foam Production | Recticel Flexible Foams, n.d.; Keeley, 2017)

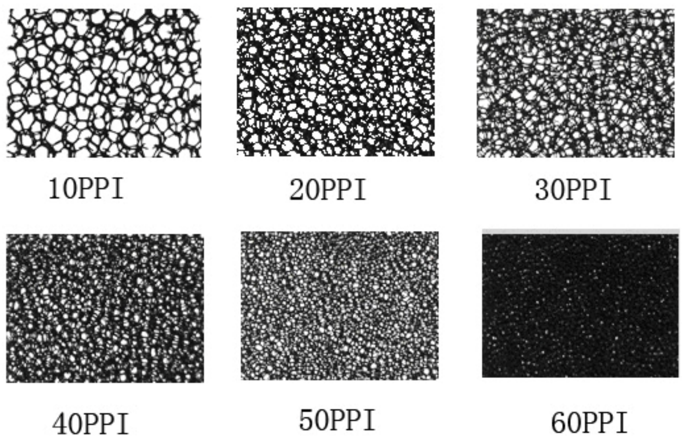



*Fig. 29: Reticulated foams: densities*

*Fig. 30: Reticulated foams: densities*

### Manufacturing

The foams can be milled or cut into a desired shape, but creating a double curved surface as needed for the water bolus can be challenging with this technique, especially considering the flexibility of the material. Another option could be to expand the PU foam in a mould, however producing the mould will be too expensive for the low desired quantities.

### Material

The most commonly used material for reticulated open cell foam is polyurethane (polyester or polyether). Which is usually used for filtration applications such as aquarium filters, but also as sound absorbers and packaging material.

### Pro's and cons

Currently open-cell reticulated PU foam is also used in the HYPERcollar3D water bolus. The disadvantages of using this foam are that it wears down rather quickly because of the water flow, that the options of optimizing the mechanical properties for a specific application are limited to the already available materials and that these properties cannot differ within the structure. Also it is not that easy to adapt the shape of the foam to the shape of head and neck as discussed earlier. The benefit of using foams is that they are very easily and widely available and relatively cheap.

## Water flow

Some first water flow tests were done by first filling the structures with water and then adding colouring agent (see fig. 31). These tests showed that the water tends to follow the shortest path between in and outlet, leaving large areas at the sides and corners of the structure unreached. Therefore it was decided that a system needs to be designed that will make sure the water is guided throughout the whole bolus volume.

Additionally it was found that the resistance in the foam structure is significantly higher than in the lattice, leading to a slower water flow and a longer time to fully cool the bolus.

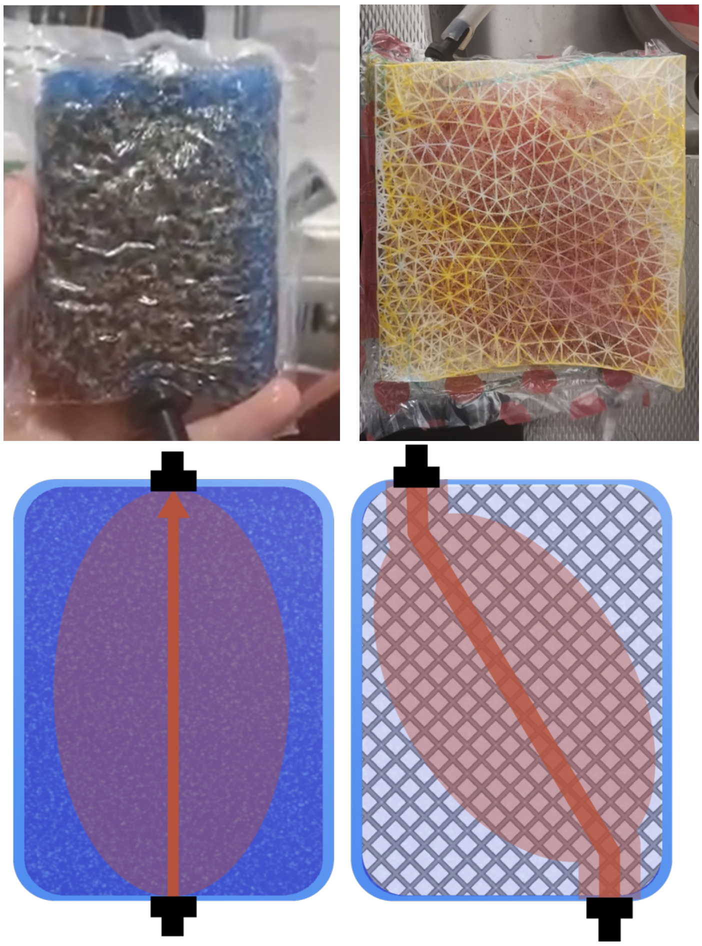
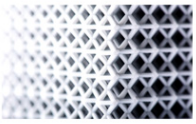


*Fig. 31: Water flow through foam vs. lattice*

# Foam vs. Lattice

| Lattice | Foam |
| --- | --- |
|  Lattice |  Foam |
| + Shape adaptable to head shape | + Easily available and manufacturable |
| + CAD model: Good reproducibility in simulations | + Cheap |
| + Little resistance, good water flow | + Currently used in HYPERcollar3D, proven to work |
| + Water guidance can be designed and printed in the structure | |
| + Mechanical properties (flexibility, strength, density) can be altered according to preference/requirements | |
| - Difficult to print, outsourcing necessary | - Not three dimensionally adaptable to head shape |
| - More expensive | - Mechanical properties are fixed, not adaptable |
| - Longer delivery/manufacture time | - Water guidance will have to be inserted afterwards |

# 2.2 OUTER ENCLOSURE

## Requirements

An outer enclosure is needed in order to keep the water inside the bolus and avoid leakage. The outer enclosure should comply to the following requirements:

### Requirement 4.2.: Outer enclosure

- Transfer cooling from water to skin
- Flexible: Able to adapt to shape of the head
- Durable, last multiple cycles
- Waterproof (IP8), no leaks
  - Not easily punctured
- Comfortable skin contact
- Avoid inflation

## Possible production methods

### Injection moulding

In injection moulding a mould is produced in which plastics are injected at high temperatures and pressure. Injection moulding an enclosure for the water bolus will not be possible, since the production of the boli will be done in low volumes. The price for injection moulding only a few boli enclosures will be way to high. Additionally injection moulded products will not provide the desired flexibility.

### Silicon mould

Making a 3D printed mould and injecting silicon into it can be a solution. The benefit of this would be to create the exactly desired shape and still maintain flexibility. The expected challenges are to make the walls thin enough to transfer the cooling from water to skin and making the enclosure watertight. The enclosure will need to be moulded in two half shells that need to be connected again by heat which may cause issues.

### 3D printed enclosure

By 3D printing an enclosure in a flexible material, it would be possible to create an organic shape adapted to the shape of the head that is still flexible enough. Additionally it would be possible to print the whole bolus including inner structure as one piece. However, there are multiple issues with this solution. First of all, it is very difficult to make a waterproof 3D print: there will always be gaps or slight inaccuracies that cause leaks. Secondly, the minimum material thickness for 3D printing is 1 mm which is too thick to conduct the cooling properties of the water to the skin. Lastly, if the structure is fully closed it will be impossible to remove support material.

### Thermoforming

Another option would be to thermoform the enclosure. In this technique a thermoplastic sheet gets heated and vacuum pressed into a mould. The issue here is that flexible materials are more difficult to thermoform, since they tend to return to their original shape. For the water bolus, especially twin sheet thermoforming is interesting, where two sheets are thermoformed simultaneously: one sheet upwards, one sheet downwards and sealed together at the desired touching points. Using this technique it could be possible to immediately create water tubes in the process. However, this is a rather specialized and expensive technique that will not be able to be tested and prototyped during this graduation project.

### Films + welding

The most feasible technique to provide an enclosure of the water bolus is to use plastic films that can be sealed together by heat. This is how the bolus is currently made. The main benefit of this technique are that it is relatively easy and cheap to do, the bolus can be made waterproof and flexibility can be maintained. The downside is that it is difficult to obtain the desired organic shape and heat sealing can be challenging if the seams are not straight. Different materials that could be used for this technique are explained on the next page.

## Materials

Currently polypropylene (PP) film and Styrene ethylene butadiene styrene (SEBS) film are used in the water bolus. The PP film is chosen because of its strength and stiffness to resist the water pressure. While the SEBS film is chosen as a more flexible and soft material to be in contact with and adapt to the skin of the patient. However, the SEBS film is very vulnerable to piercing and leaks. Other possible materials could be PE, PVC, PET, Nylon, silicone or PU .
Another possible material would be waterproof laminates. These textiles are breathable, offer a nice touch to the skin and can be sealed together using a plastic insert.

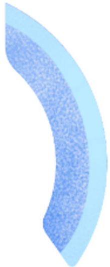
# 3 IDEATION

Based on the findings from the analysis phase and material research, different ideas were generated for both the inner structure as well as the outer enclosure. These ideas were compared on different criteria in order to come up with the best possible concepts for further development.

# 3.1 INNER STRUCTURE

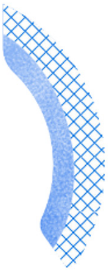
## Ideas

Based on the findings from the material research and a brainstorm session, different ideas were generated for the inner structure. A brief description of each idea is given on this page.



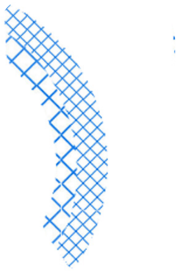
Shell + foam

3D printed 1mm, 2 dimensional thin shell (to avoid EM wave disruption) on top of which a thick foam layer is glued.



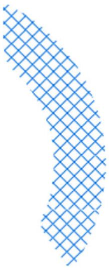
Lattice + foam

3D printed rigid lattice, shaped according to the head. A thin foam layer glued on top of it.



Rigid+flexible lattice

3D printed lattice structure, existing out of a more dense/stiff part at the back and a more open/ flexible part near the skin.



Flexible lattice

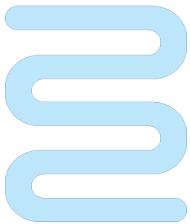
Uniform lattice structure, printed in flexible material.

Shell + thin water bolus

Rigid outer pre-shaped shell, with a very thin film/ water bag attached to it through which the water flows.

Honeygrid

Flexible 3d printed structure, existing out of hexagonal tubes with a hole pattern to guide water flow



Water tubes: twin sheet thermoforming

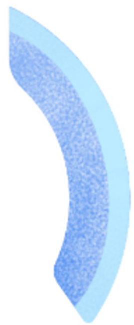
Twin sheet thermo-forming is used to seal two flexible sheets together and immediately create water tubes in the process.

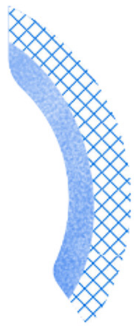
## Idea selection

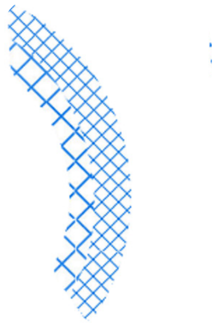
The different inner structure ideas described on the left are compared on different aspects: flexibility, rigidity, adaptability, manufacturability, durability, effective cooling and cost.  A colour scale was used to rate each idea; green for good performance, yellow for a doubtful performance or red for an inadequate performance, meaning the idea will not work.

An overview can be found on the next page.

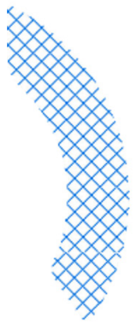
- Good performance
- Doubtful performance
- Inadequate performance

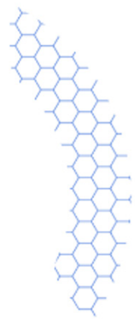


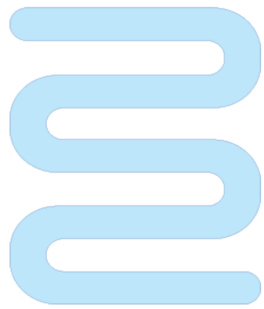




| | Shell + foam | Lattice + foam | Rigid+flexible lattice |
|---|---|---|---|
| **Flexibility** | Foam is very flexible | Foam is very flexible | Flexibility can be optimized according to preference |
| **Rigid enough to support head** | Foam is proven to provide enough support | Rigid lattice base with thin foam layer offers more support | Flexibility can be optimized according to preference |
| **Shape adaptable to head shape** | Difficult to process foam to 3D shape, the shell can only create a basic shape | Difficult to process foam to 3D shape, the shell can only create a basic shape | 3d printed structure can be created in any shape |
| **Manufacturable in small volumes** | 3D printing + cutting of foam | 3D printing + cutting foam | 3D printing |
| **Last multiple cycles** | Will last multiple cycles | | |
| **Effective cooling, good water flow** | Possibility of adding walls/channels for water guidance | Foam is denser than lattice, water will mainly flow through the lattice | Possibility of adding walls/channels for water guidance |
| **Cost** | Foam + very basic shell, very cheap | Complex flexible 3D printed structure needs to be outsourced | Complex flexible 3D printed structure needs to be outsourced |







| Flexible lattice | Shell + thin water bolus | Honeygrid | Watertubes: twin sheet thermoforming |
|---|---|---|---|
| Flexibility can be optimized according to preference | Head will quickly touch the rigid shell | Flexibility can be optimized according to preference | Thin water tubes are not very flexible |
| Flexibility can be optimized according to preference | Big rigid shell offers a lot of support | Flexibility can be optimized according to preference | Water tubes will be quite stiff |
| 3d printed structure can be created in any shape | Water bag can not be pre shaped | 3d printed structure can be created in any shape | Tubes can be folded around head shape |
| 3D printing | 3D printing + sealing film | 3D printing | Specialized thermoforming, mould needed |
| Will last multiple cycles | | | |
| Possibility of adding walls/channels for water guidance | No possibility for water guidance + head might clamp off the bolus | Hole pattern in structure can provide good water flow | Skin will not be cooled at the gaps between the tubes |
| Complex flexible 3D printed structure needs to be outsourced | Foam + film, very cheap | Complex flexible 3D printed structure needs to be outsourced | Thermoforming at external company |

# 3.2 OUTER ENCLOSURE

The different production possibilities described in chapter 2.2 are compared on different aspects: flexibility, water tightness, not easily punctured, manufacturable in small volumes, lasting multiple cycles, transfer cooling from water to skin and cost. A colour scale was used to rate each idea; green: good performance, yellow: doubtful performance or red: inadequate performance (meaning the idea will not work).

| | Sealed Plastic films | Shrink wrap | Watertight textiles |
|---|---|---|---|
| Flexibility | Flexible films can be used | | Watertight textiles are rather stiff |
| Watertight | Can be sealed as a watertight bag | Very thin, gaps are created easily | Can be sealed as a watertight bag |
| Not easily punctured | Depends on the material thickness | Film gets punctured during shrinking | Strong material, will not be punctured |
| Manufacturable in small volumes | Bought per roll, cut and seal | | |
| Last multiple cycles | Will last multiple cycles | Gets punctured very easily | Will last multiple cycles |
| Transfer cooling from water to skin (wall thickness) | Broad variety of wall thicknesses available | Very thin film | Broad variety of wall thicknesses available, usually very thin |
| Cost | Plastic films, can be bought per roll | | Watertight textile is a more specialized material which increases price |

| 3D printed enclosure | Thermoformed enclosure | Silicon |
|---|---|---|
| Can be printed in flexible material | Difficult to thermoform flexible materials | Silicon is a flexible material |
| 3D printing is usually not watertight | Can be welded watertight | It is difficult to create a fully closed watertight enclosure in silicon |
| Strong, thick material, will not be punctured | | |
| 3D printing | Specialized thermoforming, mould needed | Silicon can be bought in small volumes |
| Will last multiple cycles | | |
| Minimal wall thickness 1 mm | Broad variety of wall thicknesses available | |
| Flexible 3D printing | Specialized thermoforming, mould needed | Silicon |

- Good performance
- Doubtful performance
- Inadequate performance

# 4 CONCEPTS

The best ideas from the previous chapter were selected and converted into concepts. In this chapter one outer enclosure concept and three concepts regarding inner structure are presented and compared in terms of cost, water flow and comfort. Based on the findings, a substantiated concept selection can take place.

# 4.1 OUTER ENCLOSURE

## Flexible plastic film

After analysing different possibilities to provide a watertight outer enclosure to the water bolus, it was decided that surrounding the bolus by plastic films would be the best solution.

SEBS film would be a suitable material to use for this purpose, since it is a very flexible film which has a soft touch that offers a pleasant feel to the skin.
A pattern can be created to make sure the film will fit perfectly around all sides of the bolus and to prevent folds from forming. The different cut-outs can then be sealed together using a heating device like an impulse welder or an iron.

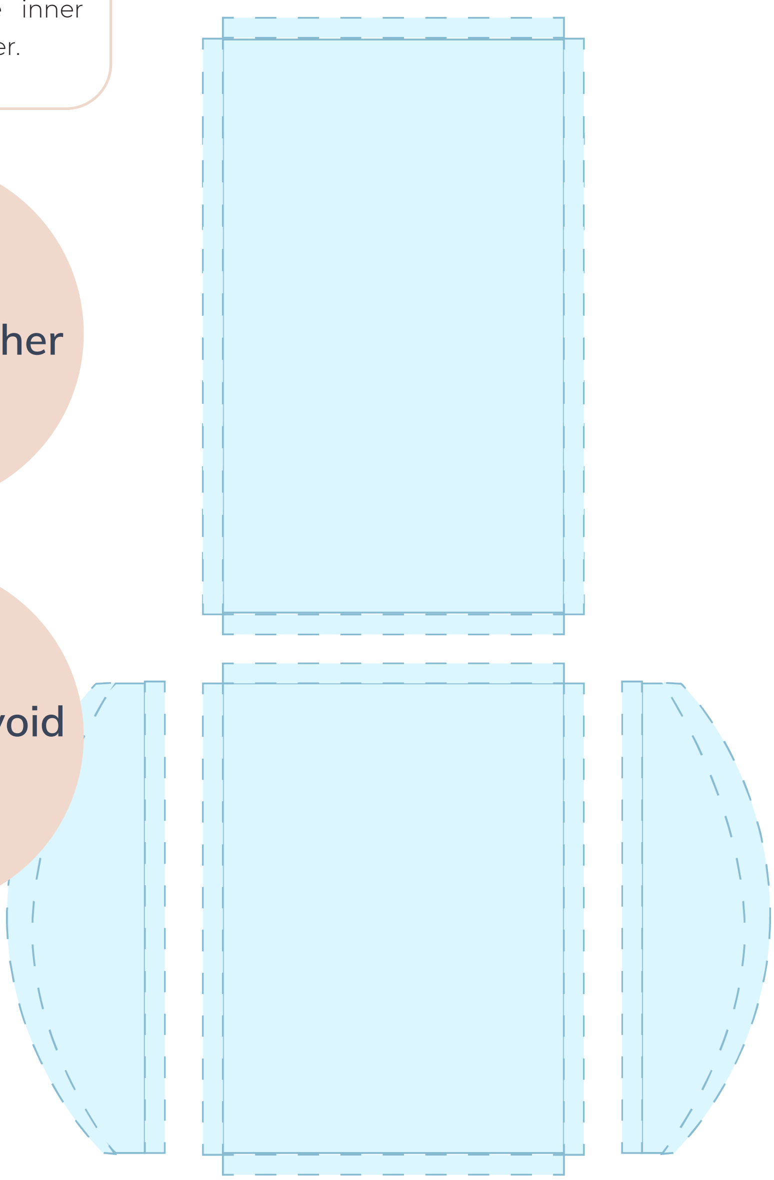
To avoid the enclosure to inflate when water starts circulating through, it will be attached to the inner structure by gluing or melting the two parts together.

Flexible plastic (SEBS) film

Sealed together

Attached to inner structure (glue or heat)

Pattern to avoid folds



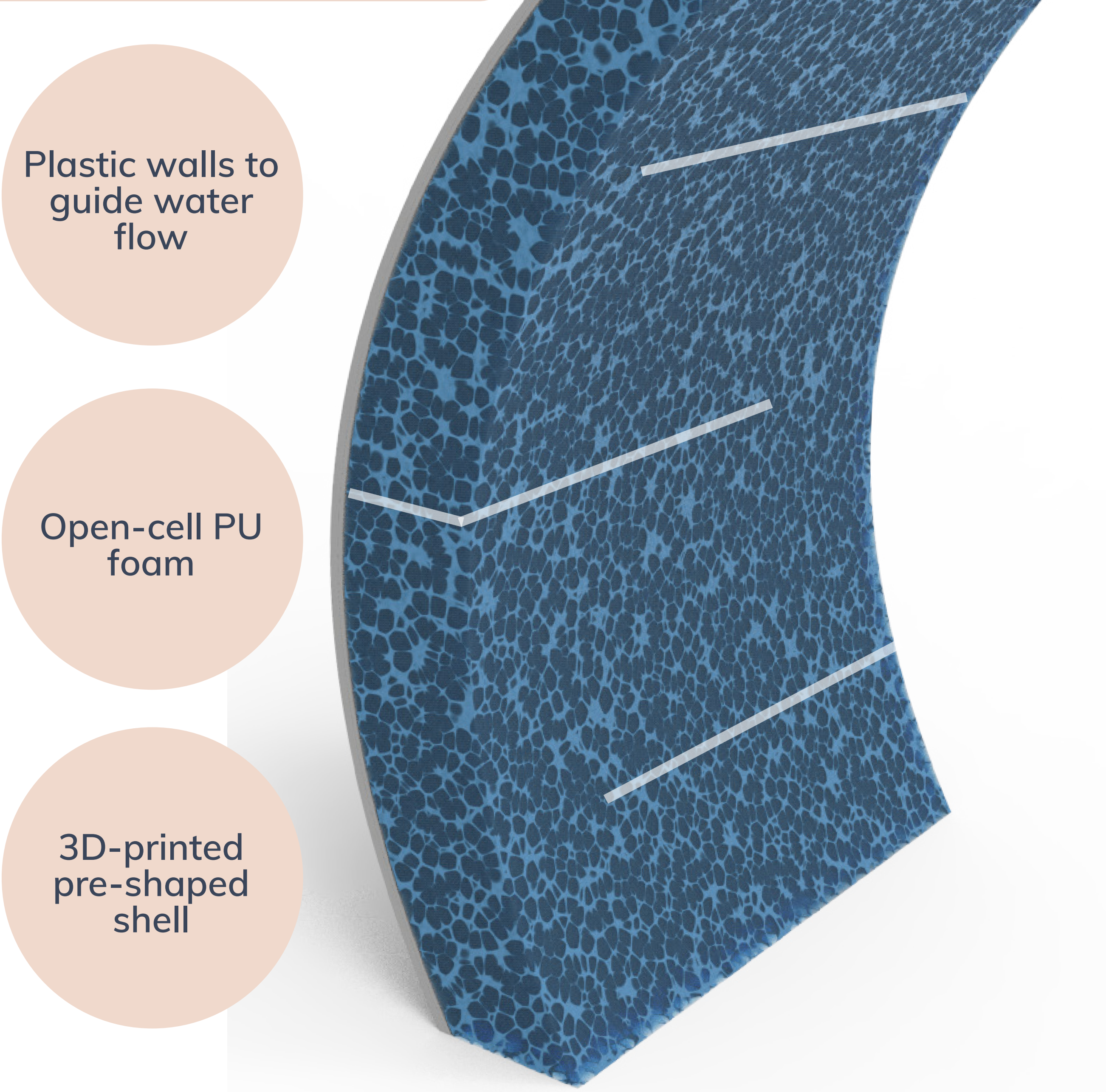
# 4.2 INNER STRUCTURE

## Concept 1: Shell + foam

The first inner structure concept starts from the same basic principle as the current water bolus: using open cell PU foam to provide structure and stability to the bolus. But to avoid the issues that occur in the current design, a few improvements are implemented.

To better follow the shape of the head, the foam is glued on a pre-shaped 3d printed shell. This shell will be printed at the minimal wall thickness of 1 mm to avoid disrupting the EM waves.

To make sure the water cools all areas of the bolus, plastic films will be added in between the foam. This will create water channels for the water to flow through.



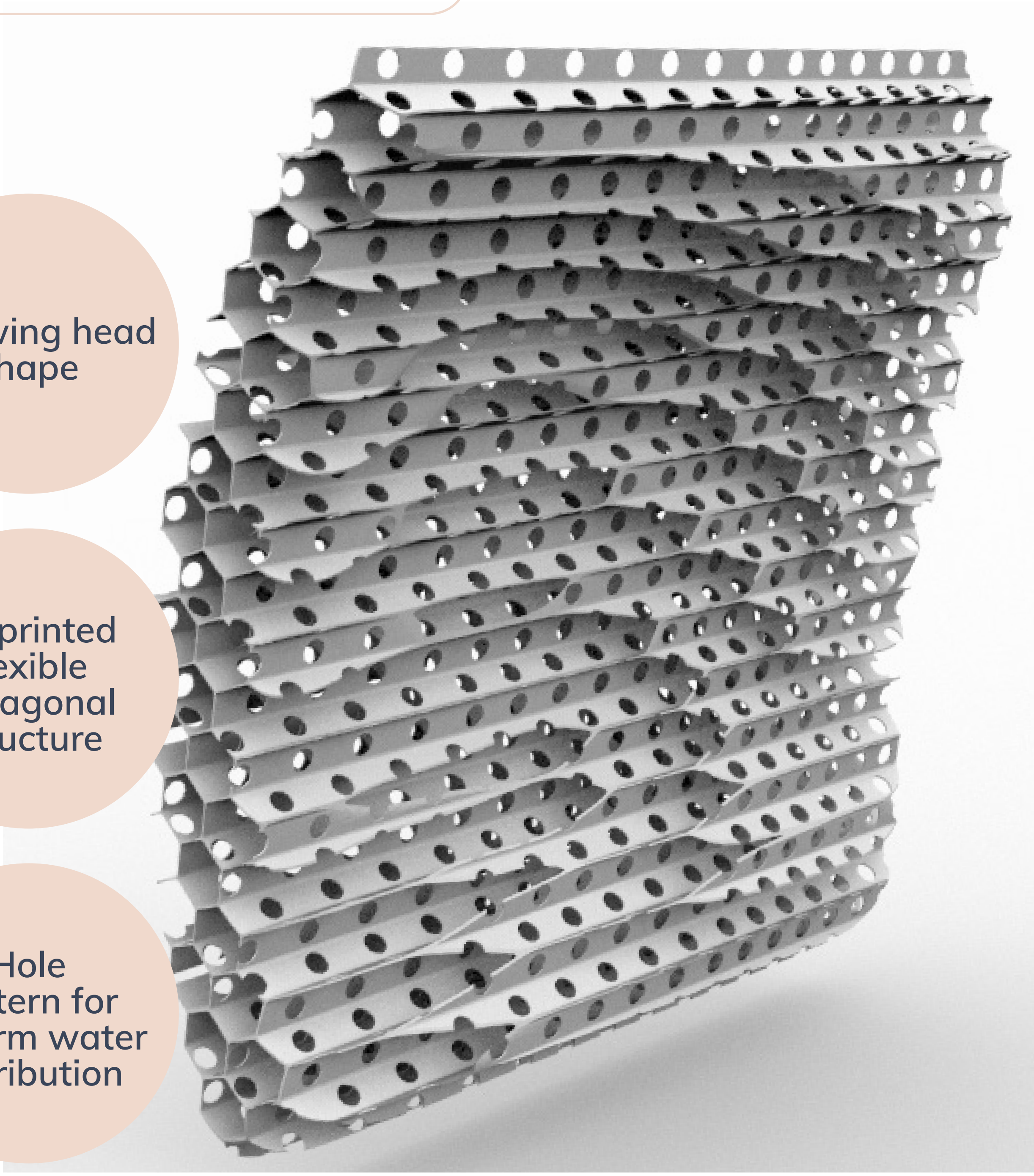
## Concept 2: Honeygrid

This concept is based on a previous graduation project done by Lisa Abdel Alim - van den Berg on the same topic.

The structure of this concept consists out of a pattern of hexagonal pipes which will be 3D printed in a flexible material to allow for variation in head dimensions.

Cut outs are created in the hexagonal structure to closely follow the head contours of the patients.

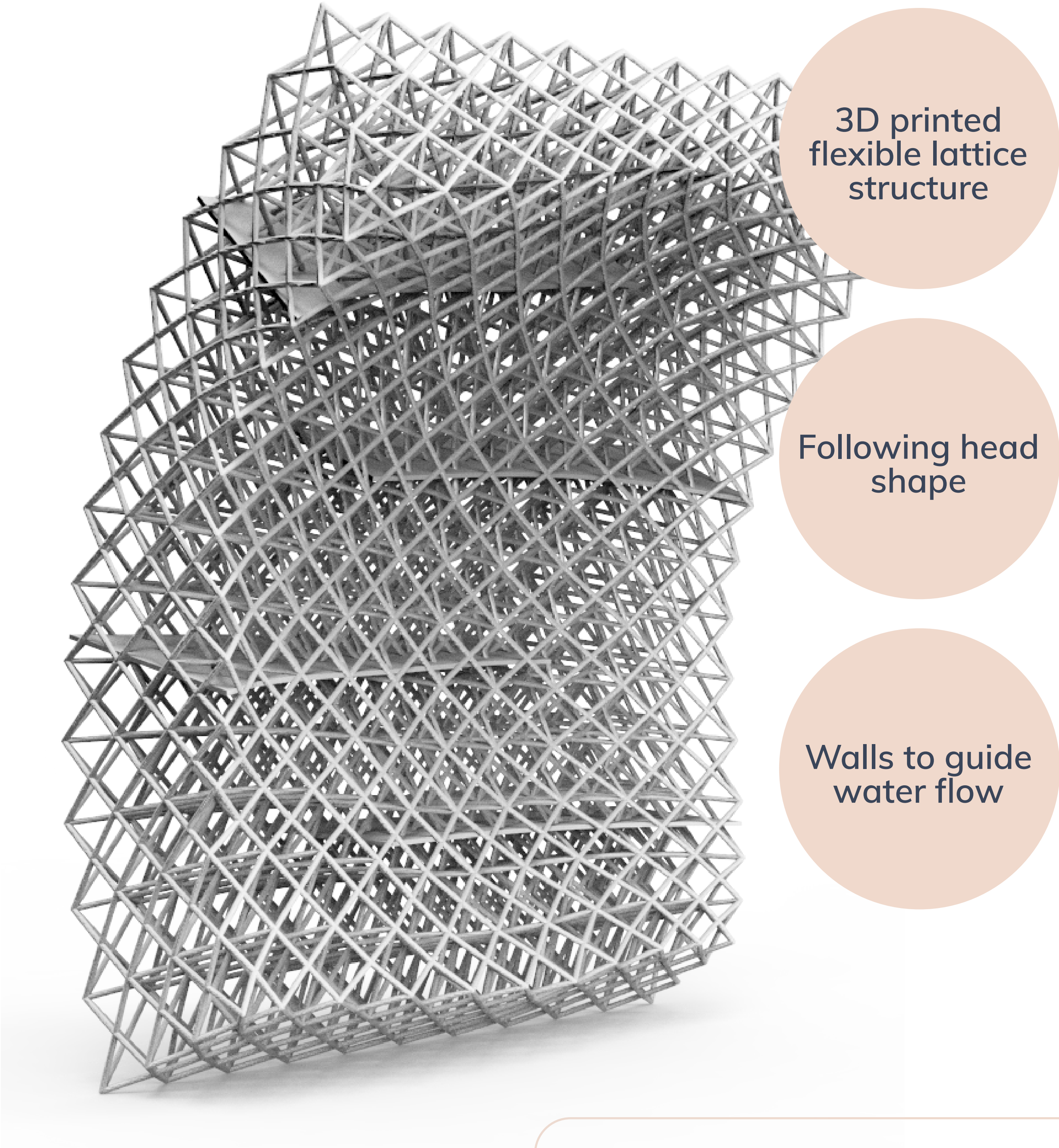
A hole pattern is implemented in the tubes. By making the spacing between the perforations bigger near the water inlet and smaller near the end of every tube, the water will be distributed uniformly throughout the bolus. (Birkelund et al., 2009)



Following head shape

3D printed flexible hexagonal structure

Hole pattern for uniform water distribution




## Concept 3: Lattice

The last concept consists out of a 3D printed lattice structure which will be printed in a flexible material. By changing the wall thickness and voxel size of the structure, the flexibility can be adjusted according to preference.

The structure is designed in a shape that will closely follow the contours of the patients' head.

To provide equal water distribution walls are printed in the structure that will provide a path for the water to flow through.

# 4.3 COMPARISON OF CONCEPTS

To make a substantiated decision on with which concept to continue, the different concepts were compared on three aspects: Material and production cost, uniform water flow and patient comfort.

COST

WATER FLOW

COMFORT

## Cost estimation (for 20 pieces)

A first rough cost estimation was made to get an idea of the price difference between the shell + foam concept and the 3D printed concepts. The bolus will only be produced in relatively small volumes, therefore the cost estimation was based on a production volume of 20 pieces. Since the volume of the Honeygrid and the Lattice is the same, the price of these concepts will also be identical.

In this brief estimation, the focus is only on the cost of the inner structure. The material and production cost of the outer enclosure is not included yet since this cost will be identical for all concepts.

### Shell + foam

The first concept mainly consists out of foam, which is already available at EMC and would only cost 2 euros per bolus. The rigid, 3D printed shell would cost 66 euros when printed at an external company. When printed in-house, the material cost would only be 2,4 euros. But considering the cost of buying a 3D printer, this would only be cheaper as from a volume of 36 pieces.

The downside of this concept is that there is more labour needed to manufacture the boli: Cutting the foam and plastic walls, gluing everything together and optionally setting up and maintenance of the printer. This all together will increase labour time by 30-60 minutes.

### Honeygrid/Lattice

The flexible 3D structures of the honeygrid and lattice concepts are to complex for in-house printing and will need to be outsourced. The benefit of these concepts is that there is no additional processing or labour needed to create the inner structure. However, this comes at a more expensive cost of 170 euros.

### Conclusion

The material costs of the 3d printed structures will be significantly higher than the material costs of the shell + foam concept. However, for the foam concept, more labour time will be needed to manufacture the boli.

## Shell + Foam

**Material**

**Foam**
Already available at EMC
**2 euros**

**3D-printed shell**
Outsource 20 pcs:
**66 euros**

OR

Print @ EMC
- 3D-printer: 2300 euros
- Material cost per piece: 2,4 euros
- 36 pieces: 66 euros
- 100 pieces: 25,4 euros

**Film**
**Glue**

**Labour**

**Preparing inner structure**
- Cutting foam
- Cutting space for walls
- Cutting walls/foil
- Glueing walls to foam
- (Printing shell + maintenance of printer)
- Glueing foam to shell

**30 - 60 minutes of extra labour**

**Glueing + Sealing**

## Honeygrid/Lattice

**Material**

**Print cost**
Outsource 20 pcs:
**170 euros**

**Film**
**Glue**

**Labour**

**Glueing + Sealing**

# Water flow

## Research question:

Is the water distributed evenly over the full bolus volume when flowing through the foam, lattice and honeygrid structures?

## Test set-up

The three different concepts: Honeygrid, Foam + walls and lattice + walls were created in small scale and inserted in a watertight box. To make sure all water flows through the structures and not around them, an additional layer of film was glued onto the structures before inserting them in the box. This test set-up was used to do a test with colouring agent and an infrared test.

## Colour test

### Methodology

To visualize the water flow, the boxes were connected to a water pump. Once the structure was fully filled with water, colouring agent was added. This process was filmed: screen shots and corresponding timing of this video can be found in figure 32.

### Results

This test showed that the water is distributed very evenly in both the lattice and honeygrid structure. However, in the foam structure the water tends to flow in the shortest path between the plastic walls, leaving large parts of the structure unreached and thus not efficiently cooled.

Another finding is that due to the more dense nature of the foam, the water encounters more resistance and takes two to three times longer to flow from in to outlet than in the 3D printed structures using the same pump. The lattice structure causes the least resistance and thus the fastest flow.

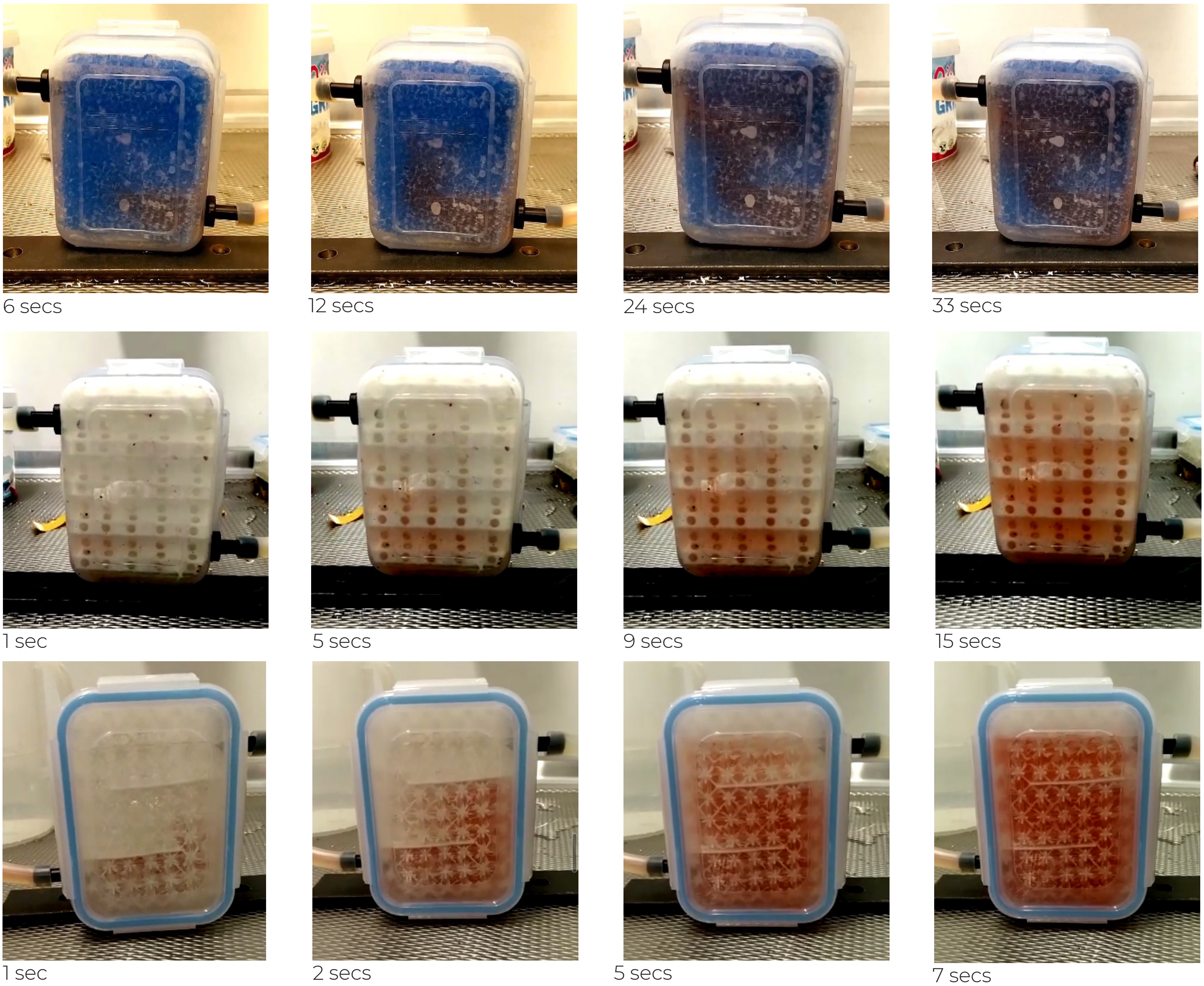



*Fig. 32: Colour agent test: foam, honeygrid, lattice*

## Infrared test

### Methodology

For the infrared test, the boxes were first fully filled with hot water (50 degrees Celsius) after which cold water (20 degrees Celsius) was injected. The change in temperature was captured using an infrared camera (FLIR TG165).

### Results

The results of the infrared test confirmed what was found in the colour test: The cooling happens homogeneously in the lattice and honeygrid structure whereas the water tends to follow the shortest path in the foam structure (see fig. 33-36).

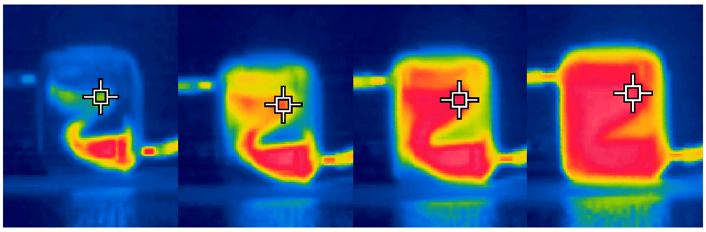


*Fig. 33: Infrared test: Foam*

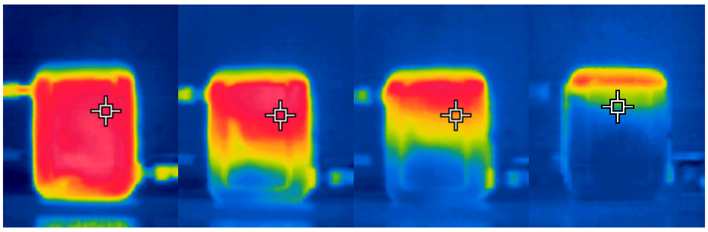


*Fig. 34: Infrared test: Honeygrid*

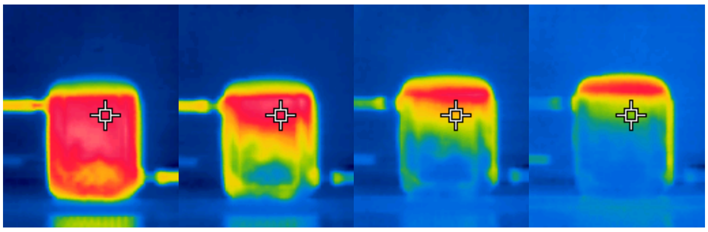


*Fig. 35: Infrared test: Lattice*

## Simulations

### Methodology

Simulations were carried out to test the water flow distribution on a larger scale. For the honeygrid the structure was simulated for a box shape, without the cut-outs that would be made in order to follow the head shape. The lattice and foam simulations were simplified by testing how the water would behave in an empty box, with walls to guide the water flow.

### Results

The simulations showed that the water would spread homogeneously in both the honeygrid structure as well as in a structure with implemented walls. The water flows throughout the full volume, without leaving areas untouched (see fig. 36-35)

An aspect to take into account when designing a walled structure is that turbulent flow might occur near the water inlet if the channels are made too narrow. However, this is less likely to happen when the inserted structures will cause resistance to the water.

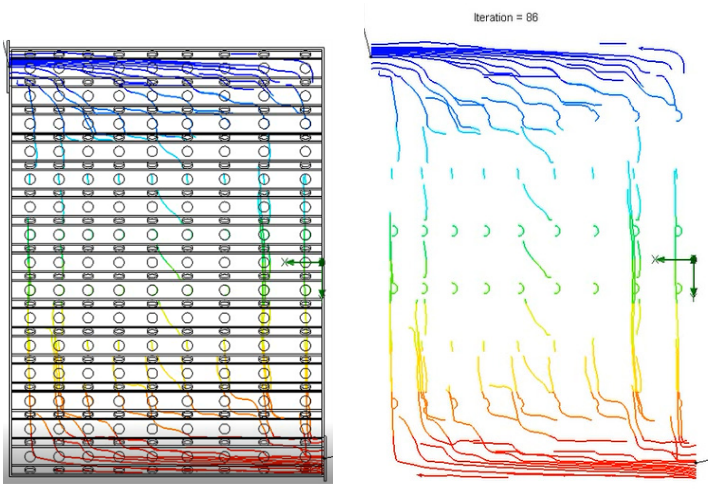



*Fig. 36: Water flow simulation: Lattice*

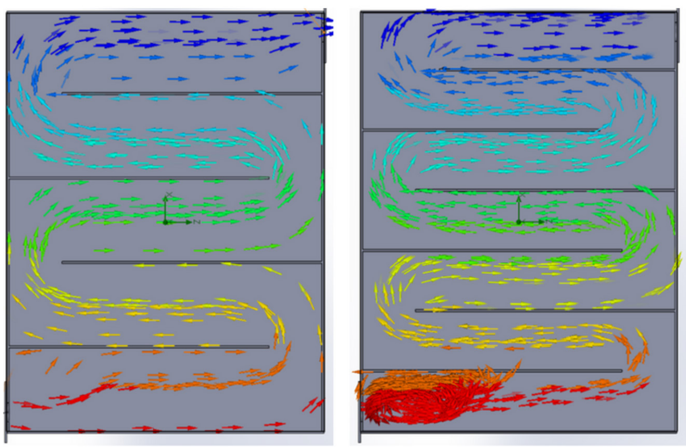


*Fig. 37: Water flow simulation: Foam*

## Conclusion

The colour test, infrared test and simulations all confirmed that both the lattice + walls structure as well as the honeygrid structure will provide an even water distribution throughout the full bolus volume. The foam on the other hand did not perform well on the tests: due to the more dense structure, the water encounters more resistance, leading it to flow slower and encouraging the water to follow the shortest path from in- to outlet. This leads to large areas of the bolus remaining uncooled.

# Comfort

## Flexibility

A more flexible structure will adapt more easily to the shape of the patient's head and cause less pressure and thus discomfort on the skin during treatment.

### Research question

How much force is needed to compress the structures up to 20mm?

### Test set-up

A tensile tester was used to measure the needed force to compress each structure up to 20mm (see fig. 38). The diameter of the compression area was 19 mm.

### Methodology

Each structure was positioned in the compression tester and tested three times at slightly different positions at a speed of 20mm/min. For each structure, the averages of these measurements were used in this analysis.

### Results

Table 1 gives an overview of the measured forces at a compression of 5, 10, 15 and 20mm.
The results show that up to a compression of 15 mm the foam is the most flexible, followed by the lattice and then the honeygrid.

However the force-displacement curve of the foam is more parabolic, which makes that the structure quickly becomes more stiff at a larger displacement between 15 and 25mm (See fig. 39).

### Conclusion

In general the measured differences in flexibility between the three concepts are not very big. However, during this test the forces were measured when compressing only a small area of the structure. When the contact area increases to the full head size, the small difference measured here may become way more significant

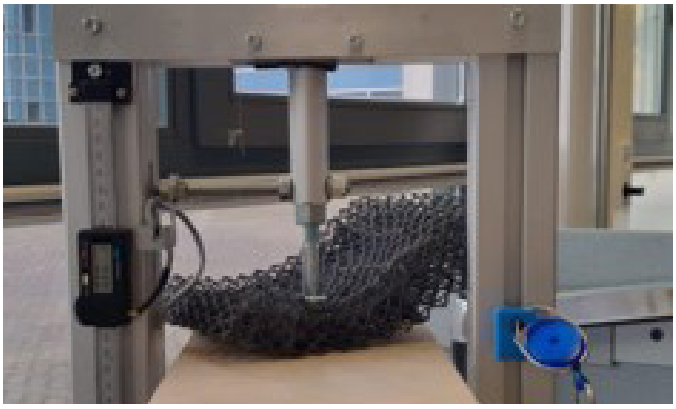


*Fig. 38: LETT tester*

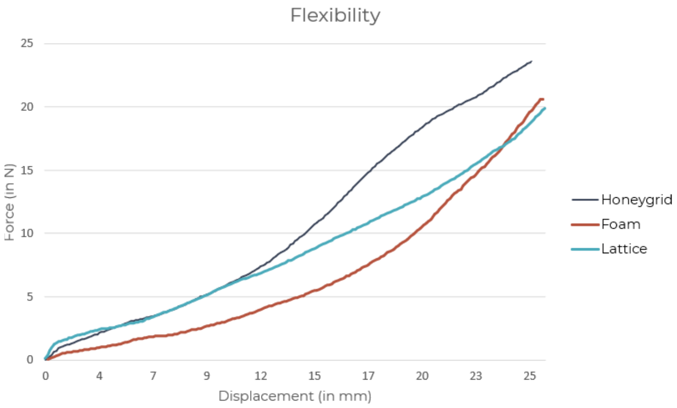



*Fig. 39: Compression test: honeygrid vs. foam vs. lattice*

| | Foam | Lattice | Honeygrid |
|---|---|---|---|
| 5 mm | 1,7 N | 3,0 N | 3,1 N |
| 10 mm | 3,8 N | 6,0 N | 6,2 N |
| 15 mm | 7,8 N | 9,5 N | 11,8 N |
| 20 mm | 14,7 N | 13,6 N | 19,1 N |

*Table. 1: Compression tests: results*

## Fit

A structure that is already pre shaped according to the shape of the head will need to be compressed less in order to adapt to and be in full contact with the skin. This will cause less pressure on the head and more patient comfort.

A very detailed preformed shape can be designed and acquired with the 3D printed concepts (lattice & honeygrid). With these concepts it would be even possible to personalize the boli exactly for every patient by making use of their CT scans (see fig. 40-41).

For the foam concept this will not be possible, the shell can provide the bolus with a very basic single curved shape but the foam cannot be manufactured in a way to closely follow the patient contours nor can it be personalized to every individual (see fig. 42).

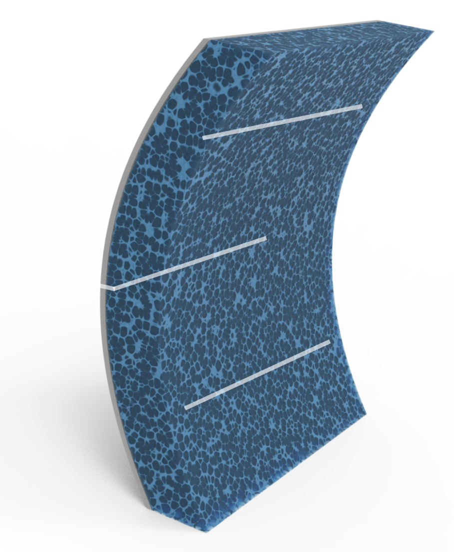


*Fig. 40: Foam: single curved shape*

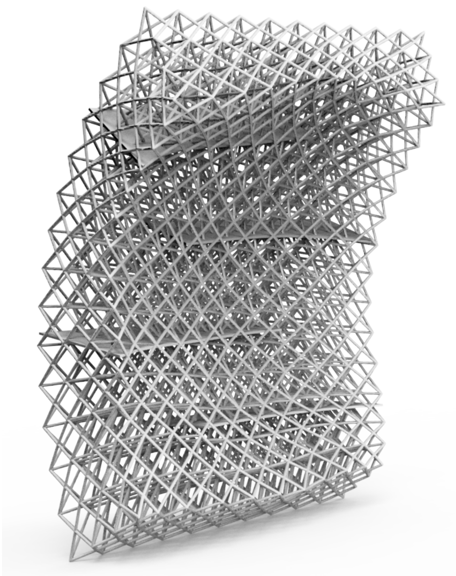


*Fig. 41: Lattice: Three dimensional head shape*

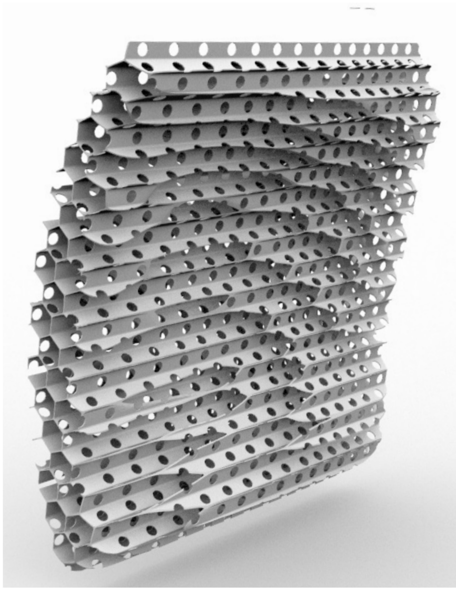


*Fig. 42: Honeygrid: Three dimensional head shape*

## Overview

An overview of the findings from chapter 4.3 can be found below.

| | Shell + Foam | Lattice | Honeygrid |
|---|---|---|---|
| Cost (inner structure) | 68 euros<br>30-60 mins labour | 170 euros | 170 euros |
| Water flow | Cooling not uniform<br>Slow water flow | Uniform cooling<br>Good water flow | Uniform cooling<br>Good water flow |
| Comfort: flexibility | Most flexible | 2nd most flexible | Least flexible |
| Comfort: Fit | Very basic head shape + no personalization | Detailed head shape + possibility for personalization | Detailed head shape + possibility for personalization |

## Concept selection

Based on the analysis in this chapter and a discussion with the stakeholders (developers and technicians) at Erasmus MC, it was decided to eliminate the shell + foam concept. This concept is the cheapest, but will not perform as well as required on comfort and water flow. It was discussed that having a more comfortable and efficient water bolus is worth the additional cost price.

The honeygrid and lattice are both performing well on the tests and will be tested and developed further in the next chapters before making a decision on the final design.

# 5 ANTHROPOMETRIC ANALYSIS

Designing a bolus that closely follows the patient contours, will contribute to solving several of the challenges defined in chapter 1.5. The bolus will connect better to the skin, avoiding gaps to occur between skin and bolus and therefore providing a more effective and uniform cooling. Less pressure will be needed to adapt the bolus to the shape of the patient, leading to a more comfortable patient experience. Lastly, having a pre-shaped bolus will make it easier to position the patient in a precise and repeatable manner.

The goal of the anthropometric analysis is to get a better understanding of variations in head and neck sizes. Since the bolus is only touching the side of the head and neck, the main focus of the analysis was on finding a surface connecting to the side of the face while avoiding the mouth and nose area of the patient.

It was explored if there is a need for different sizes of boli and how much adaptability and flexibility the bolus must have to accommodate for the variation in head and neck shapes.

# 5.1 ANTHROPOMETRICS OF DUTCH ADULTS

The CAESARNL database (Robinette et al., 1999) was used to study the variety in head and neck shapes of Dutch adults. First, one dimensional measurements were explored to get a rough idea of the needed bolus dimensions and variations, next a database of three dimensional head scans was studied to get a more detailed idea of variations. The area of interest for this analysis was the mainly the dimensions and curvature of the side of the head, while avoiding the mouth and nose area (see fig.43).

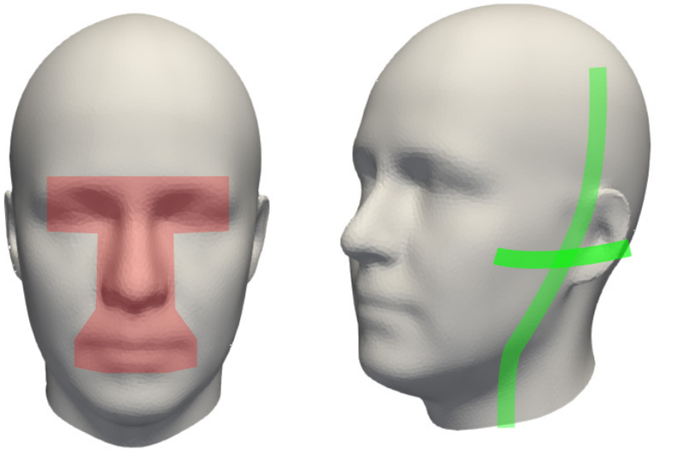


*Fig. 43: Area of interest*

## 1D Analysis

To get a first idea on the global dimensions of the bolus, a 1D measurement analysis was carried out using the CAESAR NL database (Robinette et al., 1999) and the DINED platform (Huysmans et al., 2020). For the head breadth, the head depth, neck base circumference, head circumference and face length (see fig. 44) the average measurements as well as the extremes were noted down in table 2. These 1D dimensions can be almost directly translated into dimensions of the water bolus (see fig. 45). An initial basic understanding of variation in these measurements can be obtained by looking at the standard deviations and the differences between the extremes.

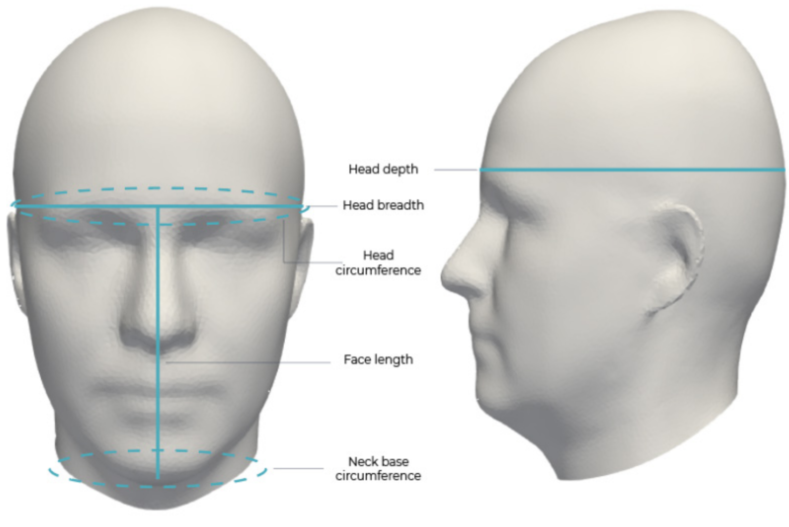



*Fig. 44: Key measurements*

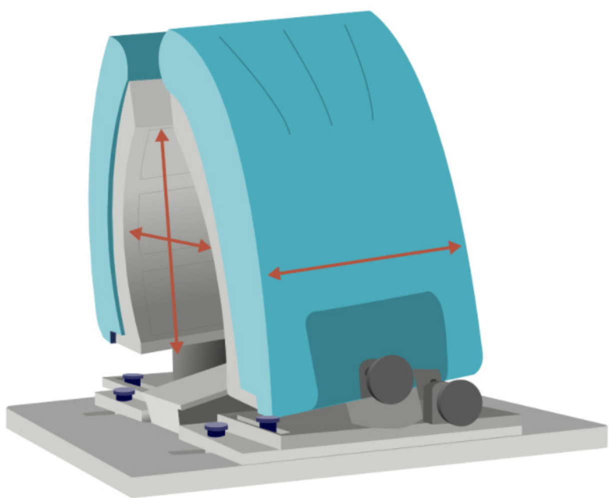


*Fig. 45: MR collar settings*

| | CAESAR (NL) 18–66, mixed | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Measures** | **P1** | **P5** | **P50** | **P95** | **P99** | **P99-P1** | **P95-P5** | **SD** |
| Head breadth (mm) | 135 | 139 | 149 | 159 | 163 | 28 | 20 | 6 |
| Head depth (mm) | 174 | 180 | 193 | 206 | 212 | 38 | 26 | 8 |
| Neck base circumference (mm) | 367 | 396 | 465 | 534 | 563 | 196 | 138 | 42 |
| Head circumference (mm) | 515 | 529 | 562 | 595 | 609 | 94 | 66 | 20 |
| Face length (mm) | 98 | 104 | 117 | 130 | 136 | 38 | 26 | 8 |

*Table. 2: Key measurements*

# 3D Analysis

A database of 1133 Dutch head scans (Robinette et al., 1999) was analysed using Paraview (Paraview, 2021) and custom developed plugins (Huysmans, 2020). This software allows to create a statistical shape model out of the individual scans: create an average head model and put the different shapes in correspondence with each other. 27 modes of variation are generated by the software, which each represent different variations in shape ranging from P1 to P99 e.g. variation in size, width or length of the heads (see fig. 46). The first 10 modes of variation already explain most of the shape variability and will be used for this analysis.

For each mode of variation, a screenshot was made of the front view and the top view of the head for both the P1 and P99 shape. The outline of each head shape was created an positioned on top of each other in Photoshop for better visibility. This created a visual and easily understandable representation of shape variations. Now the maximal distance between the average shape and the extremes could be measured at different points of the head. Out of this analysis it could be concluded that the shape variation to account for in the bolus design would be between 2 and 3 cm, a deviation of 1-1.5 cm from average. Most variation can be found in the neck area (see fig. 47).

However, since the MRcollar can be translated in y-direction, towards the ears of the patient, a part of this variation is already taken away. To include this aspect into the analysis, the head shapes were now aligned at the ears and the maximal distance between the average shape and the extremes was measured again. In this case, the shape variation is reduced to a range of 5 mm to 16 mm (see fig. 48).

# Conclusion

It can be concluded that a water bolus design that can provide a variation of 2 cm would be adaptable to every head shape. If the bolus is shaped to the average head, 1 cm of variation would already be sufficient to adapt to both the smaller and larger heads.

*Fig. 46: Modes of variation 1-3*

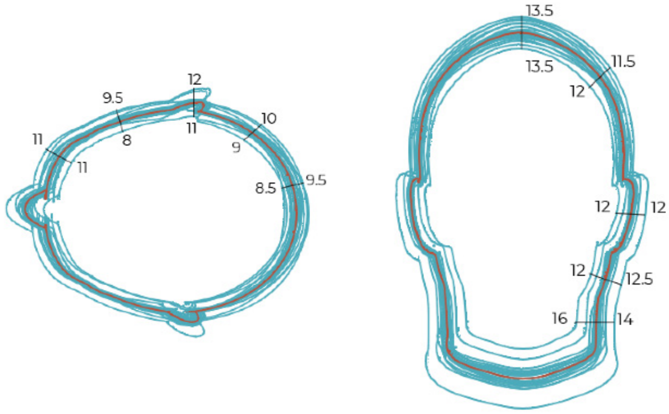



*Fig. 47: Variation in head and neck shapes*

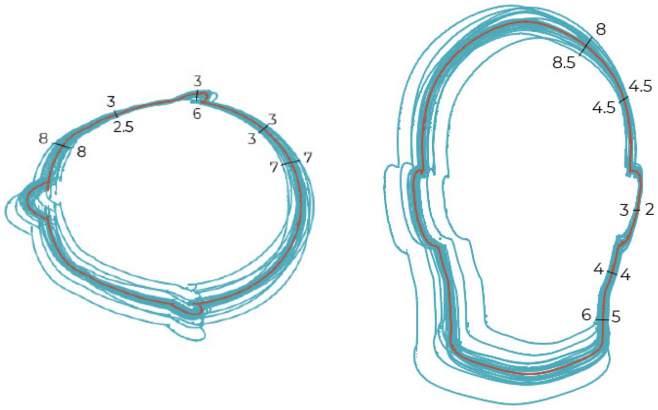



*Fig. 48: Variation in head and neck shapes after ear alignment*

# 5.2 ANTHROPOMETRICS OF HEAD AND NECK CANCER PATIENTS

## Patient anthropometry

Since, head and neck shapes of cancer patients with tumours can vary from the general population, a second analysis was carried out using CT scans from 40 patients at Erasmus MC.

To make the data ready for use, the DICOM files were converted to .OBJ files using 3D Slicer (3D Slicer, 2021) and democratiz3d. Then, WRAP (Wrap, 2020) was used to create mesh correspondence in order to be able to compare the different files. Finally, a statistical shape model could be generated again in Paraview (Paraview, 2021).

The statistical shape model could be analysed and visualized again in the same way as described in the previous chapter (see fig. 49-50).

## General Dutch population vs. H&N cancer Patients anthropometry

The analysis showed that the anthropometry of head and neck cancer patients is very similar to the anthropometry of the general Dutch population. None of the analysed patient scans showed bulges or abnormalities caused by the tumour on the skin. However, the employees at Erasmus MC mentioned that some patients do show these abnormalities.

It was remarkable that within the analysed patient group, a lot of subjects had relatively larger heads but there was also a relatively big group with smaller heads (see fig. 51). The smaller heads can be explained by the fact that deep hyperthermia treatment is a treatment that is often used as a last option when other treatments were not successful. Patients have already gone through a long process of different treatments in the head and neck region that can lead to illness and pain which cause weight loss. Also, some patients might have already undergone surgery, where parts of the tissues were removed.

It is more difficult to find an explanation for the large amount of bigger patient heads. Partially this can be due to the fact that men are twice as likely to suffer from head and neck cancer as women. Another factor that might play a role in this phenomenon is that one of the main causes for head and neck cancer is excessive drinking, which causes weight gain.

## Conclusion

It can be concluded that the anthropometry and geometry of patients is similar to the anthropometry of the general Dutch population, however within the patient group more extremes occur: relatively much bigger heads as well as smaller heads.

Therefore, the bolus should account for a bit more variation then found in chapter 5.1. The bolus should be able to accommodate for a variation between 7 mm and 21 mm. By using the average head shape to create a bolus shape, the needed variation can be halved to 3,5 - 10,5 mm.

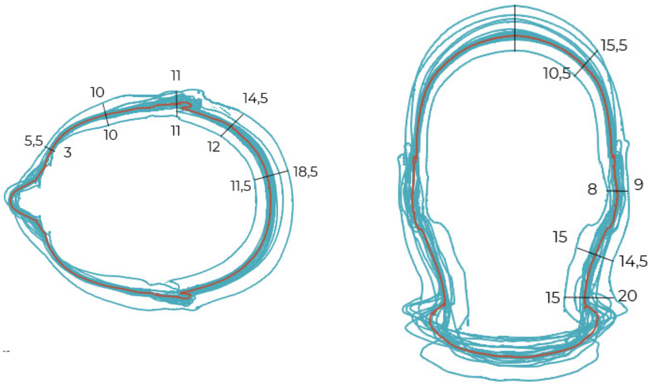



*Fig. 49: Variation in head and neck shapes of patients*

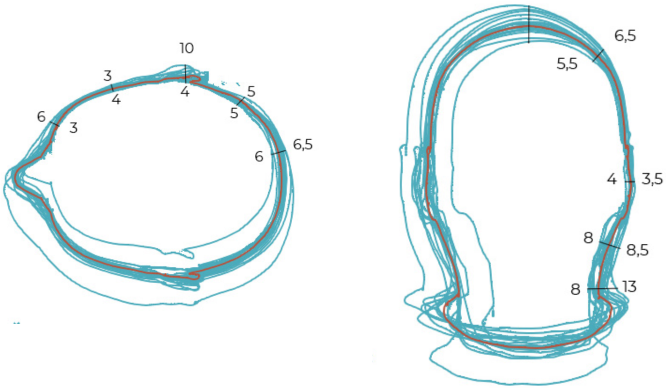



*Fig. 50: Variation in head and neck shapes of patients after ear alignment*

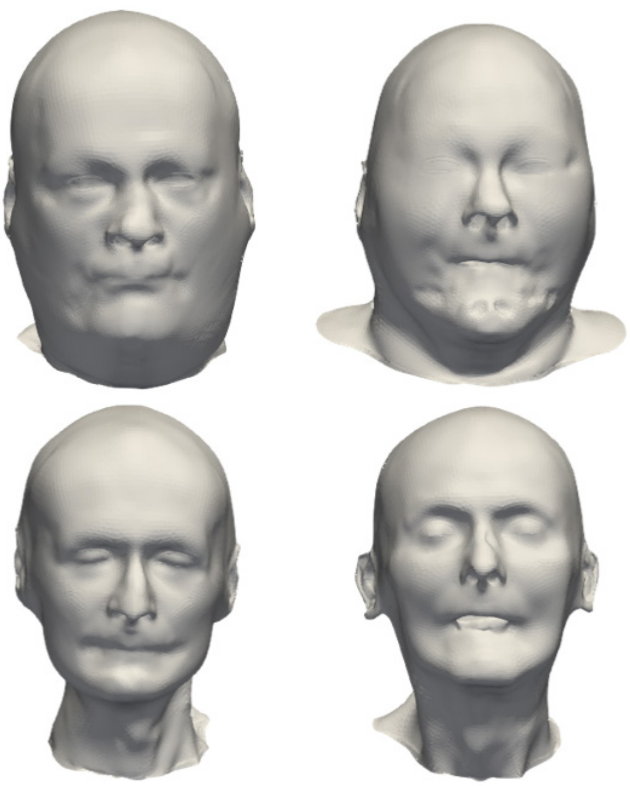


*Fig. 51: Patient scans: bigger head as well as very skinny patients*

# 6 EMBODIMENT

During the embodiment phase, both the honeygrid and lattice concept were further developed and prototyped into a feasible and functional product. The main focus points for the inner structure were: shape, water flow, flexibility and stability. Also the outer enclosure was optimized to be watertight, glueable to the structure and fitting to the sliding system.

# 6.1 BOLUS SHAPE DESIGN

## Bolus sizing system

Based on the anthropometric analysis it was decided that there are two possible sizing systems for the water bolus: (1) One bolus, based on the average shape (see figure 52). This would create a maximum variation of 1 cm between the bolus and the head. (2) two Boli, based on a P25 and P75 head (see figure 53). Smaller heads would use the smaller bolus and the larger can be used for larger heads. This would create a very good fit for most patients with a maximum deviation between head and bolus of 5mm.

Another possibility would be to make a personalized bolus for every patient, based on their head CT's or MRI's. This could be a very fast, fully automated process and could especially help to create a better fit around the ears. Nevertheless this would drastically increase the price of the boli while the sizing system discussed before will already fit most patients very well. An interesting approach would be to use one of the proposed sizing systems for most patients, and opt for a personalized bolus for patients with more extreme and specific deformities due to the tumour.

Within the scope of this project it was decided to focus on the design of one average bolus. In a later stage of development this bolus concept could be altered to two different sizes or a personalized approach if deemed necessary.

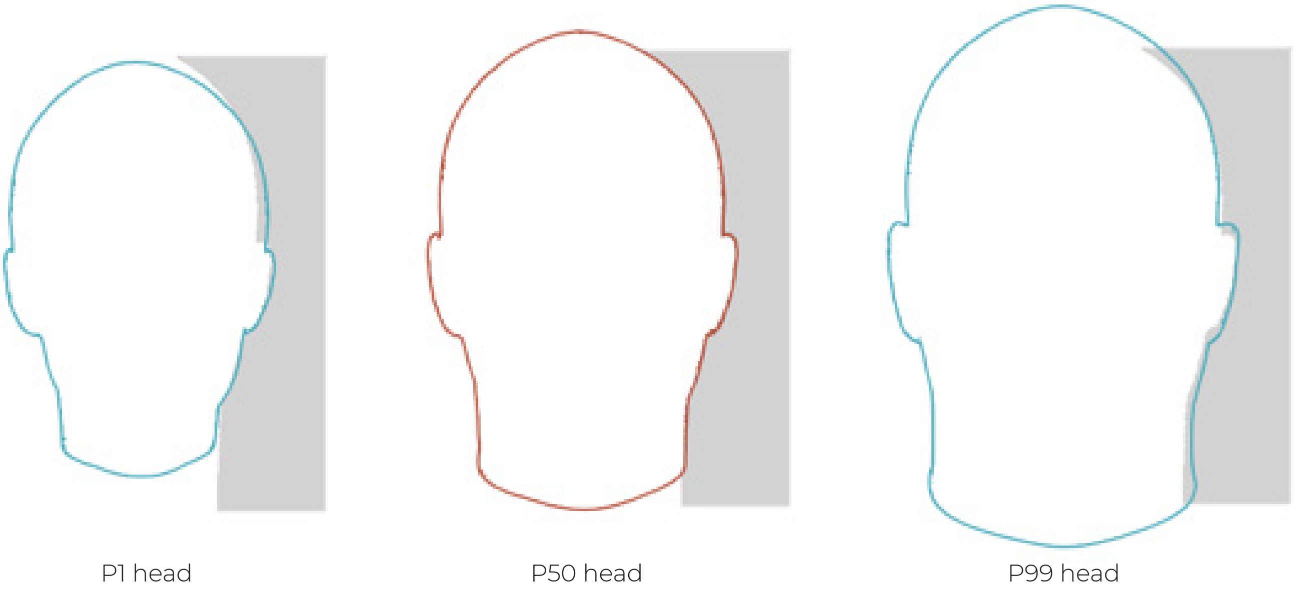



*Fig. 52: Bolus based on average head shape*

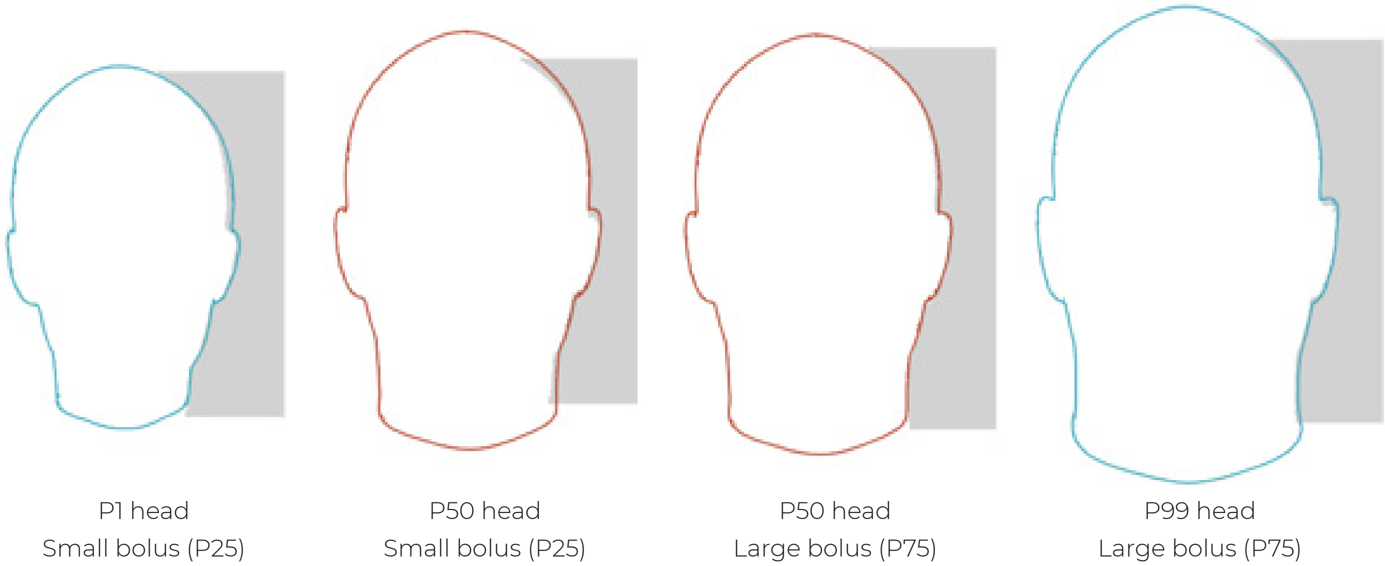



*Fig. 53: Bolus based on P25 and P75*

# 3D bolus design

The average head was virtually positioned in the MRcollar to generate a bolus exactly fitting to the skin of this model. This shape would be far too detailed for proper water flow and to fit most patients. Therefore the ear geometry was removed and the bolus was smoothened into a more suitable shape using Meshmixer. A lattice or honeygrid structure can be generated from this model using NTopology (see fig. 55).

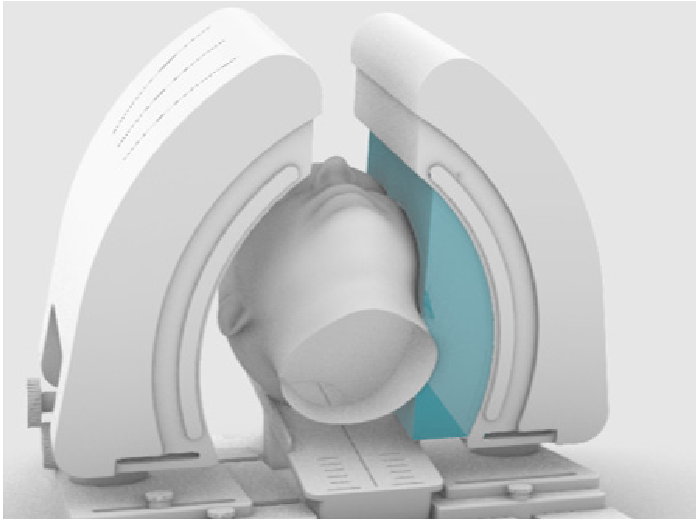


*Fig. 54: VIrtual mannequin positioning*

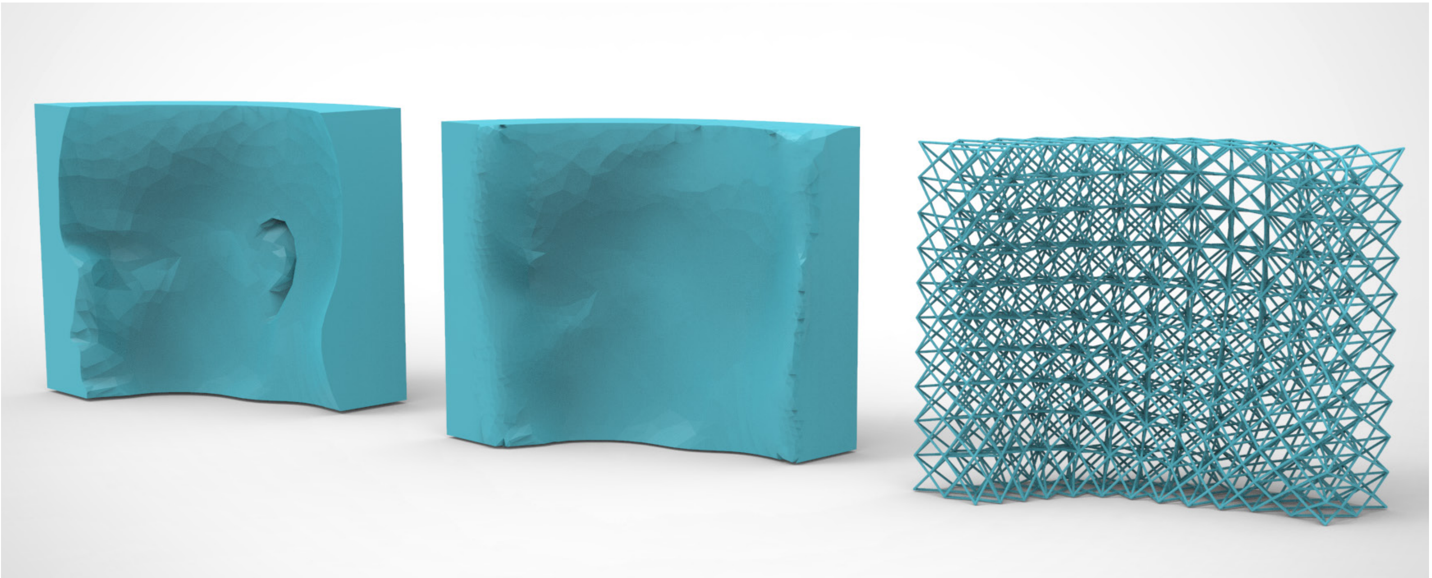


*Fig. 55: Lattice generation steps*

# Iteration 1

## Fit in MR collar

When the first shape iteration was tested in the MR collar, it was discovered that the digital positioning of the patient on which the shape design was based, was not identical to the actual positioning of the patient.

In the real setting, the patient is positioned with his shoulders almost touching the bolus, leading to a bolus that covers the lower part of the head and a large area of the neck. The first shape iteration was designed to cover a large part of the face and only a small part of the neck. Because of this mismatch between the design and the use, a large gap occurred between the neck of the patient and the bolus (see fig. 56).

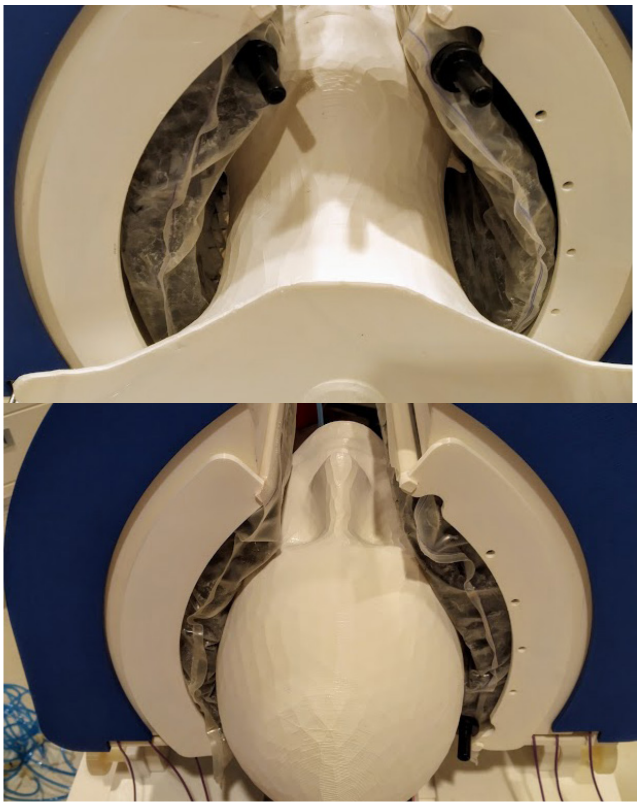


*Fig. 56: Fit in MR collar*

# Iteration 2

## Shape redesign

A second shape was created to better fit the patient during treatment. This time the P50 digital patient model was positioned more backwards in the MR collar to create a better fit around the neck area (see fig. 57). Subsequently the lattice can be generated using the same method as shown in figure 55.

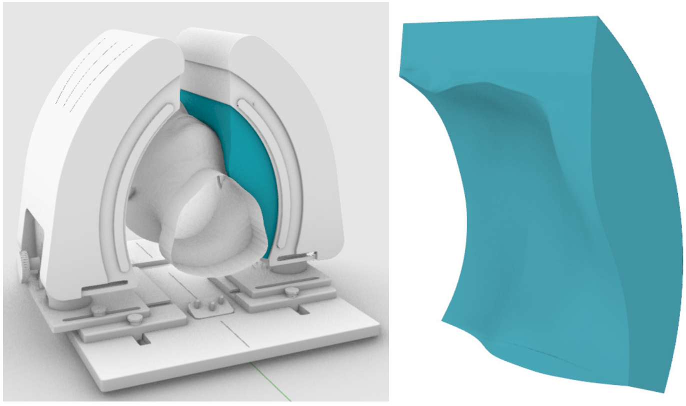


*Fig. 57: Shape redesign*

## Digital patient fit

The new bolus design was digitally positioned onto six different head models to verify the fit and see how much the bolus will need to be compressed in order to fully touch the face of the patient. This was done for a P1 and P99 head shape as well as for four selected patient scans. The patients were chosen to be varied in head sizes.

Once the bolus was positioned to fully overlap with the head models, a colour map could be created to visualize the thickness of the overlap at each point and thus the amount the bolus will need to be compressed.

It was found that for every tested head shape, the bolus has to be compressed about 15 mm for most of the surface area (green on the colour map) in order to be in full contact with the skin. In some smaller areas the needed compression increases up to a maximum of 25 mm. These values are in line with what was found in the anthropometric analysis.

In real life, the compression needed to be in contact with the skin will be less, since (1) the shape does not need to overlap and (2) the shape can also adapt to the skin in directions other than the compression direction.

To create a better fit which will need to be compressed less and cause less pressure on the patient's skin, a sizing system could be implemented or the boli could be personalized for each patient as proposed before.

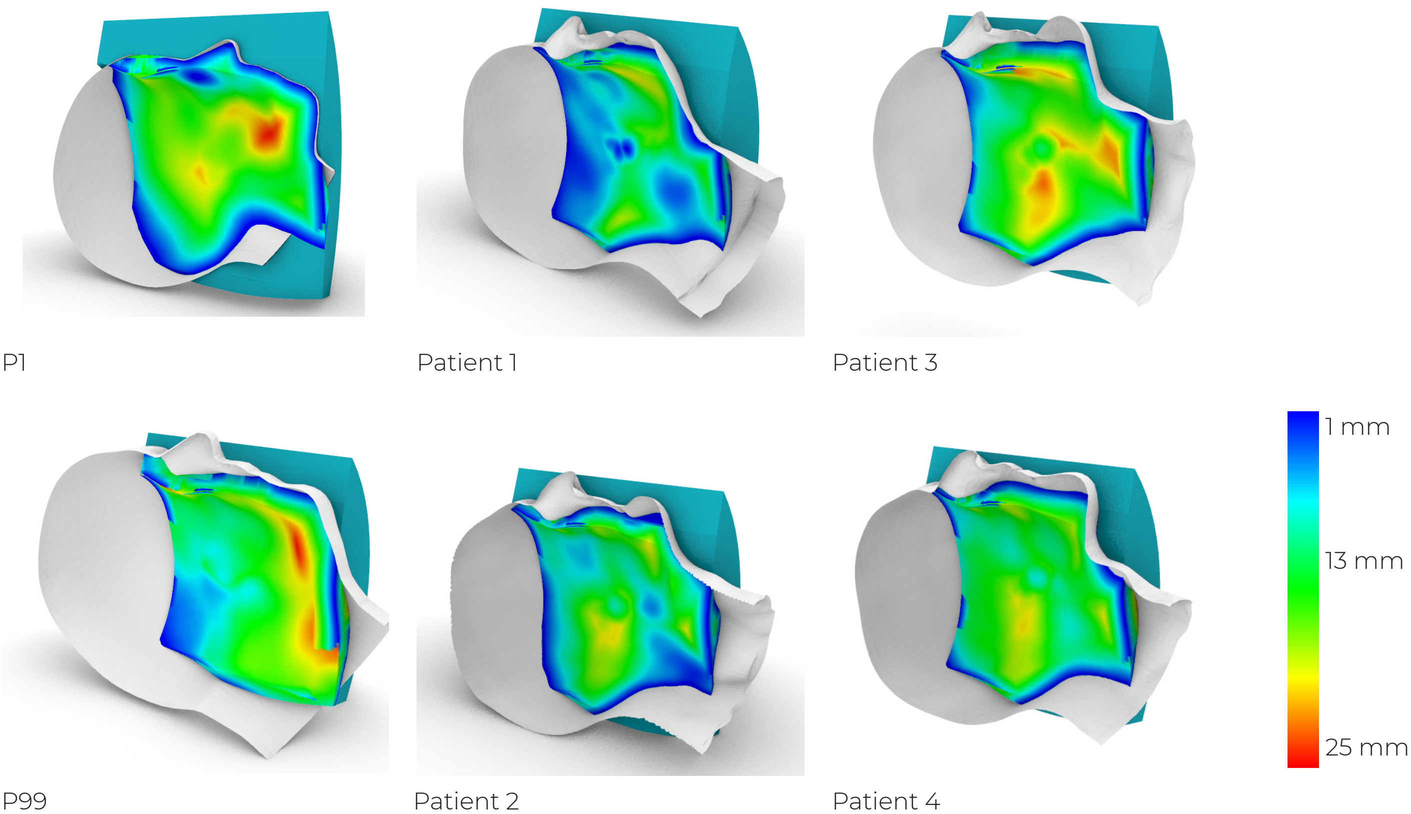



*Fig. 58: Digital patient fit*

## Fit in MR collar

When the new shape was positioned in the MRcollar and tested on the patient model, it was clear that the fit improved vastly, The bolus connected well at the top of the head, but also in the neck area (see fig. 59).

## 15 degree fit

When treating patients with tumours in specific areas in the neck area, the MR collar is tilted 15 degrees forward for better coverage of those tumours (see fig. 60).

A second bolus shape is created for use in these circumstances to keep ensuring a good fit. Within the scope of this project, the tilted bolus shape is generated, but not tested. All tests in the next chapters will be done using the non-tilted set-up of hyperthermia treatment. Once the final design and approach of the non-tilted bolus is established, this can easily be applied on the tilted shape.

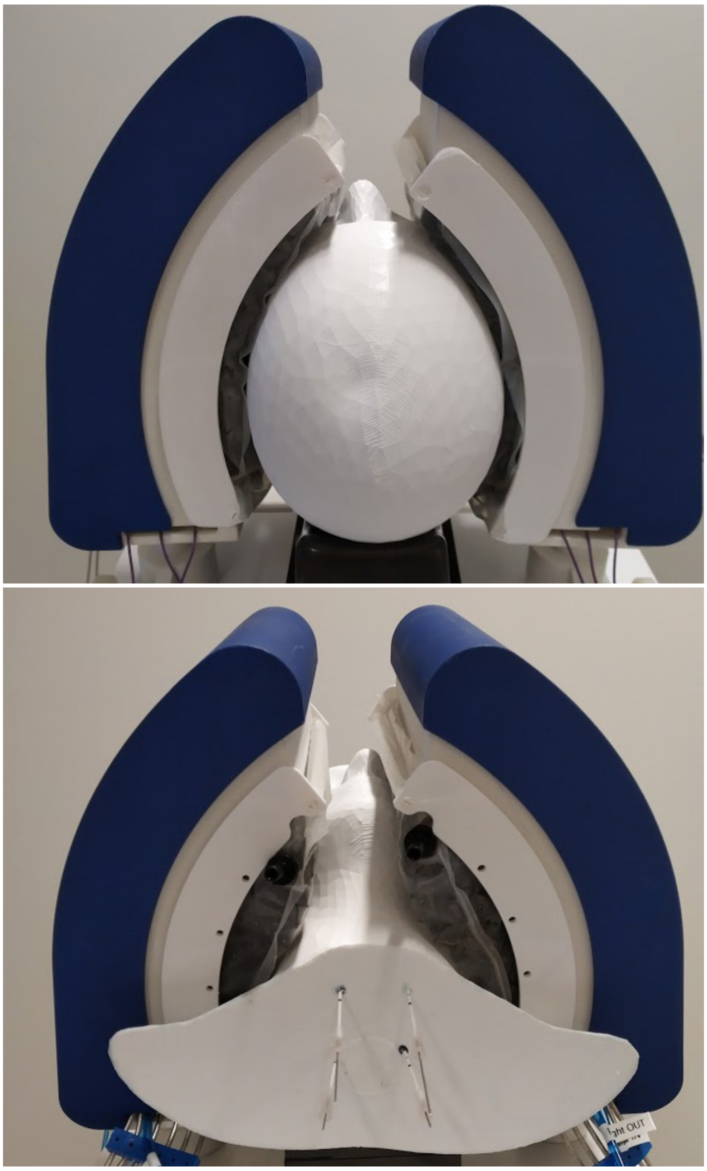


*Fig. 59: Fit in MRcollar*

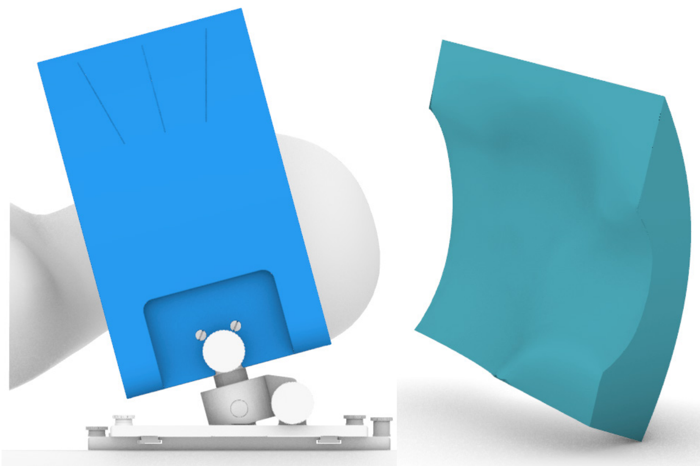


*Fig. 60: 15 degree fit*

# 6.2 WATER FLOW

## Water guidance

During the material research phase it was found that the water will follow the shortest path between in- and outlet if there is no water guidance implemented in the structure, this can lead to inefficient cooling of large areas of the bolus. In this chapter, two possible ways to guide the water flow are designed and tested.

### Honeygrid

The honeygrid structure consists out of perforated hexagonal tubes (see fig. 61). A study of Birkelund et al. (2009) showed that a uniform flow distribution can be created by perforating the in- and outlet tube in an irregular way. The spacing between the perforations gradually decreases from 30mm near the inlet to 11mm towards the end of the pipes (van Den Berg, 2017). By designing the perforations with a diameter of 5mm the flow resistance is minimized and a high pressure build-up can be prevented. (Arunachalam et al.,2009)

### Lattice

In the lattice structure, walls were added to create channels for the water  to flow through. These channels will be printed at a minimal wall thickness of 0,5 mm in the shape and will force the water flow to reach and cool all areas of the bolus. The envisioned water flow is shown in figure 62.

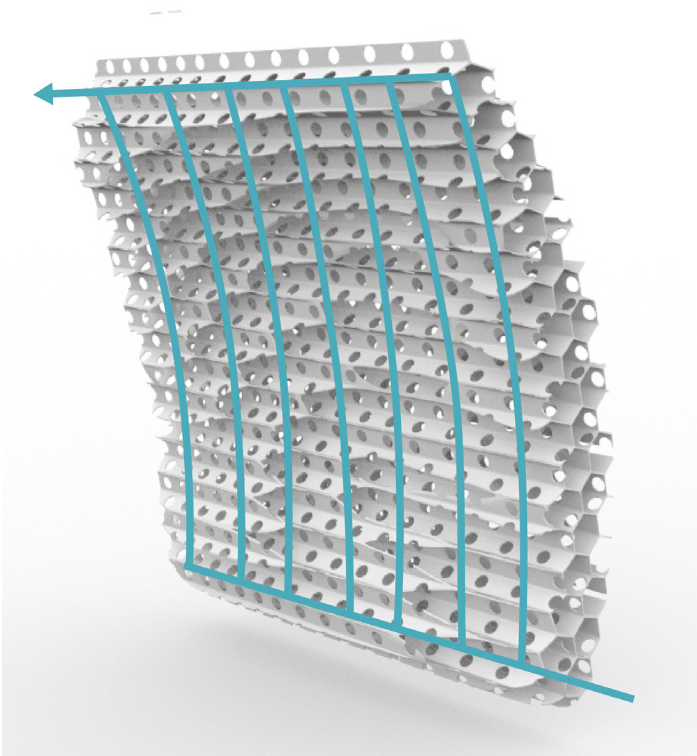


*Fig. 61: Envisioned water flow, Honeygrid*

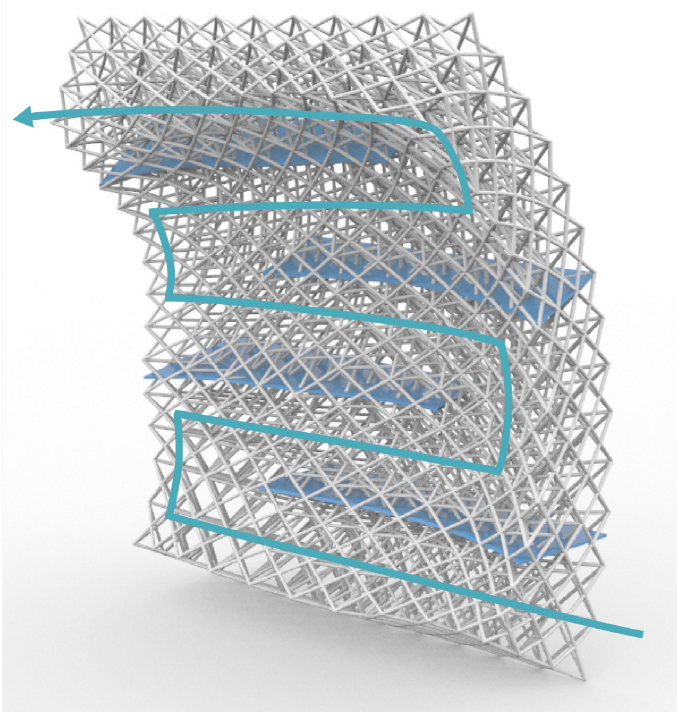


*Fig. 62: Envisioned water flow, Lattice*

# Infrared tests

To visualize the water flow in each design, an infrared camera was used. Each bolus was positioned inside the MR collar and filled with cold water. Once the bolus was fully filled with water, hot water was inserted in the bolus. The camera was used to make a video of the water distribution over time. For each 15 second interval, a snapshot of the situation is shown on the right. A limitation of this test set-up is that the water bolus is not compressed during the water circulation, as it would be during the treatment.

In both boli designs, the water has fully spread throughout the surface area after around 80 seconds. (see fig. 63)

## Honeygrid

In the honeygrid structure, the water first flows primarily on the left side of the bolus, leaving a large piece on the right, middle side untouched. However, in the areas that are reached quickly, the water spreads quite evenly.

## Lattice

In the lattice structure on the other hand, the water covers a larger area more quickly but spreads less homogeneously, leaving a few spots open.

## Conclusion

Both the lattice as well as the honeygrid ensure a rather good and equal water distribution, covering the full water bolus volume after a certain period of time. However for both structures there is still room for improvement.

# Temperature loss in-out

The influence of time and water circulation on the temperature was measured for a situation where the bolus is not heated and not in contact with skin. When filling the bolus with water at 35 degrees Celsius, the temperature of the water measured at the outlet was 34,9 degrees Celsius. It can be concluded that this temperature drop is negligible and will not affect cooling efficiency.

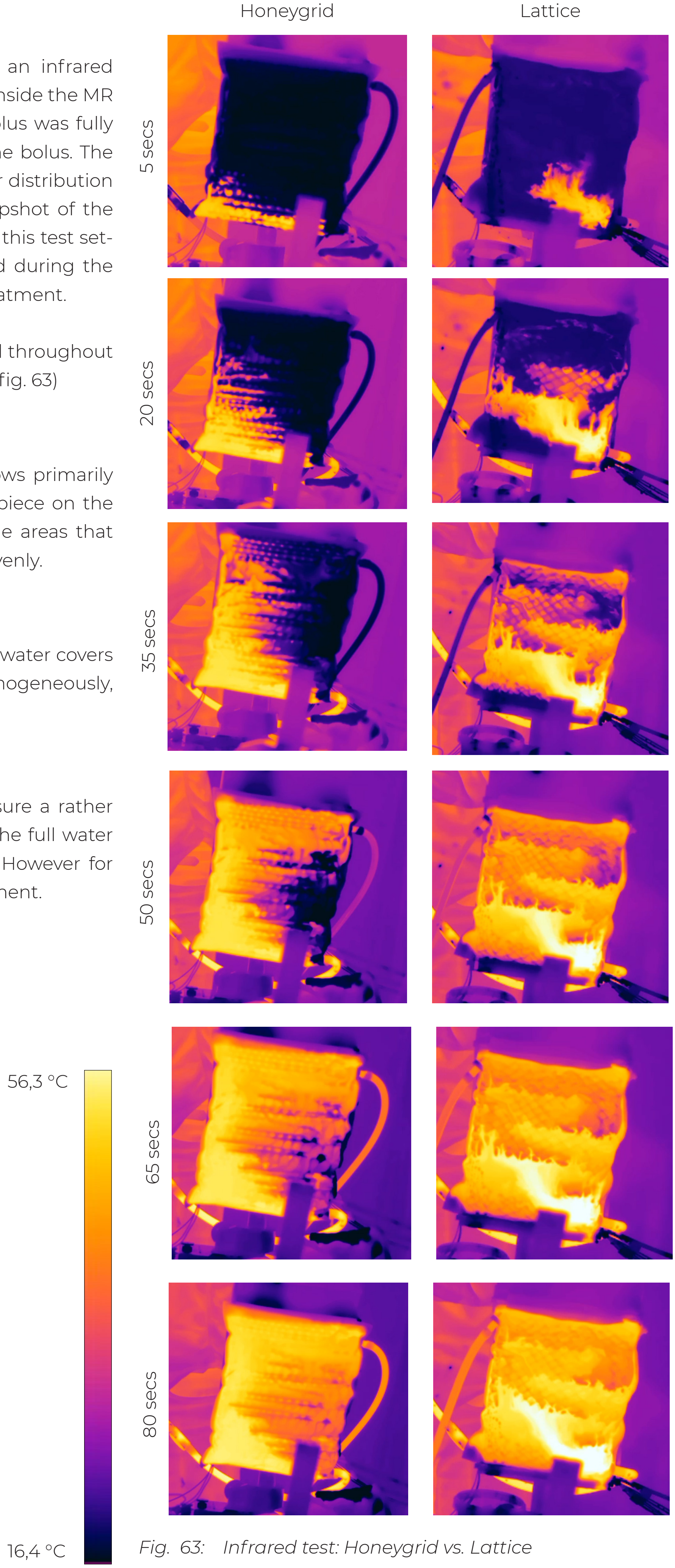



*Fig. 63: Infrared test: Honeygrid vs. Lattice*

# 6.3 FLEXIBILITY AND STABILITY

Both designs were printed at Materialise using a technique named multi jet fusion. This production technique makes use of powder as support material which can be easily removed after print.

The material used for the inner structure is Ultrasint TPU 90A-01. This material offers a high flexibility (shore hardness 88A) combined with a good resistance against wear and abrasion. However, even when printing in the same material, the flexibility and stability of the boli is strongly dependant on the way the structure is designed.

## Honeygrid

### Flexibility

As already mentioned in chapter 4.3 the honeygrid structure is slightly less flexible than the Lattice structure. This can not be optimized, since it is already printed at the minimum possible wall thickness. The tubes can also not be made larger, because at the thinnest areas of the bolus there is only one closed hexagonal tube remaining. But, overall the honeygrid is already pretty flexible.

### Stability

The main issue that was found after printing the honeygrid structure was the shape stability. The structure is stronger in the direction of the tubes than in the perpendicular direction, which causes the structure to not stay in the desired curved shape, but to form a flat surface. This will cause problems when trying to create a pre-shaped outer enclosure and when reproducing the shape in the simulations for pre-treatment planning.

Another downside from the honeygrid structure is that due to its two dimensional nature, the shape will not be suppressed downwards uniformly when force is applied, but tends to shift to the left or the right first, losing the pre-created anatomical shape.

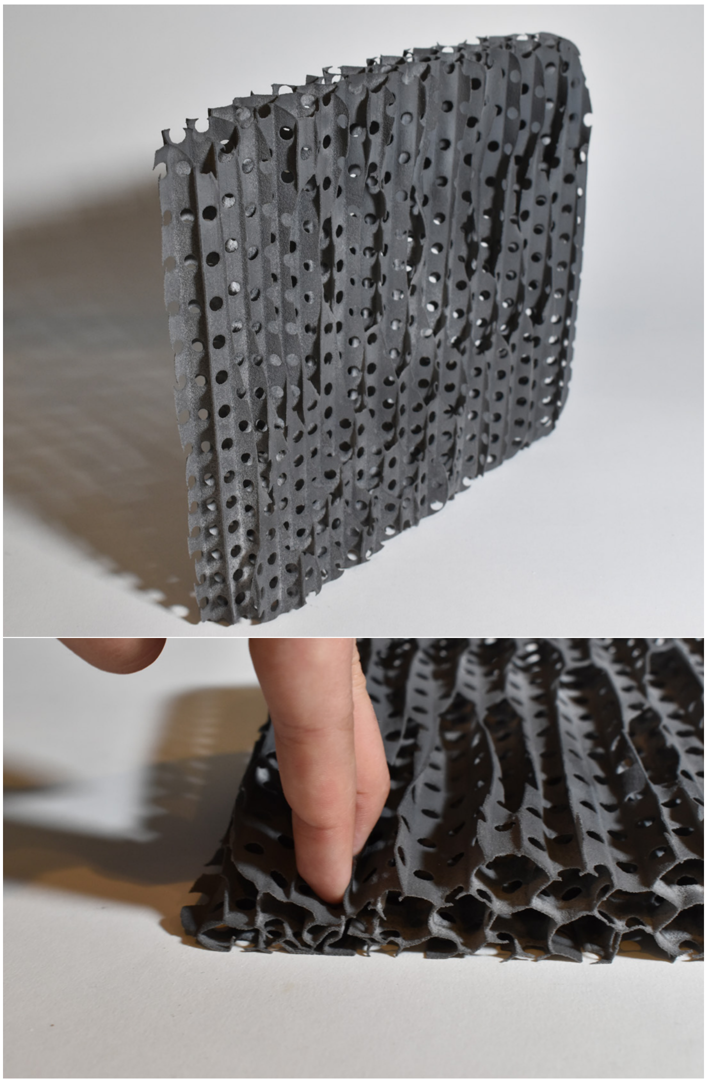


*Fig. 64: Honeygrid print*

# Lattice: Iteration 1

## Flexibility

As already mentioned before, the lattice is more flexible than the honeygrid structure. Furthermore, it is still possible to improve the flexibility by making the structure less dense and/or by decreasing wall thicknesses.

The principal problem that was discovered after printing this structure was that the 1mm thick walls, parallel to the compression direction were way too stiff and barely compressible. This would cause serious patient discomfort and non sufficient contact between bolus and skin.

## Stability

Since the lattice is a three dimensional structure which can absorb forces in all directions. It has the ability to maintain its pre designed shape  and return to it after compression.

Additionally, this three dimensional structure will allow for a more uniform compression of the top surface and a more equal pressure distribution.

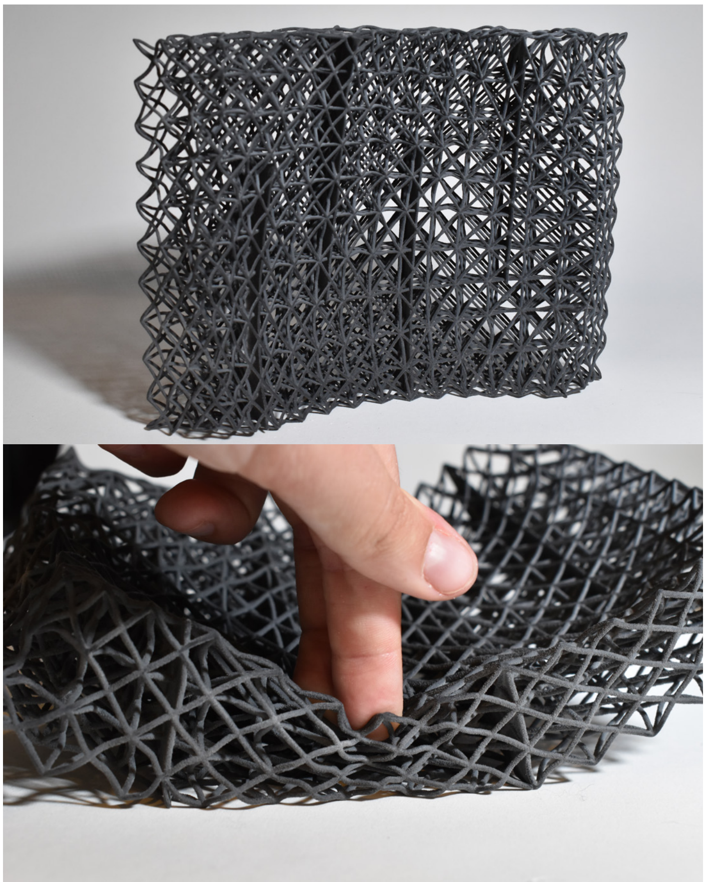


*Fig. 65: Lattice iteration 1 print*

# Lattice: Iteration 2

## Flexibility

For the second lattice iteration, the structure was made drastically more flexible by decreasing the amount of unit cells in the compression direction from three to two and by decreasing the wall thickness (see fig. 66).
The walls for water guidance were made thinner (0,5 mm) and designed in a zigzag way following the lattice pattern (see fig. 67). This made it way easier to compress them.

## Stability

Even though the lattice was made more flexible, the overall shape stability as well as the capability for uniform compression remained the same in this iteration.

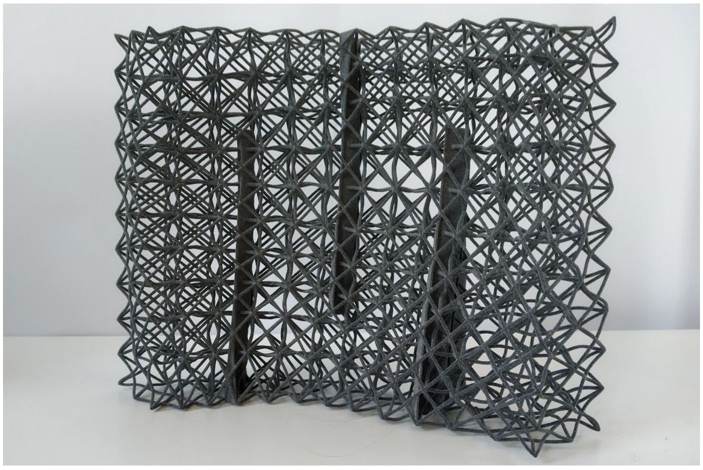


*Fig. 66: Lattice iteration 2 print*

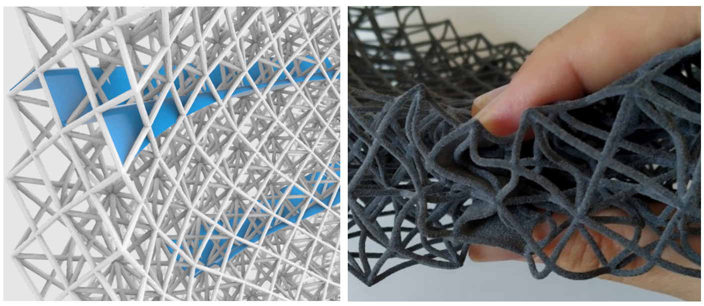


*Fig. 67: New walls design*

# 6.4 WATERTIGHT ENCLOSURE

## Sealing

During the conceptual phase it was decided to create a pattern out of plastic film to ensure a perfect fit of the enclosure around the bolus. This pattern was created digitally using Slicer for Fusion 360. Multiple methods of sealing were tried: using a pattern in one piece, using a pattern consisting out of three pieces, sealing the edges inwards, sealing the edges outwards and using flexible plastic tape for additional protection of the seams (see fig. 68-69). Nevertheless, the enclosure kept leaking around the corners even after numerous attempts. Furthermore, it would be very time consuming, inefficient and thus expensive to create each bolus this way.

Therefore it was decided to create the outer enclosure by first making a bag with three straight seals using an impulse welder, then inserting the bolus and lastly close the enclosure by sealing the last edge (see fig. 70). The dimensions and sealing approach can be found in appendix D.

The benefit of this approach is that it drastically improves production time and makes it possible to make the bolus watertight.

The downside of this approach is that the enclosure is not perfectly made to fit, which may cause creases at the surface and gaps between structure and film near the corners. This issue can be minimized by choosing a very flexible film that can be stretched around the shape and adapt to it.

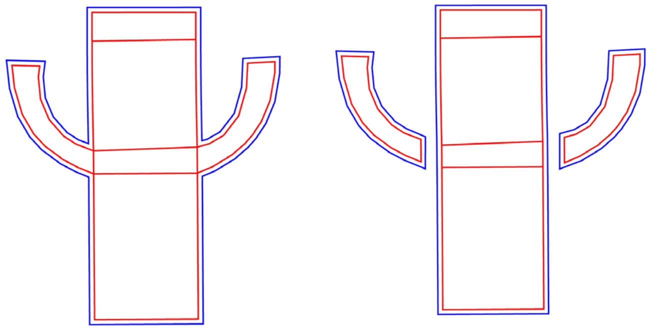


*Fig. 68: Different patterns tested*

*Fig. 69: Different sealing approaches*

*Fig. 70: Final pattern and sealing approach*

## Material choice

In the current water boli, PP film is used at the back of the boli and SEBS film is used at the side that is in contact with the patient. One of the problems with this solution is that it is difficult to seal two different materials together. It would be advisable to create the outer enclosure out of a single material to simplify the sealing process.

Additionally, the PP film is very stiff and difficult to bend in shape and the SEBS film is very flexible, but tear sensitive. That's why there is a need for a new material choice.

### PU film

A material that is currently being used for the waterboli for superficial hyperthermia treatment is polyurethane film. This film is slightly flexible, easy to seal and very tear resistant. This material would perform well in the new water bolus design

## SEBS film

SEBS film is a very flexible film which has a soft feel. It has the highest grade of medical approval and will not cause allergic reactions. This material would be ideal to be stretched in shape around the bolus and give a comfortable feel to the skin of the patient. Additionally it can be produced in a colour of choice, hiding the inner structure and possible glue traces. This will give the bolus a more reliable look.

The main issue with the currently used film is that it is rather thin (0,2 mm) and tears very easily, causing leaks. It is expected that this problem can be resolved by choosing a film with a larger wall thickness. The influence of this increased wall thickness on the surface temperature is explored in the next paragraph.

In a later stage of development it was discovered that the SEBS film is not resistant to glue, causing the material to detoriate immediately after glue is applied. Therefore, it was decided to continue with PU film.

## Influence of wall thickness on temperature

When increasing the wall thickness of the outer material, it is important to explore which influence this will have on the cooling transfer between bolus and skin. The goal is to keep the temperature of the bolus surface at 35 degrees Celsius. If the film isolates too much, the inflow temperature has to be increased, which in an extreme case could lead to burns to the patient in case of leakage.

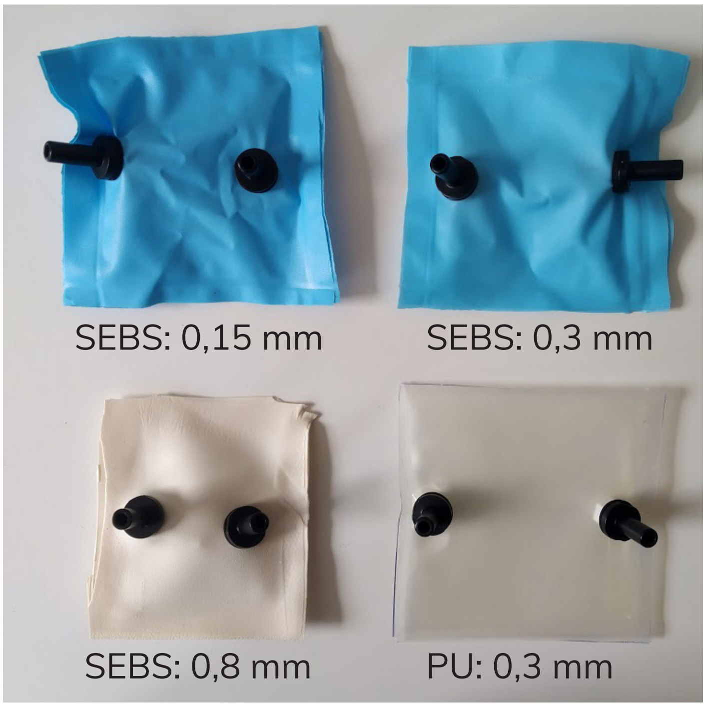



*Fig. 71: Temperature test set-up*

It is known that a film of 0,15 mm will be too thin for use in the bolus because it tears easily, while a film of 0,8 mm is much thicker than needed, decreasing flexibility and making it difficult to seal. The ideal thickness will be somewhere in between these values.

Four small samples of SEBS and PU films at thicknesses of 0,15 mm, 0,3 mm and 0,8 mm were filled with water at 35 degrees Celsius (see fig. 71). Once the water was circulating through, the surface temperature was measured for each sample. It was found that the loss in temperature ranges between 0,7 degrees Celsius and 1,6 degrees Celsius for wall thicknesses between 0,15 mm and 0,8 mm (see table 3). These temperature drops are negligible and can be easily compensated for by increasing the inflow temperature, without causing risk for burns to the patients in case of leakage.

A more significant aspect to take into account when increasing the wall thickness is the heat conductivity of the plastic film. Which can be described by Fourier's law:

$$q_a = -k\frac{\Delta T}{d} \qquad [W/m^2]$$

Where k is the heat conductivity of the plastic film (this is similar for every plastic), ΔT the temperature difference between the water and the skin and d the wall thickness. This formula shows that the heat flux halves when wall thicknesses are doubled. When a final design is made, the temperature loss between water and patient still has to be tested.

| | Surface temperature | |
|---|---|---|
| | SEBS | TPU |
| 0,15 mm | 34,3 °C | |
| 0,3 mm | 34,1 °C | 34,1 °C |
| 0.8 mm | 33,4°C | |

*Table. 3: Surface temperature vs. material thickness*

# 6.5 ATTACHMENT INNER STRUCTURE - OUTER ENCLOSURE

To ensure the water flows through the structure as intended and not around it and to prevent the bolus from inflating like a balloon when filled with water, it is important that the outer enclosure is attached to the inner structure.

## Heat

First it was tried to use heat to melt the plastic film and the structure together. This was not possible since the melting temperature of the 3d printed material is higher than the melting temperature of the film. This causes the film to break apart before the parts are welded.

## Glue

Then it was tried to glue the two parts together using a watertight glue. The gluing process can be done by rolling the film up and then gluing and pulling it around the structure piece by piece. First, Handson spray glue was used to glue the two parts together, later Saba contact 70T was used to improve the water resistance of the glued connection.

When trying to glue the SEBS film to the structure, it was discovered that this film was not chemically resistant to glue. Different glues were tried, but each time the material would tear very easily immediately after applying the glue. Therefore it was decided to seal and glue the boli using PU film.

### Iteration 1

When trying to glue the structures it became clear that gluing the honeygrid structure is rather difficult, since the contact area of the upper surface is very small: only a few 0,5 mm walls are touching the film (see fig. 72). The contact area could be enhanced by compressing the top layers, but by doing this, the pre designed anatomical shape would go lost. The consequence of this problem is that the film did not stick to the structure at all when filled with water (see fig. 74).

Since the lattice structure is designed to conform to the outer shape, the contact area of the top surface is bigger, resulting in a better and stronger glue connection (see fig. 73).
Nevertheless, there were still some areas, especially near the water inflow where the forces caused by the water pressure are the greatest, in which the film did not stay connected to the structure.

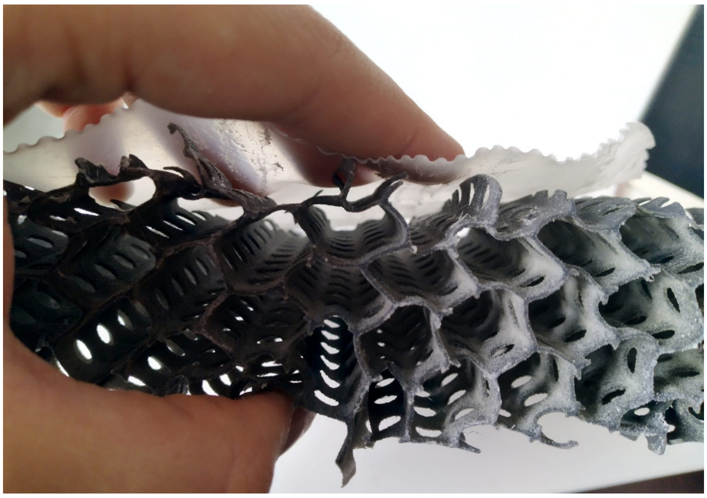


*Fig. 72: Glue surface honeygrid*

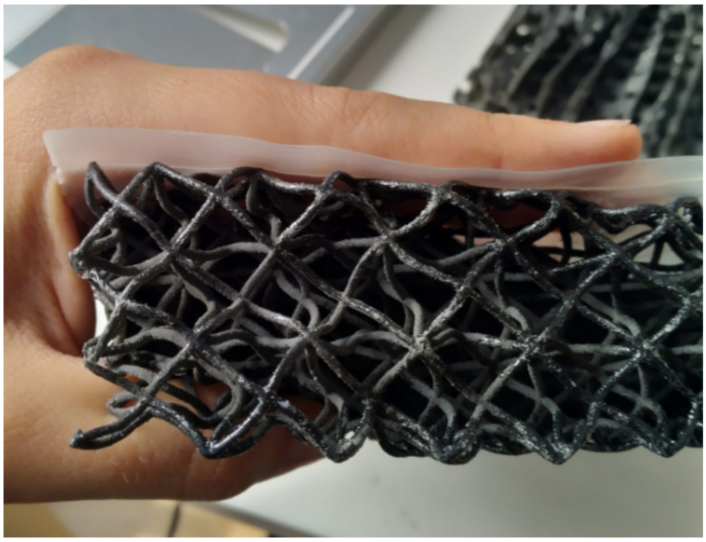


*Fig. 73: Glue surface Lattice*

*Fig. 74: Lattice vs. Honeygrid iteration 1 glue adhesion, while circulating with water*

## Iteration 2

In the second iteration the contact area between inner structure and outer film was enlarged by printing a closed surface on top and below of the structure (see fig. 75). This solution would ensure a very solid connection between the two parts, and would prevent any inflation of the bolus from happening.

However, after printing this prototype it became clear that this drastically decreased the flexibility of the structure, making it especially difficult to compress the middle area of the boli. Furthermore, even when the wall thickness was designed at 0,5 mm, it could only be printed at the minimal wall thickness of 1 mm. This would generate a way too thick outer isolating surface.

*Fig. 75: Iteration 2: Fully closed glue surface*

## Iteration 3

For the third iteration a combination of the past two iterations was made, leaving the structure open as is but adding a few additional closed surface areas to ensure good connection (see fig. 76). By adding these surface areas below and above the position of the walls, it is made sure that the connection at these spots is good and the water will follow the intended path.

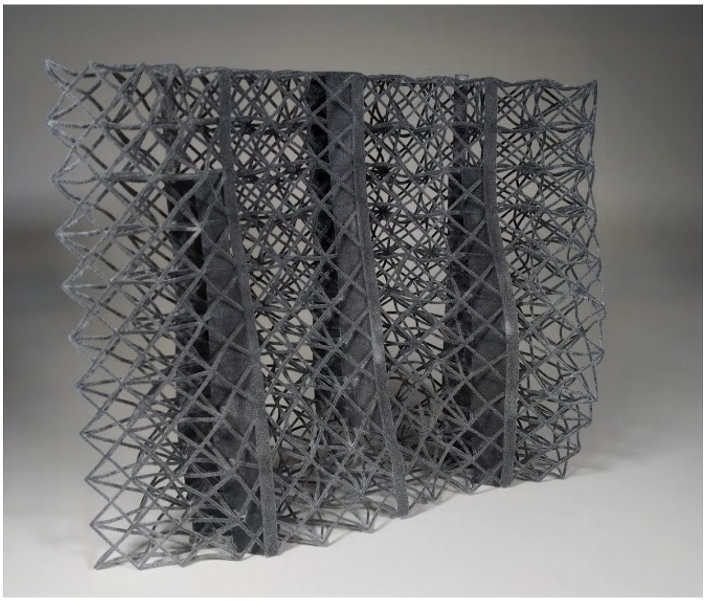


*Fig. 76: Iteration 3: Small surface areas to improve adhesion at the walls.*

# 6.6 CONNECTION TO MR COLLAR

In previous projects a system to attach the bolus to the applicator was already developed (Bi, 2014) and optimized (van den Berg, 2017). This design consists out of a front and back sliding panel which are connected to each other by two support beams. The different components are fixed together by a force fit geometry at each corner (see fig. 77).

Nevertheless, there was no solid system in place yet to attach the bolus to the rails. In the project of van den Berg (2017), it was tried to attach the bolus to the rails using silicon glue, but this showed to be a very time consuming and not so durable connection approach, Therefore it was recommended to implement a mechanical connection instead (see fig. 78).

It was decided to seal an additional loop at the top and bottom of the film while sealing the bolus. This loop can be slid around the beams to attach the bolus to the sliders.

The final alteration that was made to the existing sliding system was to change the force fit connection between the different parts. In the original design the beams were forced into the side panels by sliding them into the openings at the top and bottom of the panels. Since the direction of this sliding is the same direction as the force when attaching the bolus to the applicator, the connection would detach very easily.

In the redesign this force fit is replace by a hexagonal gap and pin connection, which will reduce the risk of detaching, while still making it possible to replace the bolus when needed.

*Fig. 77: Existing sliding system*

*Fig. 78: Connection bolus - sliding system*

*Fig. 79: New connection beams - side panels of the sliding system: hexagonal force fit.*

# 6.7 CONCLUSION: LATTICE VS. HONEYGRID

| | Honeygrid | Lattice |
|---|---|---|
| Effective and uniform cooling | Uniform cooling<br>Good water flow | Uniform cooling<br>Good water flow |
| Comfort: flexibility | Flexible | Very flexible |
| Comfort: Pressure points | Non-uniform compression | Uniform compression |
| Shape stability | Does not stay in predefined shape | Stays in predefined shape |
| Production | Difficult to glue<br>More difficult to generate and adapt for new purposes | Possible to glue<br><br>Easy to generate in any shape |
| Optimization | Optimization possible in perforation pattern | Optimization possible in water guidance, densities, flexibility |

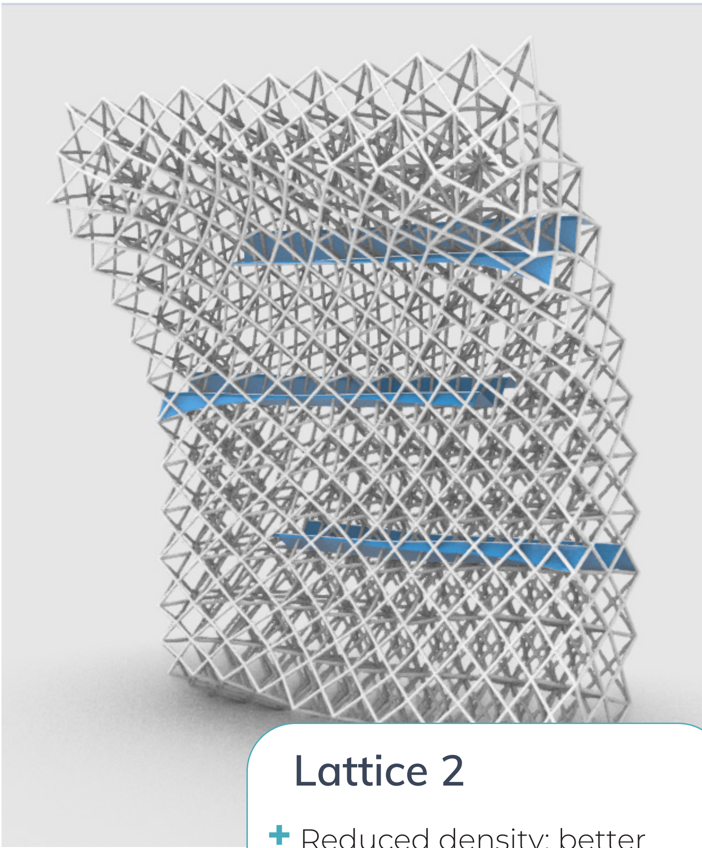
As described throughout this chapter the water flow in both concepts is equally as good, but the flexibility and stability properties of the lattice structure are better. Additionally the lattice is less likely to cause pressure points, since the compression happens more uniformly. Producing the lattice is easier than producing the honeygrid, both in the digital modelling phase as well as for gluing. Lastly, for future development and optimization the lattice has a lot of possibilities for improvement by tweaking the densities, guiding the water exactly as desired or optimizing the flexibility vs. stability. The honeygrid structure offers way less room for optimization.

Taken all these factors in account, it was discussed and decided together with the developers of the MRCollar (Sensius) to continue with the lattice structure for the final design iteration.

# 6.8 INNER STRUCTURE ITERATIONS OVERVIEW

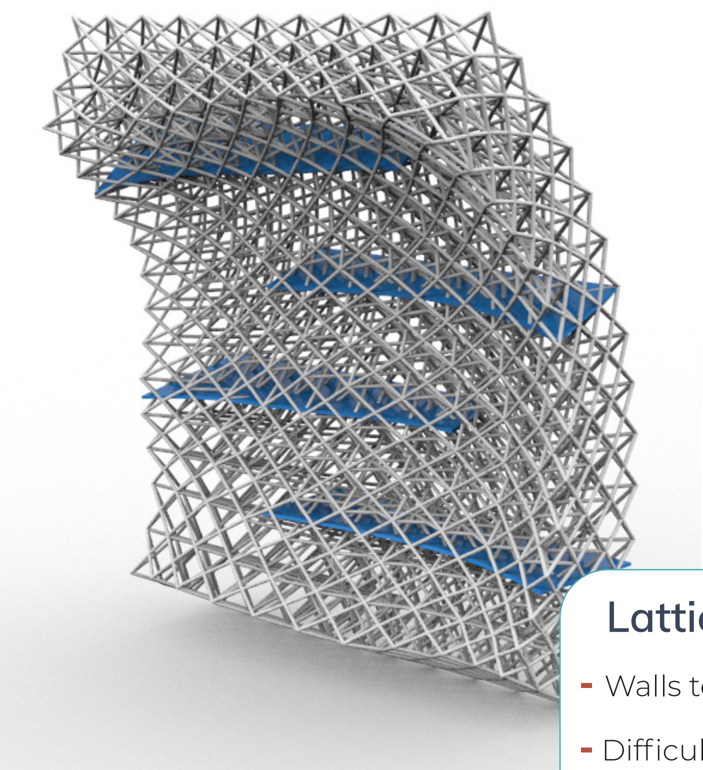
**Honeygrid 1**

- Poor stability properties
- Very difficult to glue



**Lattice 2**

+ Reduced density: better flexibility
+ Zigzag walls for better compressing
- Difficult to glue

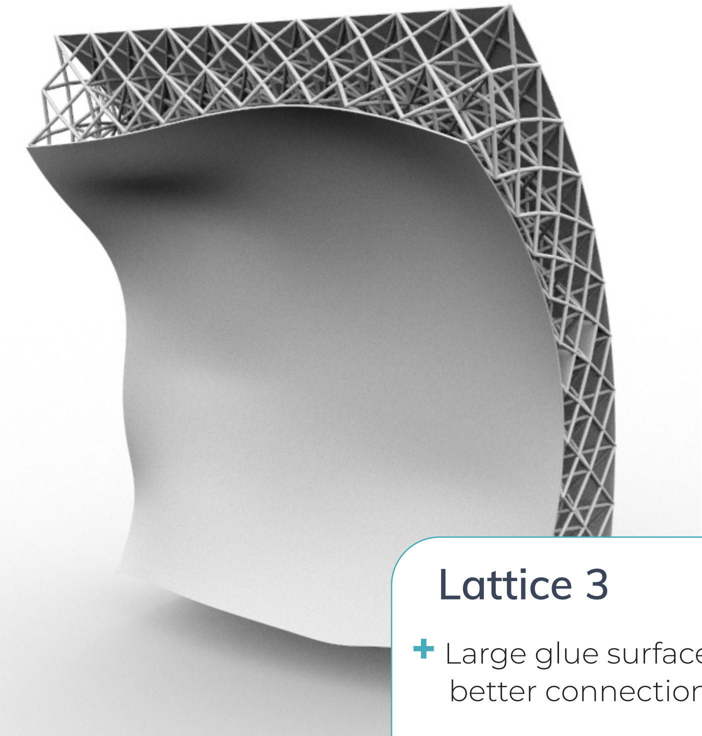


**Lattice 1**

- Walls too stiff
- Difficult to glue

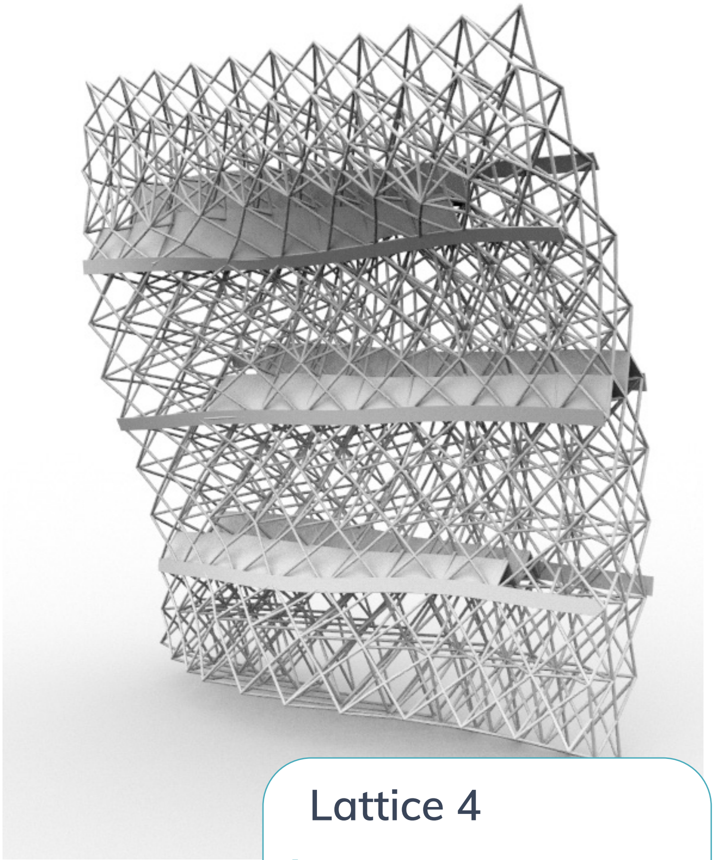
## Honeygrid 2

- + Large glue surface for better connection
- - Not flexible enough
- - High wall thickness



## Lattice 3

- + Large glue surface for better connection
- - Not flexible enough
- - High wall thickness



## Lattice 4

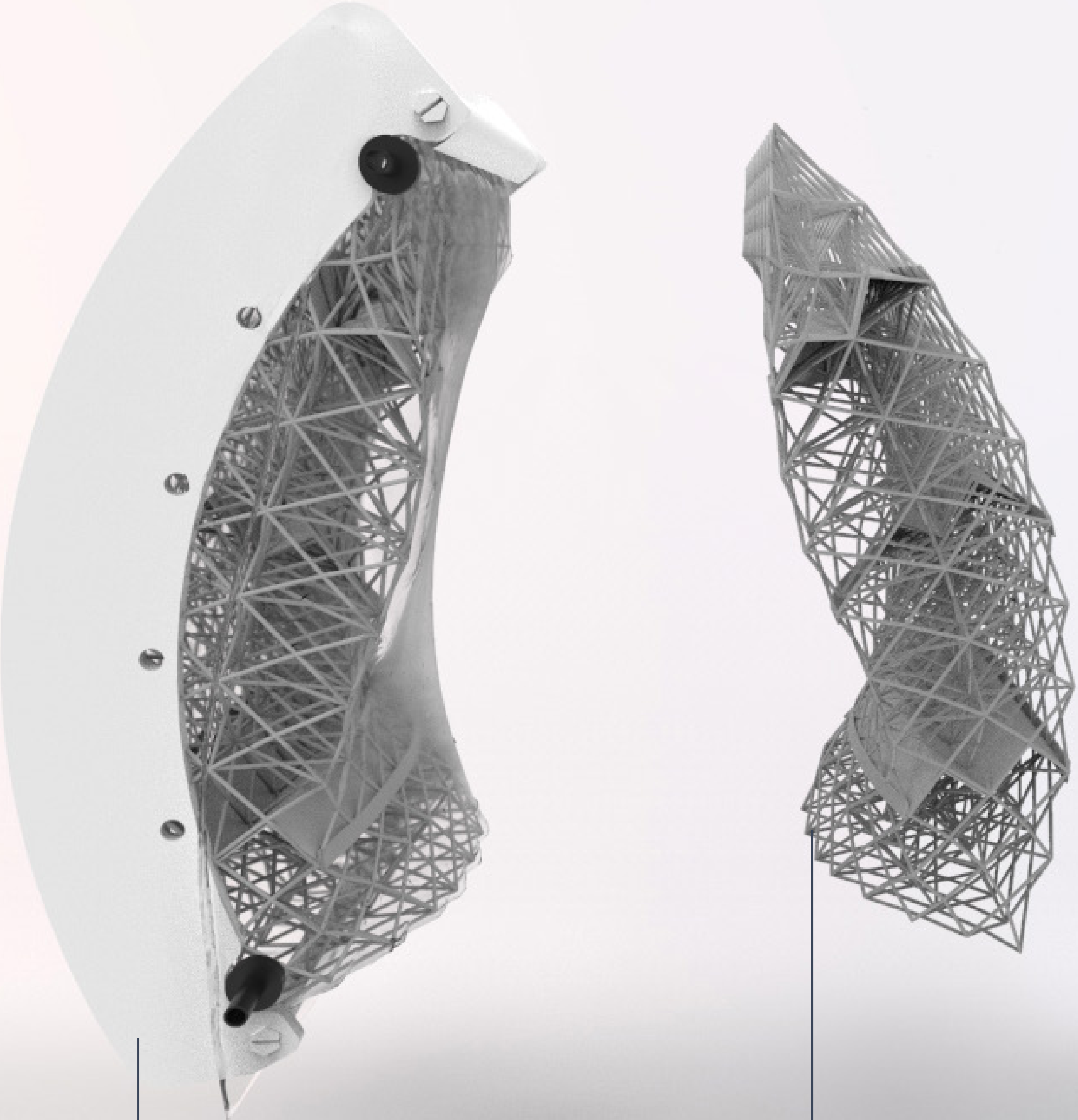
- + Small glue surfaces for improved connection
- + Reduced density & wall thickness, Improved flexibility
- + Improved shape, better fit around neck

# 7 PRODUCT PRESENTATION

After several experiments, iterations and optimizations, during the embodiment phase, the final water bolus design and prototype can be presented in this chapter.

# 7.1 FINAL PRODUCT DESIGN

## Exploded view



Full bolus set-up

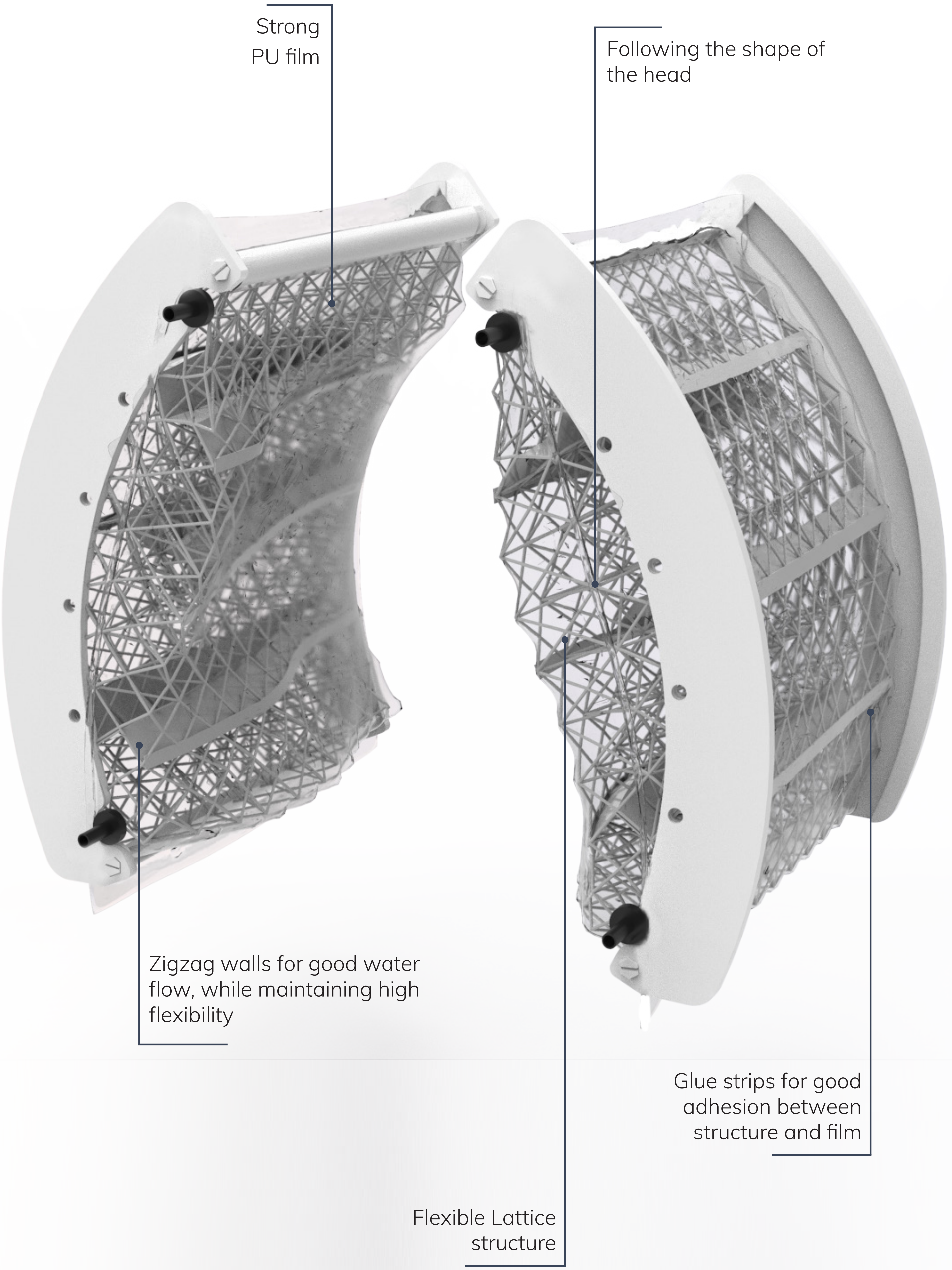
Flexible lattice (TPU) + walls for water guidance

Outer enclosure: Sealed PU film

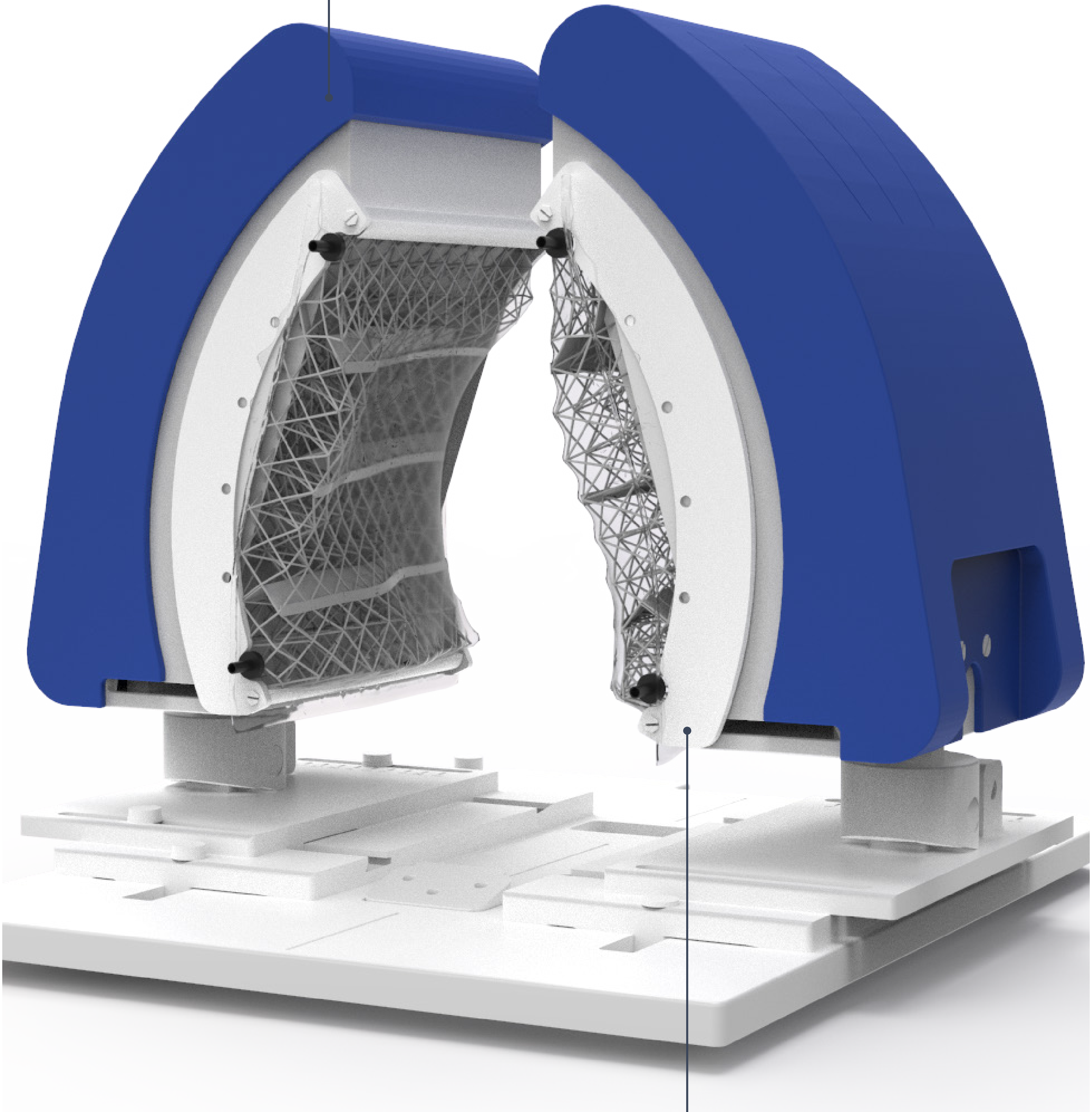
Sliding connection mechanism

Water in- outlet

# Key features



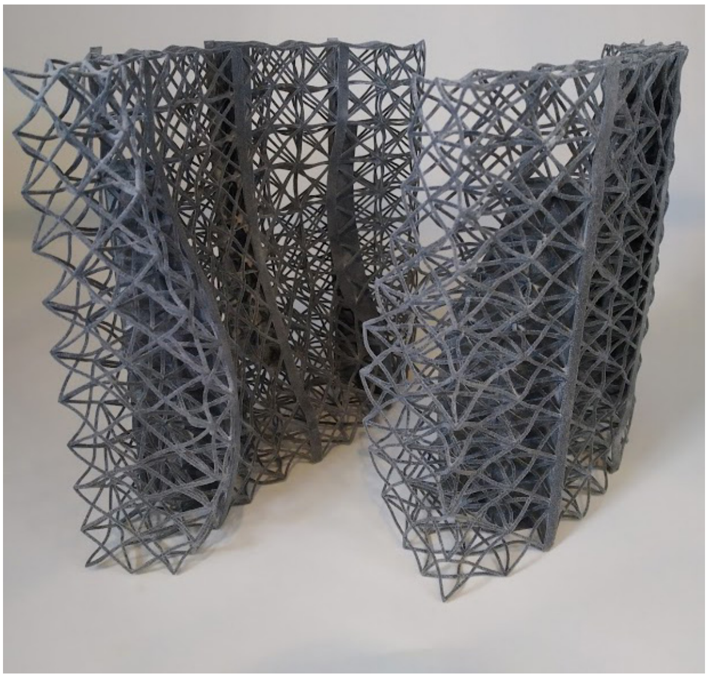
Designed to function and fit in the MRcollar

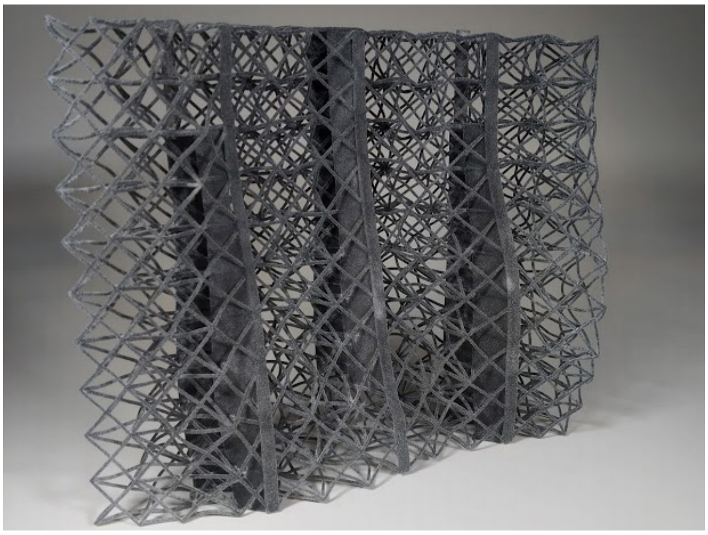


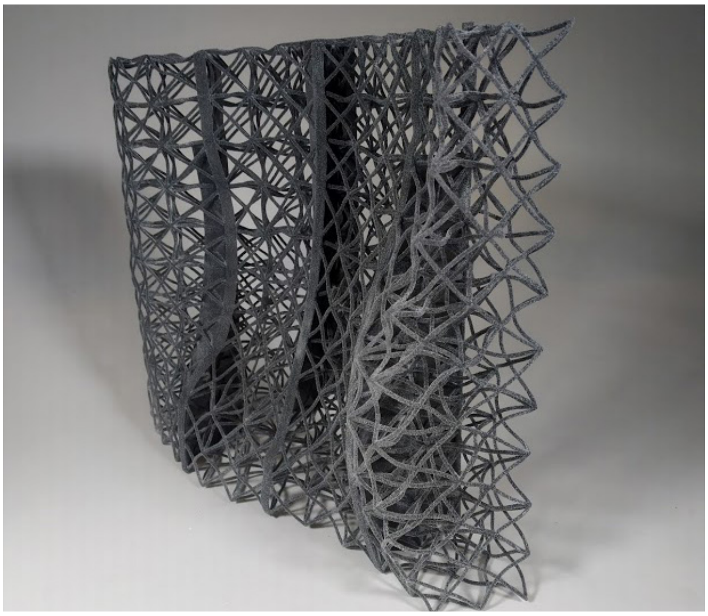
Improved connection mechanism

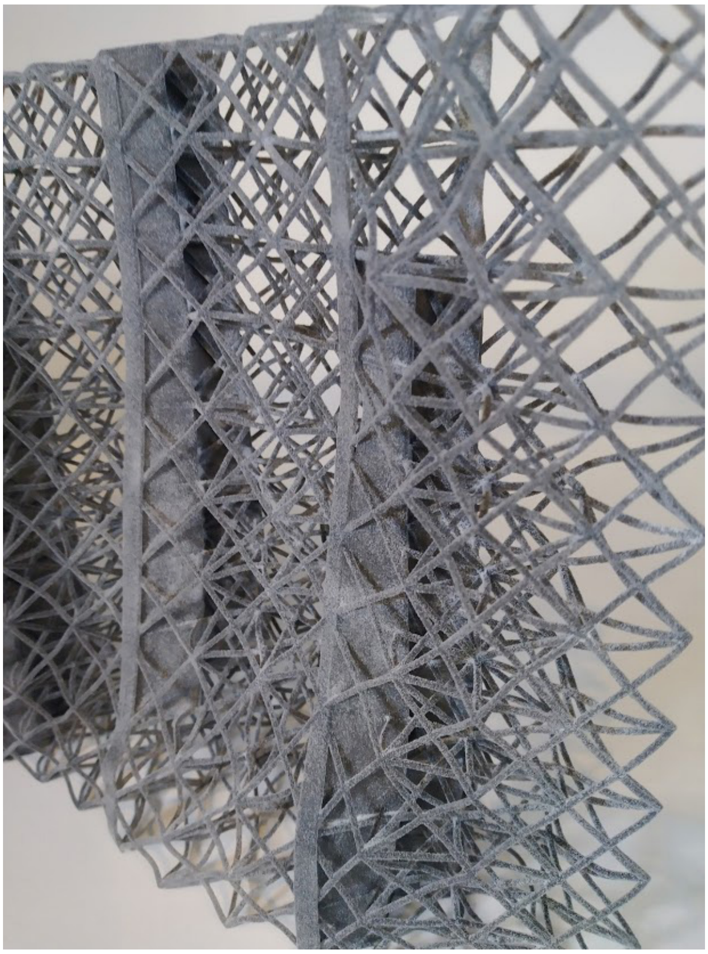
# 7.2 FINAL PROTOTYPE

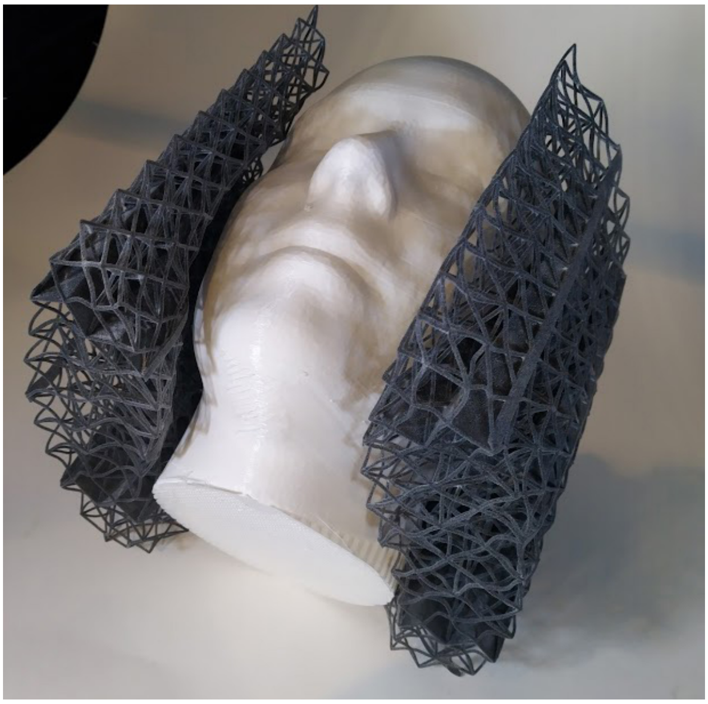
## Inner structure





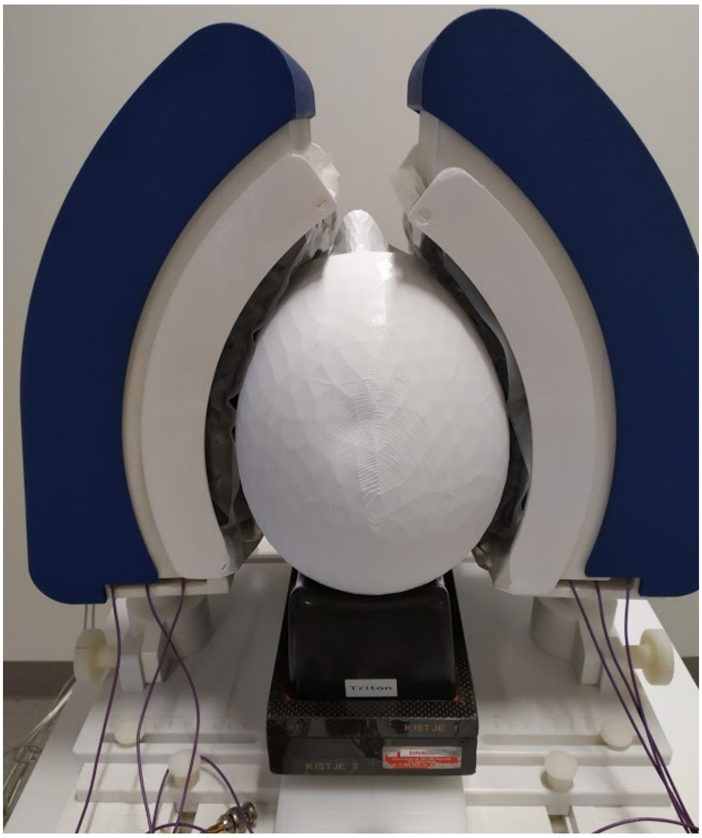


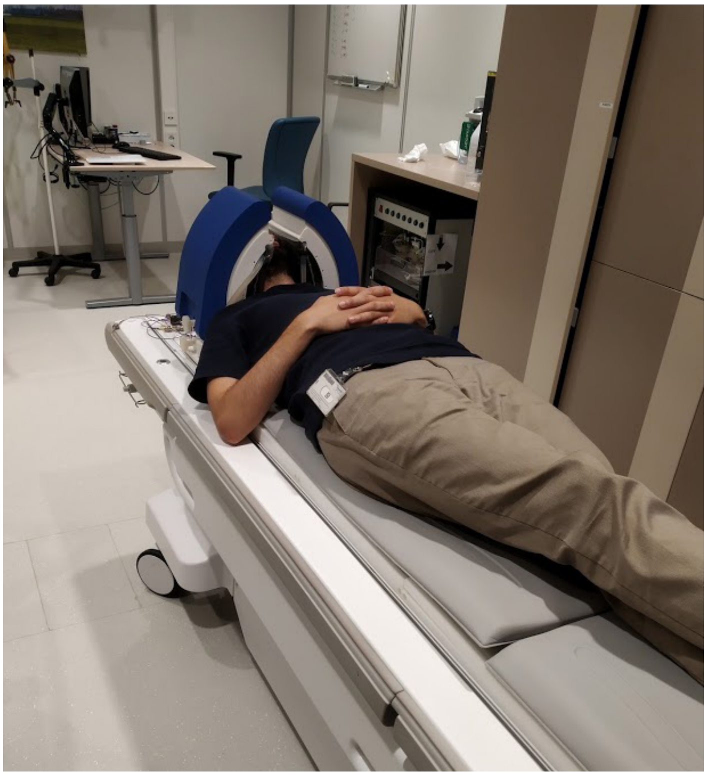


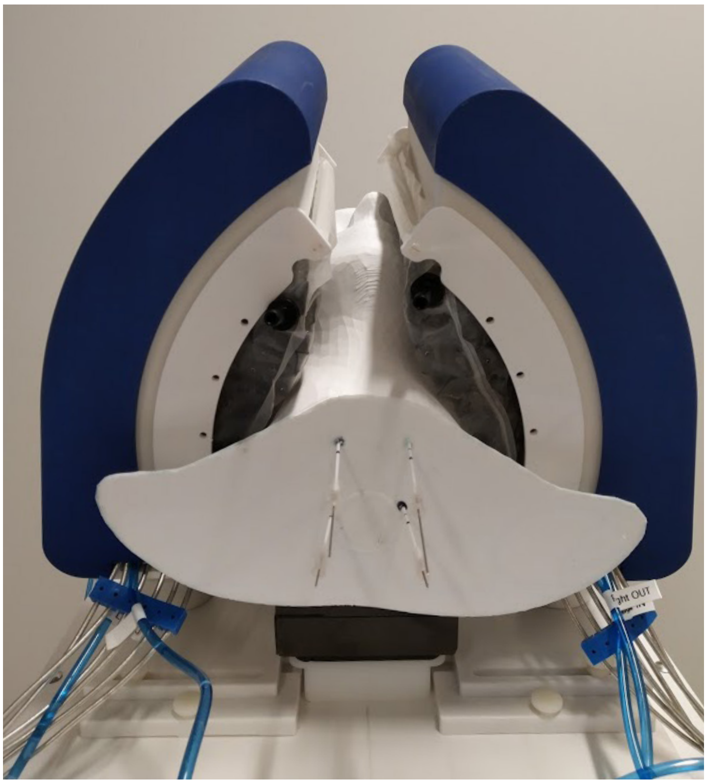


## Full water bolus

# Set-up in MRcollar





# 8 FINAL VALIDATION

Different experiments were carried out at Erasmus Medical Centre to validate the final bolus design on the challenges defined in chapter 1.2: patient comfort, effective and uniform cooling, shape stability, functionality in MR collar and usability by clinician. By doing these test it can be checked if the new bolus design performs sufficiently on these aspects and where there is still room for improvement.

# 8.1 PATIENT COMFORT

## Flexibility

### Test set-up

A tensile tester was used to measure the needed force to compress the last structure iteration between 5 to 20mm. The diameter of the compression area was 19 mm.

### Methodology

The structure was positioned in the compression tester and measurements were taken three times at slightly different positions at a speed of 20mm/min. The average of these measurements was used in this analysis. The compression test was done for a random spot of the lattice structure, but also at the walls for water guidance.

### Results

By using the same test set-up as the compression test described in chapter 4.3, the results of these two tests could be easily compared as shown in table 4 and figure 80.

Overall, the final lattice structure is drastically more flexible as the first lattice iteration, the honeygrid and the foam structure, with a maximum needed force of 0,9 Newton. Around the walls, the structure becomes more stiff but is still flexible enough for easy compression.

### Conclusion

The new bolus design performs very well on flexibility, only a very small force is needed in order to compress it. There is a difference in flexibility between the walls and the rest of the structure, the comfort tests will show whether this causes discomfort to the users.

| | Honeygrid | Lattice It. 1 | Lattice It. 2 | Lattice It. 2 at walls |
|---|---|---|---|---|
| 5 mm | 3,1 N | 3,0 N | 0,5 N | 2,9 N |
| 10 mm | 6,2 N | 6,0 N | 0,7 N | 5,6 N |
| 15 mm | 11,8 N | 9,5 N | 0,8 N | 9,4 N |
| 20 mm | 19,1 N | 13,6 N | 0,9 N | 14,2 N |

*Table. 4: Compression test*

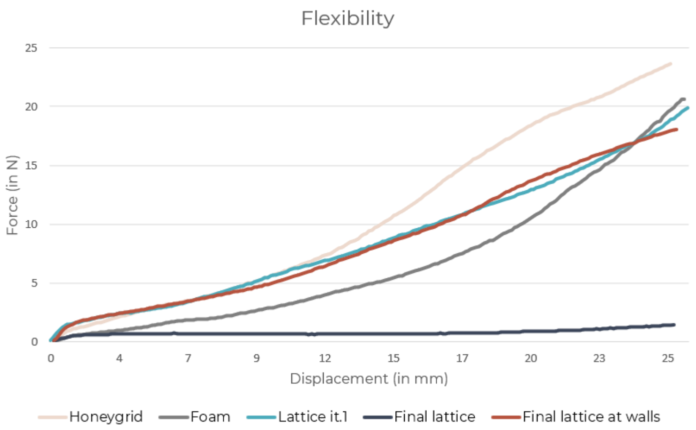



*Fig. 80: Compression test*

# Fit

## Test set-up & methodology

The MRcollar with the water-filled bolus and P50 patient dummy was inserted in the MR scanner to get a better view on how the bolus was connecting with the skin. An MRI scan was made for both the non-tilted set-up (for which the shape was ergonomically designed) as well as for the 15 degree tilted set-up. Since the left bolus was leaking during the test, the water level dropped significantly causing the imaging  to be disrupted on this side. However, the test results can still be clearly seen on the right bolus.

*Fig. 81: MRcollar set-up in MR scanner*

## Results

The results of the MRI scans can be seen in figures 82 and 83.  For both the non-tilted and tilted set-up, the bolus was connecting to the dummy very well, leaving no gaps. Only around the ear area some gaps occur, which can be explained by the fact that the test dummy ears are not flexible. It is important to consider that this test was carried out with a P50 patient model, for which the bolus was modelled. Some more fit tests could be carried out to check the fit on different head and neck sizes.

These results might imply that creating an additional tilted bolus design is not necessary. However, additional comfort tests on the tilted set-up would be advisable before making this decision

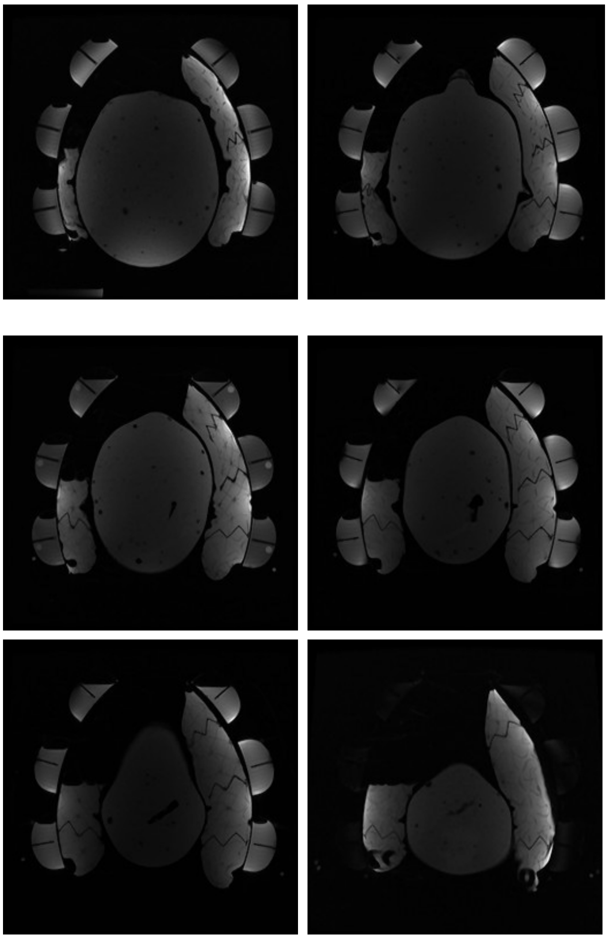


*Fig. 82: Non-tilted fit*

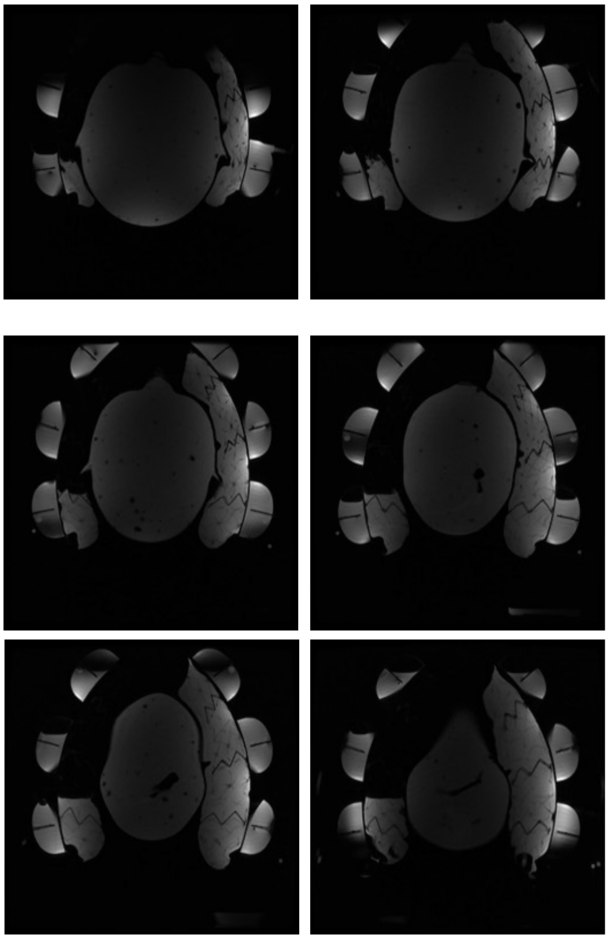


*Fig. 83: 15 degree tilted fit*

# User tests

## Test set-up

7 Erasmus MC employees were asked to participate in the user test to evaluate the comfort in the water bolus. Each participant was positioned in the full MRcollar set-up after which water was circulated for 5 minutes.

*Fig. 84: User test: MRcollar set-up*

## Methodology

Immediately after being removed from the set-up, the participants were asked to fill out two questionnaires (see appendix E and F): (1) A local perceived comfort map, where they could rate the comfort levels at different regions of the head and (2) a questionnaire in which different aspects of comfort could be rated from -- to ++. After filling out the questionnaires, a brief semi-structured interview was carried out to allow the participants to share their remarks on the comfort of the new bolus design.

Since the same questionnaires were used as during a previous water bolus design project (van den Berg, 2017), the findings of the new bolus design could be compared with the results of the HYPERcollar3D water bolus.

## Results

An overview of all responses can be found in Appendix H.

### Local perceived comfort map

The participants were asked to rate 8 predefined areas on the head from 1 to 5. Where 1 represents no discomfort and 5 represents extreme discomfort.

An overview of the results from the local perceived comfort mapping can be found in figure 87. For each questioned area, the average discomfort level is displayed, as well as every individual response.

In general the pressure distribution was considered to be quite equal over the skin. The comfort maps, as well as the interviews and questionnaire all indicate that the participants did not experience much point pressures. However, some areas were considered a bit uncomfortable by certain participants.

The main issue that occurred is that the skin sticks to the plastic film at first contact and does not easily slide to a different position. This causes the cheeks to get squished together when the MRcollar is pushed in position (see fig. 85), creating discomfort. This happened to five out of seven participants. It was however found, that the patients are able to reposition the skin to a more comfortable position with their hands after the collar is closed.

Another region of discomfort for some subjects was the back of the neck. This discomfort is not related to the water bolus design but to the applicator design. The neck cushion was considered uncomfortable by some patients, as well as the cables and tubes for water flow that are touching the shoulder and neck (see fig. 86).

Lastly, three patients experienced an increased pressure around the ear. This uncomfortable feeling usually only occurred on one side of the head, this might be caused by the flexible walls being positioned exactly at the ear for those patients.

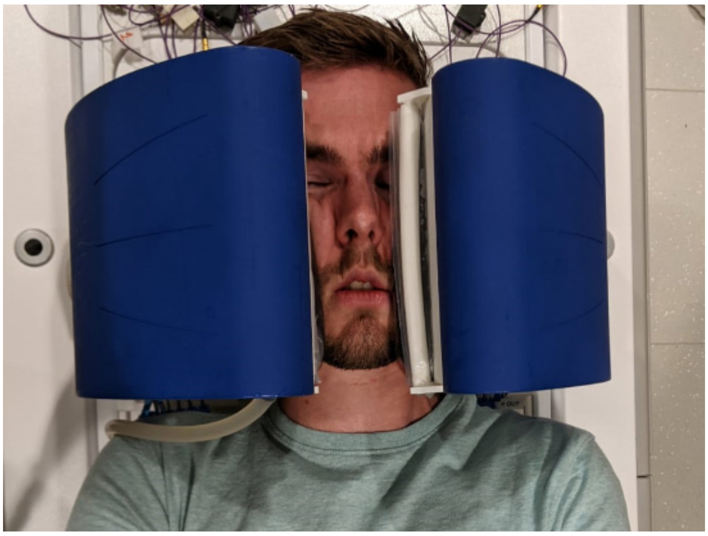


*Fig. 85: Cheeks getting squished*

*Fig. 86: Cables and water tubes touching the neck and shoulder*

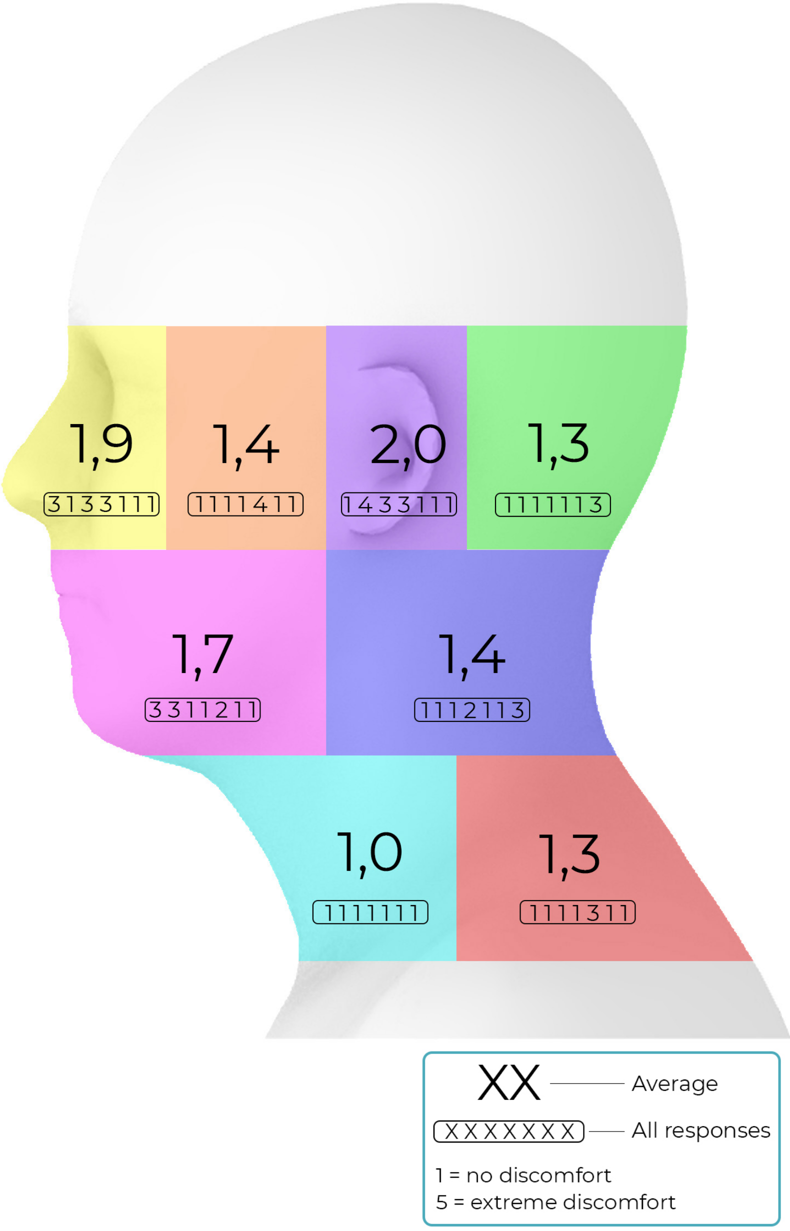



*Fig. 87: Local perceived comfort map, results*

### Questionnaire

The responses to the questionnaire showed that the new water bolus performs very well on comfort. As seen in figure 88 all questioned topics performed better or equally as good as the HYPERcollar3D tests carried out by Lisa van den Berg (2017).

The bolus was rated high in comfort, with an average score of 4,1 out of 5. Not many pressure points were experienced by the users, as also found in the local perceived comfort map. The breathing was not obstructed by the bolus and even though the original soft SEBS film was replaced by a PU film, the material was still considered pleasant on the skin by the subjects. The bolus was also considered to look friendly and reliable by the respondents.

### User remarks

After filling out the questionnaires, the users were given the opportunity to share any remarks they had about their experience during the test. Most participants mentioned that the pressure was distributed quite evenly, apart from some areas of discomfort like the squished cheeks or the ears. Three participants mentioned that they did not consider the water bolus set-up as uncomfortable, but also not as pleasant since there is quite some pressure applied on the head. One participant mentioned that the water tubes were a bit unpleasant, because they were touching her neck and shoulder. One participant stated she gets claustrophobic easily, but did not experience it in this case since the gap for breathing and visibility is big enough. One user did not want to participate in the study cause she considered it as being too claustrophobic.

## Conclusion:

The new bolus design performs very well on patient comfort. It scored better or equally as good as the HYPERcollar3D on all aspects: comfort, pressure points, breathing, material and appearance, with an average score of 4,1 out of 5. According to the participants, the pressure is distributed evenly, this shows that the water bolus sufficiently follows the shape of the head. Two problem areas that occurred were the region around the ear and the jaws/cheeks, which are being squished together. The cheek problem can be solved by asking the patient to reposition the skin after closing the collar. Regarding the ear area it would be interesting to get a better view on which area of the bolus is touching the ear to see what causes this discomfort.

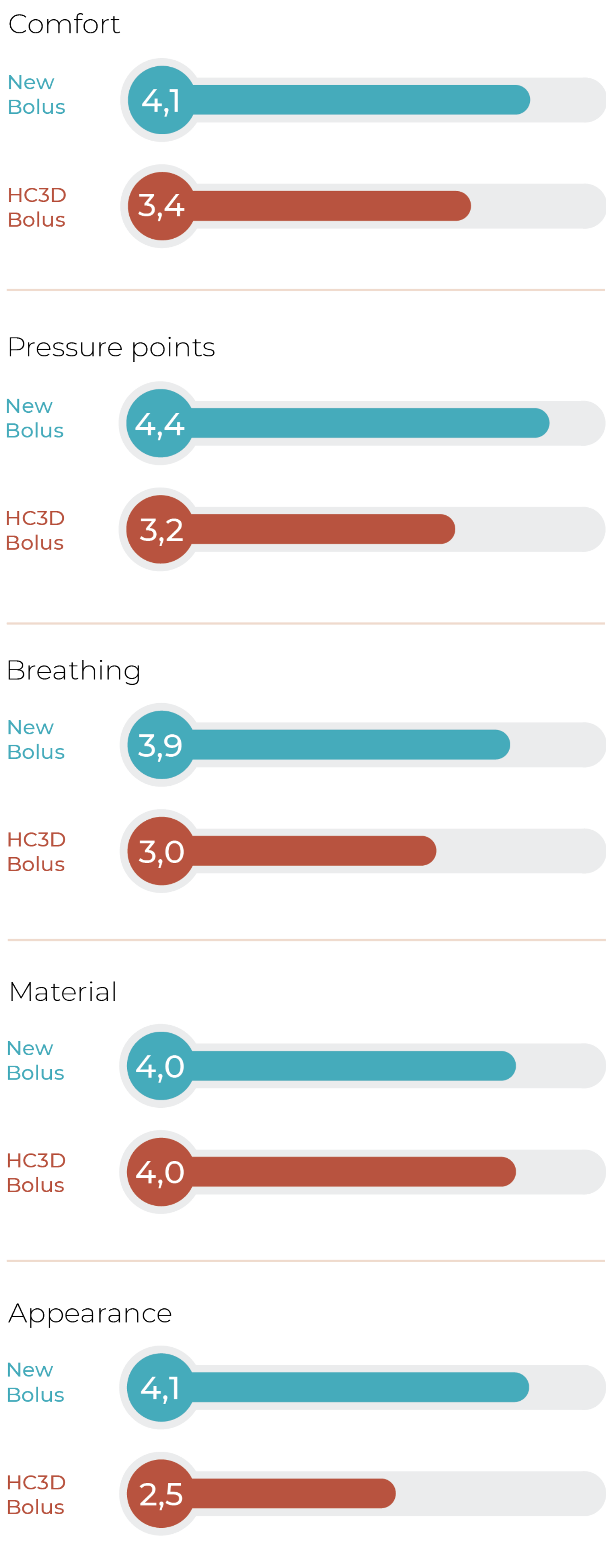



*Fig. 88: Questionnaire results*

# 8.2 EFFECTIVE AND UNIFORM COOLING

## Water flow test: infrared

### Test set-up and methodology

To capture the water flow and distribution, the bolus was connected to the MRcollar and filled with cold water (20 °C). Once the bolus was fully filled with water, hot water (40 °C) was inserted in the bolus. An infrared camera was used to make a video of the water distribution over time. For each 15 second interval, a snapshot of the situation is shown on the right. A limitation of this test set-up is that the water bolus is not compressed during the water circulation, as it would be during the treatment.

### Results

The infrared images of the test are shown in Figure 89. Since the outer enclosure was now adhering very well to the walls thanks to the added glue surfaces in the final design, the impact of the walls on the water flow is clearly visible. The water follows the intended path throughout the full bolus volume. However, this test shows that the distance between the walls is slightly too big, causing the areas just above each wall to remain unreached for a relatively long time.

### Conclusion

The water is flowing through the bolus volume as intended, guided by the channels and covering the full bolus volume. This shows that the principle of implementing walls and gluing them to the outer enclosure works. However, in this design the distance between the walls is too big. Adding one more wall to the bolus design (as in the previous iteration, see chapter 6.2) will help distributing the water more evenly.

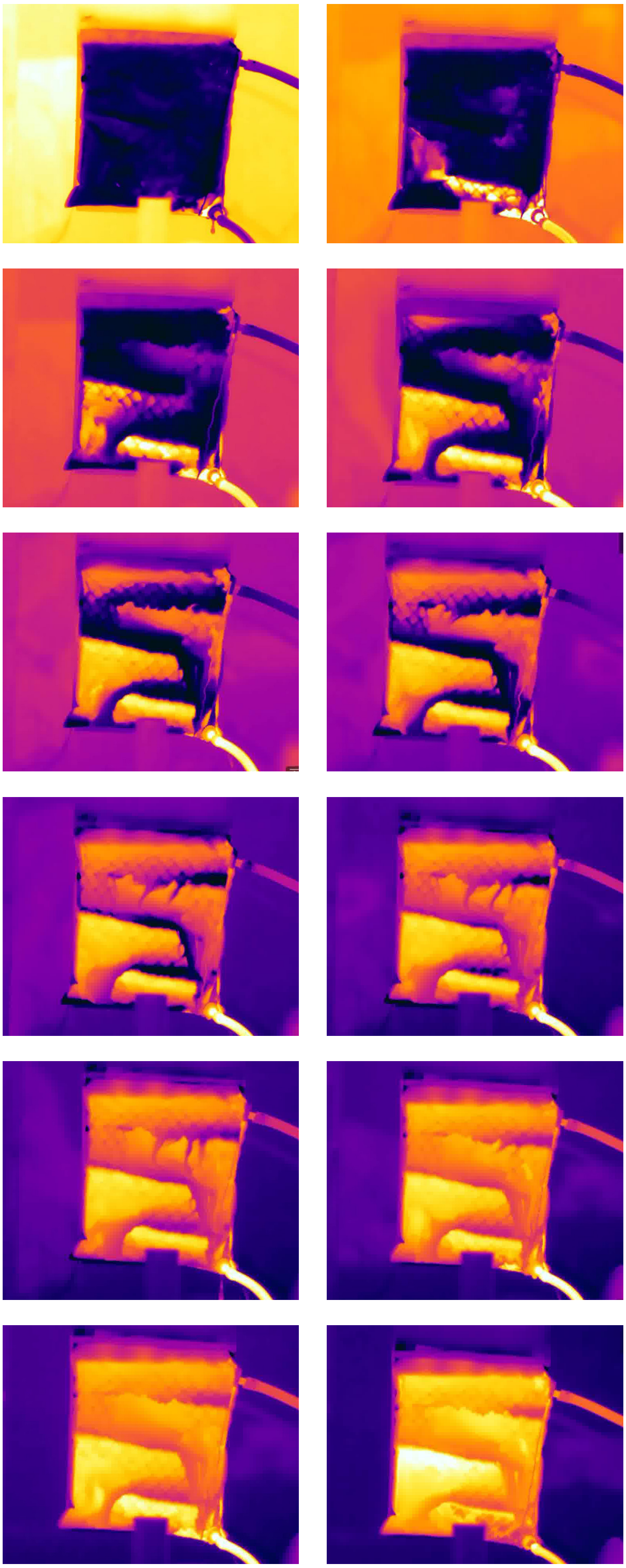


*Fig. 89: Infrared images of water flow*

# Skin cooling

## Test set-up

To test the cooling efficiency of the water bolus, a user was positioned in the MRcollar for 10 minutes. Water was circulating through the bolus at 24°C. This temperature is lower than the actual treatment temperature of 35 °C, but will ensure a clear visual overview of the cooling area when taking an infrared image.

## Methodology

One infrared image was taken right before the participant was positioned in between the boli, a second infrared image was taken immediately after the cooling session.

## Results

The starting temperature of the skin around the cooling area was between 33 and 35 °C, where the cheeks and the ears are the coldest areas and the area around the ears is the most warm area (see fig. 90).
After 10 minutes of water circulation, most of the contact area has cooled down to 25-26 °C (see fig. 91). The area just around the ear is being cooled slightly less efficiently, remaining at a temperature between 29 and 30 °C, which can be explained by a lack of skin-bolus contact in this region.

Also the temperature of the area right below the ear, from ear to neck, shows a slightly higher temperature of 27,5 °C. This might be caused by the presence of the carotid artery in this region, heating up the skin temperature very quickly after bolus removal, but can also be due to a bad connection in this area.

Lastly, one small heat spot occurred around the jaw, no clear explanation was found for this phenomenon.

## Conclusion

Overall, the cooling of the skin takes place quite evenly. At an inlet water temperature of 24 °C, most of the skin gets cooled to a temperature between 25 and 26 °C. Only the area just around the ear gets cooled less efficiently due to a lack of bolus-skin contact in this region.

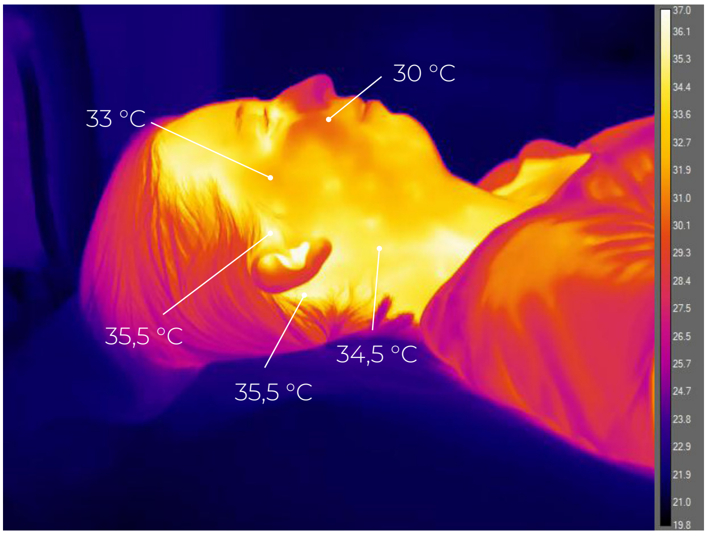



*Fig. 90: Skin temperature before cooling*

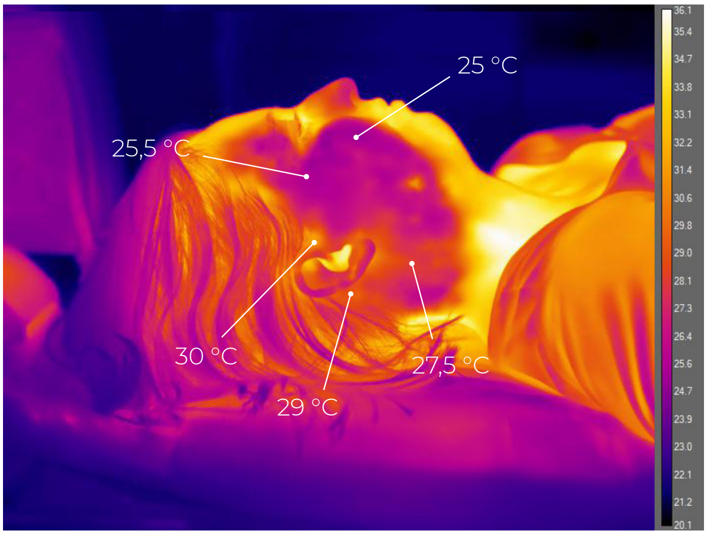



*Fig. 91: Skin temperature after cooling*

# 8.3 SHAPE STABILITY

In order to provide predictable and reproducible water bolus properties, and also stable and accurate positioning; It is important that the water bolus stays in the pre-designed shape during treatment. The curve at the back should attach fully to the applicator. This will also ensure that the EM waves will be conducted properly through the bolus, without encountering air gaps.

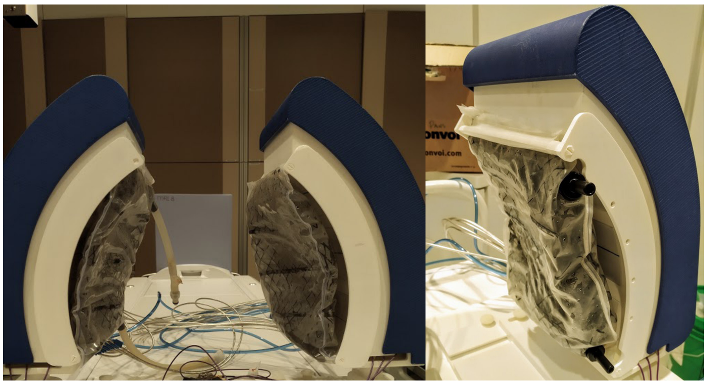


*Fig. 92: Shape stability in MRcollar: Gaps between bolus and applicator.*

## Results

The downside of the drastically improved flexibility of the latest water bolus design is that it also loses its shape more easily. When trying to seal and glue the bolus, it tends to deform already a bit, due to the force applied by the film.

Additionally, when the bolus is inserted in the MRcollar, it can be clearly seen that it does not fully maintain its predefined curve. A small gap appears between the collar and the bolus (see fig. 92). However, when a patient is positioned in the bolus it automatically gets pushed against the MRcollar wall as can be seen in the MR images of chapter 8.1 and figure 93.

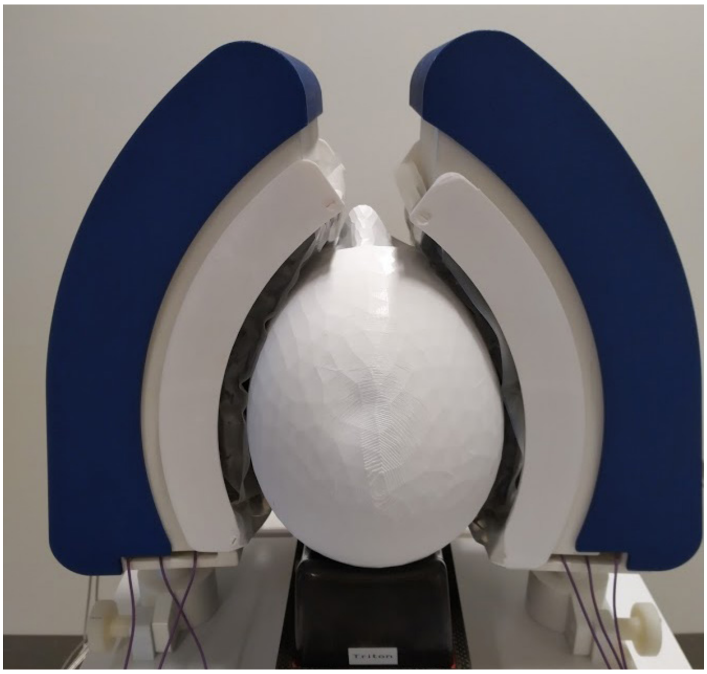


*Fig. 93: Shape stability when patient is positioned in MRcollar: Bolus gets pushed in place.*

## Conclusion

The enhanced flexibility of the final bolus structure, negatively influences the shape stability. Some more variations in density and wall thickness could be made to find an optimal balance between shape stability and flexibility. A possible solution would be to keep the same amount of unit cells in the compression direction to keep flexibility, but increase the amount of unit cells in the directions perpendicular to the compression, to improve the stability of the shape.

# 8.4 FUNCTIONALITY IN MRCOLLAR

## Specific absorption rate

Simulations were carried out by a technician at EMC to see how the new bolus shape influences the specific absorption rate (SAR) distribution in the patients tissue. Simplified, how will the new bolus shape affect the electromagnetic waves.

The software sim4life was used to simulate this. A patient is digitally positioned in the applicator with attached bolus volume after which the treatment is simulated. This was done for the HYPERCollar3D bolus and for the new MRcollar bolus.

It was seen that the new bolus design does not cover the full antenna range, which might lead to a less efficient treatment. The design should be extended a little bit towards the top and bottom of the applicator to allow the electromagnetic waves to penetrate better towards the tissue. This proposed extended volume was added to the shape and simulated again (see fig. 94).

The parameters that are used to measure the SAR distribution are THQ, TC25, TC50 and TC75:

- The target-to-hot-spot-quotient (THQ):
    - Ratio between the average SAR in the tumour tissue and the maximum SAR in the healthy tissue. Indication of hot-spots prominence relative to the average SAR. This shows how much can the temperature be increased without damaging tissue.
- Target coverage 25%, 50%, 75% (TC25, TC50, TC75):
    - Coverage of SAR: Percentage of the target (tumour) volume which passes 25%, 50% or 75% of the maximum SAR patient values. E.g. if the maximum SAR is 100 Watt, how much of the target volume passes the value of 25, 50 and 75 Watt.

For each of these parameters applies: the higher the value the better.

### Results:

The THQ and TC values are shown in table 5. It can be concluded that the new bolus shape does not disrupt the heating and performs equally as good or slightly better as the previous bolus. By extending the bolus shape slightly at the top and at the bottom, the EM waves can penetrate better towards the patient, improving the SAR distribution.

| | HYPERcollar 3D | New design | New design, extended |
|---|---|---|---|
| THQ | 0,58 | 0,66 | 0,68 |
| TC25 | 59 % | 68 % | 69 % |
| TC50 | 35 % | 30 % | 41 % |
| TC75 | 11 % | 5 % | 10 % |

*Table. 5: THQ and TC values after simulation*

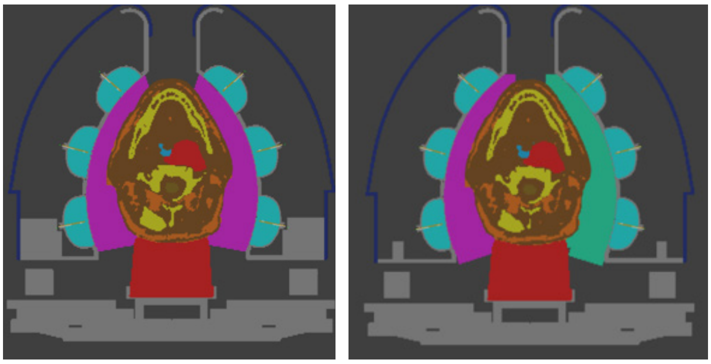


*Fig. 94: Simulation of new design (left) and extended design (right)*

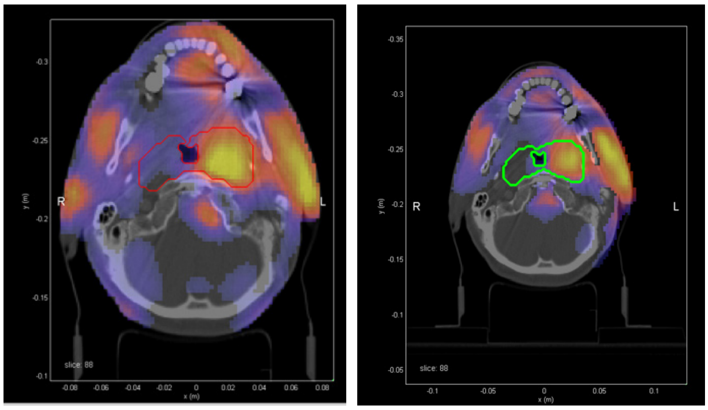



*Fig. 95: Simulation HYPERcollar3D (left) and new design (right)*

# 8.5 USABILITY BY CLINICIAN

## Sliding system

Seven Erasmus MC employees were asked to rate the sliding mechanism as well as the old velcro attachment on connection effort and durability on a scale from 1 to 5 (see appendix F and H).

The results are shown in figure 96. The new sliding mechanism was rated considerably higher than the velcro connection on both connection effort and connection durability. By changing the old slide-in, force fit by the push-in, hexagonal fitting, the side panels did not disconnect from the beams anymore during any of the tests.

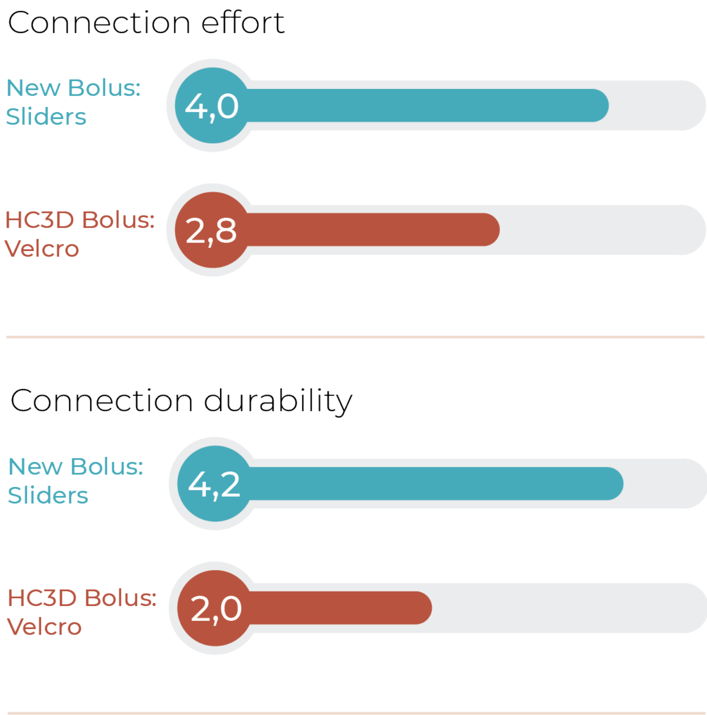



*Fig. 96: Usability test: results*

# 8.6 COST ESTIMATION

An estimation of the cost price of one bolus, for a production volume of 20 pieces (10 full set-ups) can be found below.

| | Material | Firm | Units | Cost/piece | Total |
|---|---|---|---|---|---|
| Inner structure | Ultrasint TPU 90A-01 | Materialise | 1 | € 200,00 | € 200,00 |
| Outer enclosure | PU film | Epurex | 0,12 m² | € 6,00 /m2 | € 0,72 |
| Glue | Sabacontact 70T | Esails.nl | 0,12 m² | € 27,50 / l<br>€ 5,50 / m² | € 0,66 |
| Sliding connectors | PLA (print in-house) | 123-3d.nl | 0,76 kg | € 16,12 / kg | € 12,25 |
| Labour | | | 30 minutes | € 40,00 / h | € 20,00 |
| TOTAL | | | | | **€ 233,63** |
| Cost full Set-up (2 boli) | | | 2 | € 233,63 | **€ 467,26** |

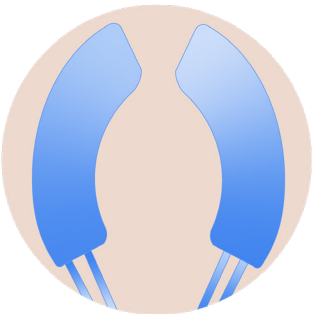
# 9 CONCLUSIONS & RECOMMENDATIONS

# 9.1 CONCLUSIONS

Even though there are still opportunities for optimization, it can be concluded that the new bolus design performs well on all five predefined challenges:

Patient comfort

The user evaluations showed that no serious discomfort was experienced by the participants. The pressure is distributed quite evenly, showing that the shape nicely follows the contours of the head. The material was considered as pleasant to the skin and since the outer film is now glued and not inflating anymore there was a big enough gap for breathing and seeing. Additionally, the appearance of the bolus was perceived as friendly and reliable. All these factors combined will reduce the stress experienced by the patients during treatment. Some users experienced some slight discomfort around the ear, and for a lot of test subjects the cheeks got squished together when closing the collar. This issue can be resolved by allowing the patients to slightly reposition themselves before starting the treatment.



Effective & uniform cooling

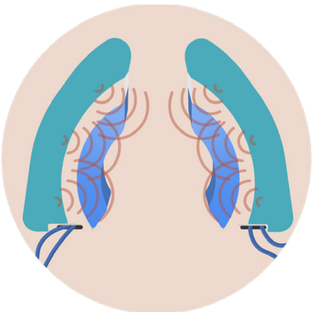
The infrared images showed that the principle of using walls to guide the waterflow works. The water follows the intended path throughout the bolus, covering the full volume. In the last structure iteration, the distance between the walls was a bit too large, causing the areas right above each walls to remain uncooled for a rather long period of time. In a future design, an additional wall could be added to make the water distribution more efficient.

The transfer of cooling from water to skin was also shown to take place quite evenly: at a water temperature of 24 °C, most of the skin area cools down to 25-26°C. Only the area right around the ear tends to cool down a little less due to a mediocre fit and thus contact in this region.

Shape: stable predictable and reproducible

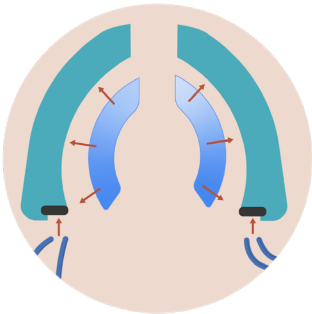
Since the outer enclosure is now glued to the inner structure, inflation of the bolus is avoided causing the bolus to keep its intended shape. This will also decrease the amount of water needed to fill the shape and make the overall bolus shape and properties more stable, predictable and reproducible in simulations and treatment.

Overall the lattice structure maintains it shape quite well due to its three dimensional force absorption, but the enhanced flexibility of the final bolus structure negatively influences the shape stability. When the bolus is inserted in the MRcollar, it does not fully maintain its predefined curve. A small gap appears between the collar and the bolus. Some more variations in density and wall thickness could be made to find an optimal balance between shape stability and flexibility.



Functionality in MRcollar

All materials in the water bolus are plastics, and thus MRI compatible. By choosing a different, stronger material for the outer enclosure and developing a procedure to seal and glue the film, the bolus can be produced completely watertight and is not punctured easily. When digitally simulating the treatment with the new bolus, it was found that the new shape does not disrupt the electromagnetic waves. However, to fully cover the antenna range and improve the SAR distribution in the tissue the bolus should be slightly extended at the top and bottom.



Usability by clinician

The previously developed sliding system makes it very easy and fast to connect the bolus to the MRcollar. The existing slider design was improved by changing the connection between the parts to a hexagonal force fit, ensuring that the sliders do not disconnect during handling. Additionally a sealed loop was added to the outer enclosure to create a fast and secure connection between bolus and sliding mechanism. In a user survey, the sliding mechanism scored significantly better on durability and convenience than the previous Velcro connection in HYPERcollar3D.

# 9.2 RECOMMENDATIONS

During the final validation of the new water bolus design, several opportunities for further optimization of the water bolus were found:

1. To improve the water flow distribution, an additional wall can be added in the inner structure. Increasing the amount of walls from three to four. This will cause the water inlet to be placed at the opposite side as the water outlet and hence also solve the problem of the water inlet tubes causing discomfort at the neck and shoulder area.

2. The balance between flexibility and stability properties of the water bolus can still be optimized, by exploring different wall thicknesses and densities. An interesting direction, to keep the high flexibility but improve the stability of the bolus, would be to keep the amount of unit cells in the compression (Z-)direction the same, but enhance the amount of unit cells in the other two (X- and Y-) directions. Another possibility would be to make a gradient lattice which is more dense/stiff near the antennas surface and more open/flexible near the skin.

3. It would be interesting to explore in more detail how creating a lattice with different densities can guide the water flow even more accurately throughout the bolus volume or to specific areas that require better cooling.

4. User tests should be carried out on the 15 degrees tilted water bolus set-up. It still has to be researched if the current bolus design will also be comfortable in the tilted set-up, or if it would be better to create a different bolus that is generated specifically for this positioning.

5. Even though the PU film that is used in the final design performs sufficiently, a more flexible film would follow the bolus shape more closely, would be easier to stretch around the structure and would be less likely to form folds. Additionally a non-transparent film might give the bolus a more aesthetic and reliable look, hiding the glue.

6. The bolus still has to be tested in the full set-up, where also the electromagnetic waves are applied.

7. The bolus shape has to be extended slightly to top and bottom, to ensure full antenna coverage and hence better SAR distribution.

8. If the production volume will be increased, it would be recommendable to find a more efficient, automated approach to glue and seal the outer enclosure.

9. Regarding the fit of the bolus it could be interesting to use the average bolus for most of the patients, but create a personalized bolus when patients show more extreme deformities due to the tumour.

# REFERENCES & APPENDICES

# REFERENCES


Arunachalam, K., Maccarini, P. F., Schlorff, J. L., Birkelund, Y., Jacobsen, S., & Stauffer, P. R. (2009).
Design of a water coupling bolus with improved flow distribution for multi-element superficial hyperthermia applicators. International Journal of Hyperthermia, 25(7), 554-565.

Bi, D. (2014). HYPERcollar: Integrated Re-design of a Clinical Hyperthermia Head and Neck
Applicator. MSc Thesis. Delft: TU Delft.

Bijwerkingen en klachten van oppervlakkige hyperthermie. (2018). https://www.kanker.nl/soorten-behandelingen/hyperthermie/wat-is/bijwerkingen-en-klachten-van-oppervlakkige-hyperthermie?pk_campaign=navigatie&pk_kwd=volgendartikel

Birkelund, Y., Jacobsen, S., Arunachalam, K., Maccarini, P., & Stauffer, P. R. (2009). Flow patterns and heat convection in a rectangular water bolus for use in superficial hyperthermia. Physics in medicine and biology, 54(13), 3937.

Chow, L. Q. M. (2020). Head and Neck Cancer. New England Journal of Medicine, 382(1), 60–72.

Common toxicity criteria manual. (1999).

Democratiz3D. (2021). Retrieved 22 April 2021, from https://www.embodi3d.com/democratiz3D/

DINED (Mannequin):
Huysmans, T., Goto, L., Molenbroek, J., & Goossens, R. (2020). DINED Mannequin. Tijdschrift voor Human Factors, 45(1), 4-7.

Durometer Shore Hardness Scale. Retrieved 29 April 2021, from https://www.smooth-on.com/page/durometer-shore-hardness-scale/

Erasmus MC - patiëntfolder: Diepe hyperthermie. (n.d.). Retrieved February 15, 2021, from https://patientenfolders.erasmusmc.nl/folders/diepe_hyperthermie

FDM 3D printing materials compared | Hubs. (2021). Retrieved 29 April 2021, from https://www.hubs.com/knowledge-base/fdm-3d-printing-materials-compared/

Foam Production | Recticel Flexible Foams. Retrieved 23 March 2021, from https://recticelflexiblefoams.com/about-us/our-expertise/our-technologies/foam-production.html

Horsman, M. R., & Overgaard, J. (2007). Hyperthermia: a Potent Enhancer of Radiotherapy. Clinical Oncology, 19(6), 418–426.

Huysmans, T. (2020). Paraview Custom Filters for Statistical Shape Modeling [computer software]. TU Delft. Delft, The Netherlands.
Hyperthermie bij kanker. (2018). https://www.kanker.nl/soorten-behandelingen/hyperthermie/wat-is/hyperthermie-bij-kanker-0

Keeley, C. (2017). Open Cell vs. Closed Cell Foam: What's the Difference?. Retrieved 23 March 2021, from https://www.cgrproducts.com/open-cell-vs-closed-cell-foam/

Kitware. (2021). Paraview (Version 5.8.1) [computer software].

Marur, S., & Forastiere, A. A. (2008). Head and neck cancer: Changing epidemiology, diagnosis, and treatment. Mayo Clinic Proceedings, 83(4), 489–501.

Pan, C., Han, Y., & Lu, J. (2020). Design and Optimization of Lattice Structures: A Review. Applied Sciences, 10(18), 6374.

Paulides, M. M., Bakker, J. F., Neufeld, E., Zee, J. van der, Jansen, P. P., Levendag, P. C., & van Rhoon, G. C. (2007). The HYPERcollar: A novel applicator for hyperthermia in the head and neck. International Journal of Hyperthermia, 23(7), 567–576.

Paulides, M. M., Dobsicek Trefna, H., Curto, S., & Rodrigues, D. B. (2020). Recent technological advancements in radiofrequency- andmicrowave-mediated hyperthermia for enhancing drug delivery. In Advanced Drug Delivery Reviews (Vols. 163–164, pp. 3–18). Elsevier B.V.

Paulides, M. M., Verduijn, G. M., & Van Holthe, N. (2016). Status quo and directions in deep head and neck hyperthermia. Radiation Oncology, 11(1), 21.

R3DS. (2020). Wrap (Version 12.2) [computer software]].

Redwood, B. Additive manufacturing technologies: An overview | Hubs. Retrieved 22 June 2021, from https://www.hubs.com/knowledge-base/additive-manufacturing-technologies-overview/

Rijnen, Z., Togni, P., Roskam, R., Van De Geer, S. G., Goossens, R. H. M., & Paulides, M. M. (2015). Quality and comfort in head and neck hyperthermia: A redesign according to clinical experience and simulation studies Int J Hyperthermia, 31(8), 823–830.

Robinette, K. M., Daanen, H., & Paquet, E. (1999, October). The CAESAR project: a 3-D surface anthropometry survey. In Second International Conference on 3-D Digital Imaging and Modeling (Cat. No. PR00062) (pp. 380-386). IEEE.

Slicer. (2021). 3D Slicer (Version 4.11) [computer software]].

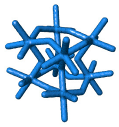
Technology – Sensius. (n.d.). Retrieved February 14, 2021, from https://www.sensius.biz/technology/
van Den Berg, L. (2017). Ergonomic water bolus design for hyperthermia treatment of head and neck cancer patients. 1–133.

van der Zee, J. (2002). Heating the patient: a promising approach? Annals of Oncology, 13(8), 1173–1184.

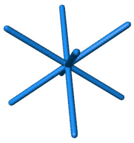
Vormen van hyperthermie. (2018). https://www.kanker.nl/soorten-behandelingen/hyperthermie/wat-is/vormen-van-hyperthermie?pk_campaign=navigatie&pk_kwd=volgendartikel

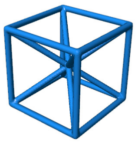
Wang, J., & Rai, R. (2016). Classification of Bio-Inspired Periodic Cubic Cellular Materials Based on Compressive Deformation Behaviors of 3D Printed Parts and FE Simulations. Retrieved 1 June 2021, from

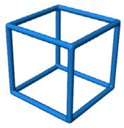
# APPENDIX A: UNIT CELLS

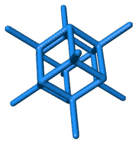

Auxetic

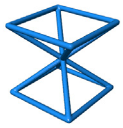

BC star tet

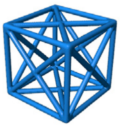

BC

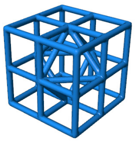

BC cubic

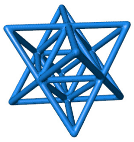

Cubic


Dodecahedron

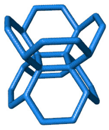

Edge octa

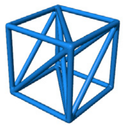

FC cubic

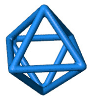

NaCl

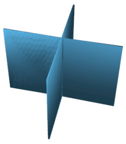

Octa tet

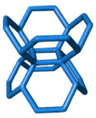

Star tet

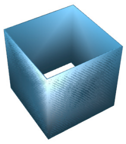

Trunc octa

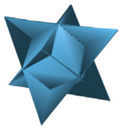

Tetrahedral

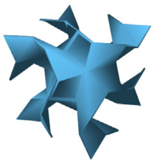

Vertex octa


Cubic centre


Trunc octa

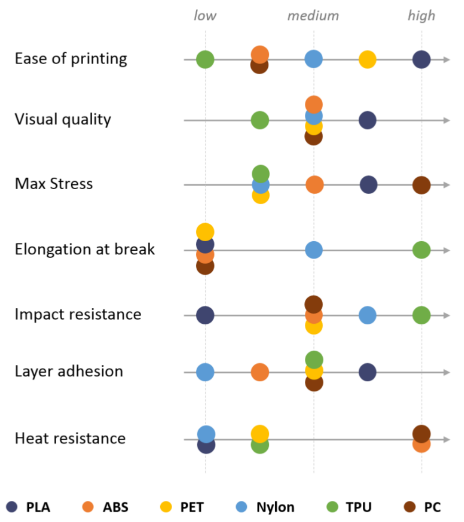

Cubic face


Dodeca


Gyroid

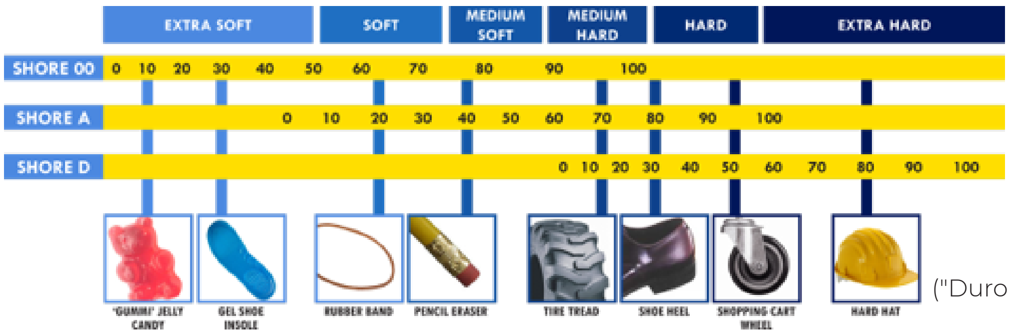
# APPENDIX B: MATERIALS FOR 3D PRINTING

## Rigid




("FDM 3D printing materials compared | Hubs", 2021)

## Flexible




("Durometer Shore Hardness Scale", n.d.)

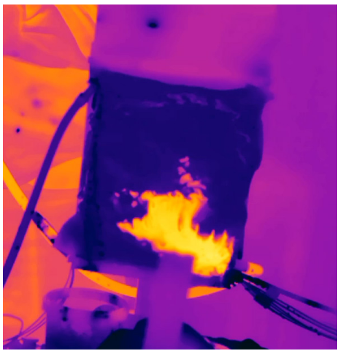
| | | |
|---|---|---|
| **FDM** | | |
| Ultimaker TPU | 95A | https://ultimaker.com/nl/materials/tpu-95a |
| 123 3D Jupiter TPE | 45D | https://www.123-3d.nl/123-3D-Filament-flexibel-blauw-2-85-mm-TPE-0-5-kg-Jupier-serie-i1549-t222.html |
| NinjaTek Cheetah TPU | 98A (50D) | https://www.123-3d.nl/NinjaTek-Cheetah-TPU-Fire-1-75-mm-0-5-kg-semi-flexibel-i924-t226.html |
| REAL filament TPU | 98A | https://www.123-3d.nl/REAL-filament-rood-2-85-mm-TPU-98A-0-5-kg-i3336-t222.html |
| NinjaTek Ninjaflex TPU | 85A | https://www.123-3d.nl/NinjaTek-NinjaFlex-TPU-Fire-3-mm-0-5-kg-flexibel-3DNF0329005-i3694-t222.html |
| | | |
| **SLS** | | |
| Oceanz Flexible (TPU) | 88A | https://www.oceanz.eu/materialen/oceanz-flexible/ |
| | | |
| **Multi-jet Fusion** | | |
| Materialise Ultrasint TPU 90A-01 | 88A | https://www.materialise.com/en/manufacturing/materials/ultrasint-tpu-90a-01 |
| | | |
| **SLA** | | |
| Flexible resin | 80A | https://formlabs.com/store/materials/flexible-80a-resin/ |
| Elastic resin | 50A | https://formlabs.com/store/materials/elastic-resin/ |
| | | |
| **Polyjet** | | |
| Agilus 30A-95A | 30-95A | |

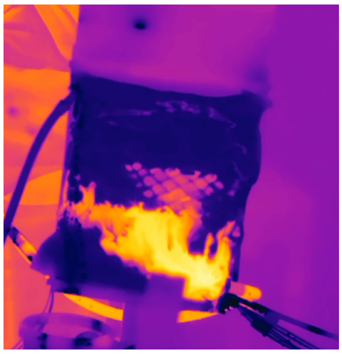
# APPENDIX C: INFRARED TESTS

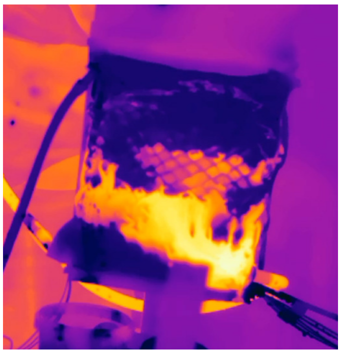
## Lattice

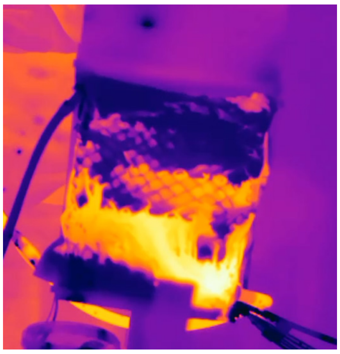

0 secs

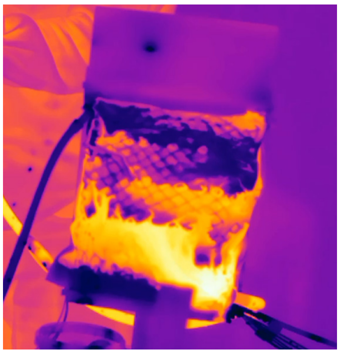

5 secs

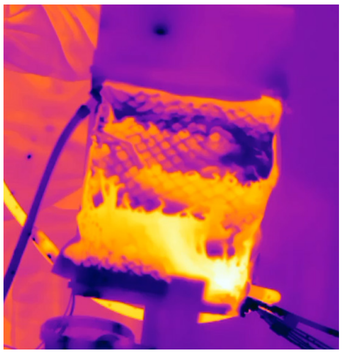

10 secs

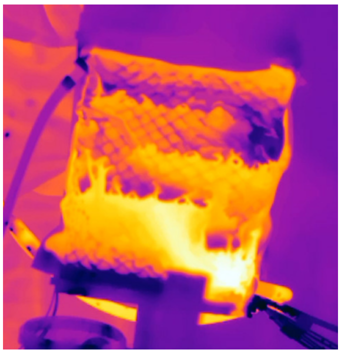

15 secs

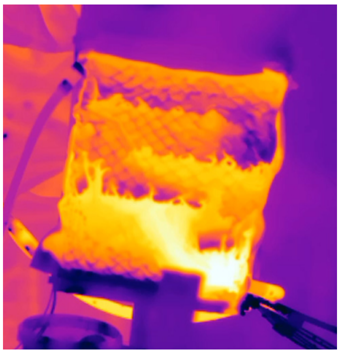

20 secs

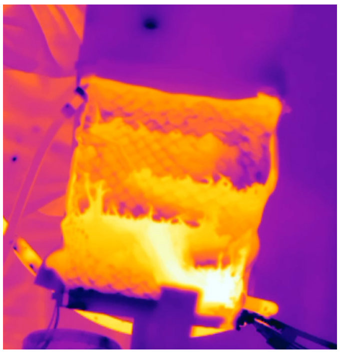

25 secs

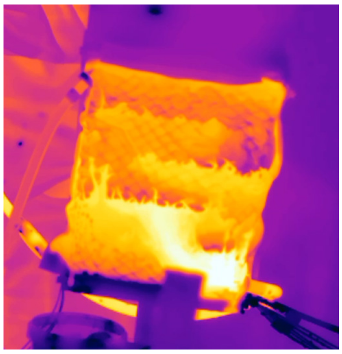

30 secs

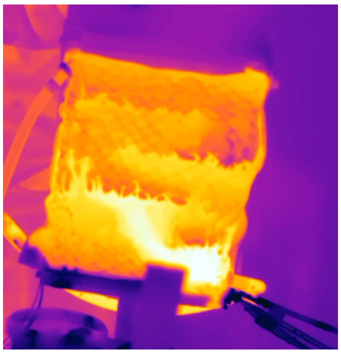

35 secs

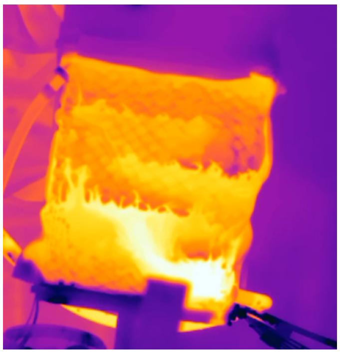

40 secs

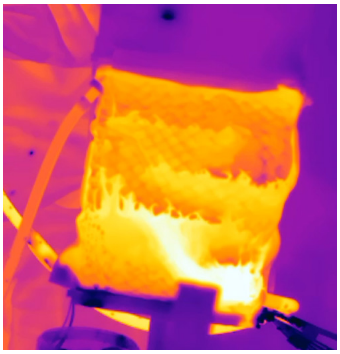

45 secs

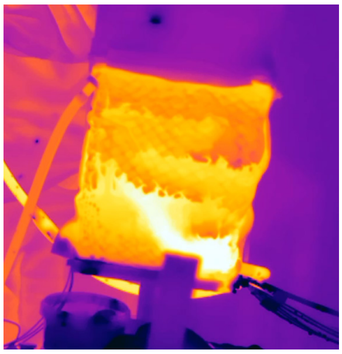

50 secs

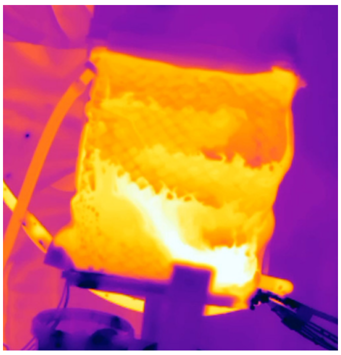

55 secs

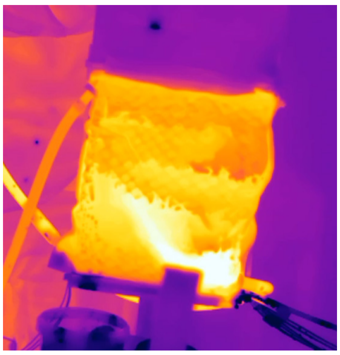

60 secs


65 secs


70 secs

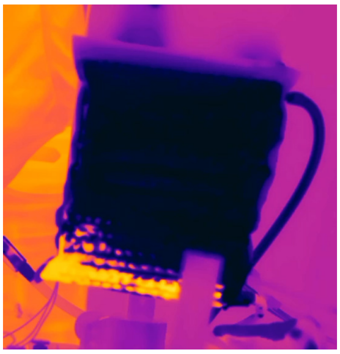

75 secs


80 secs

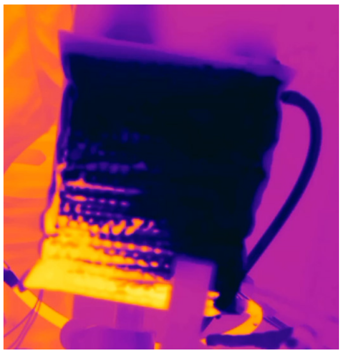

85 secs

## Honeygrid


0 secs


5 secs


10 secs

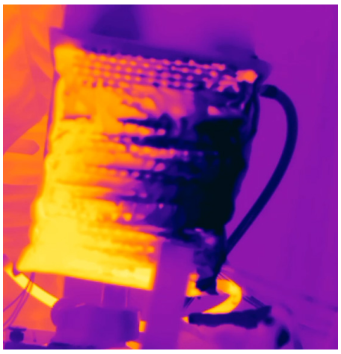

15 secs


20 secs

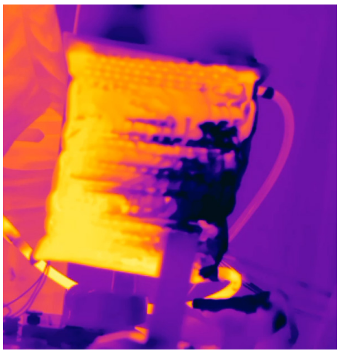

25 secs

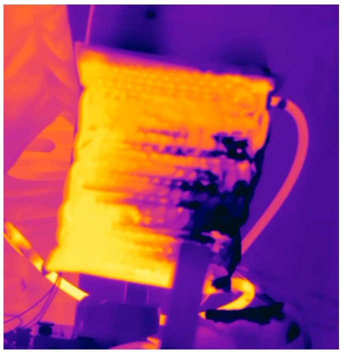

30 secs

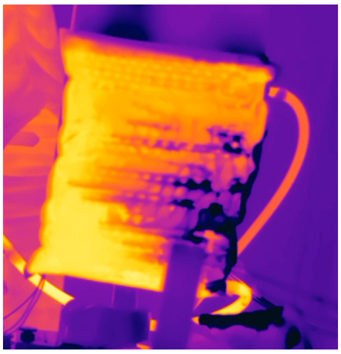

35 secs

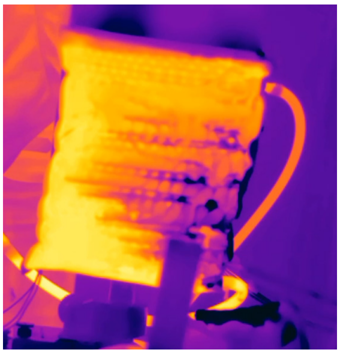

40 secs

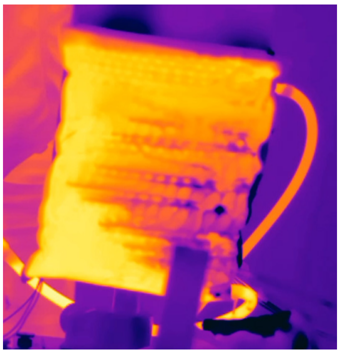

45 secs

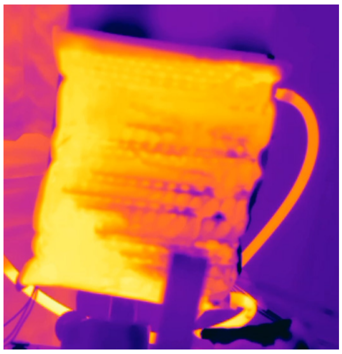

50 secs

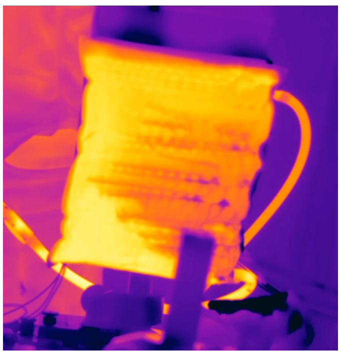

55 secs

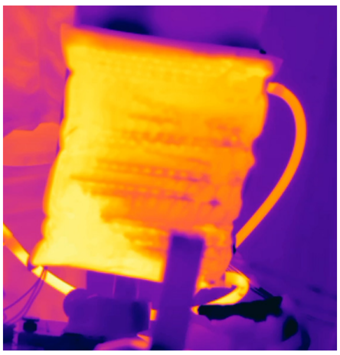

60 secs

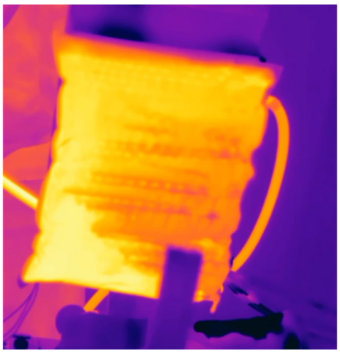

65 secs


70 secs

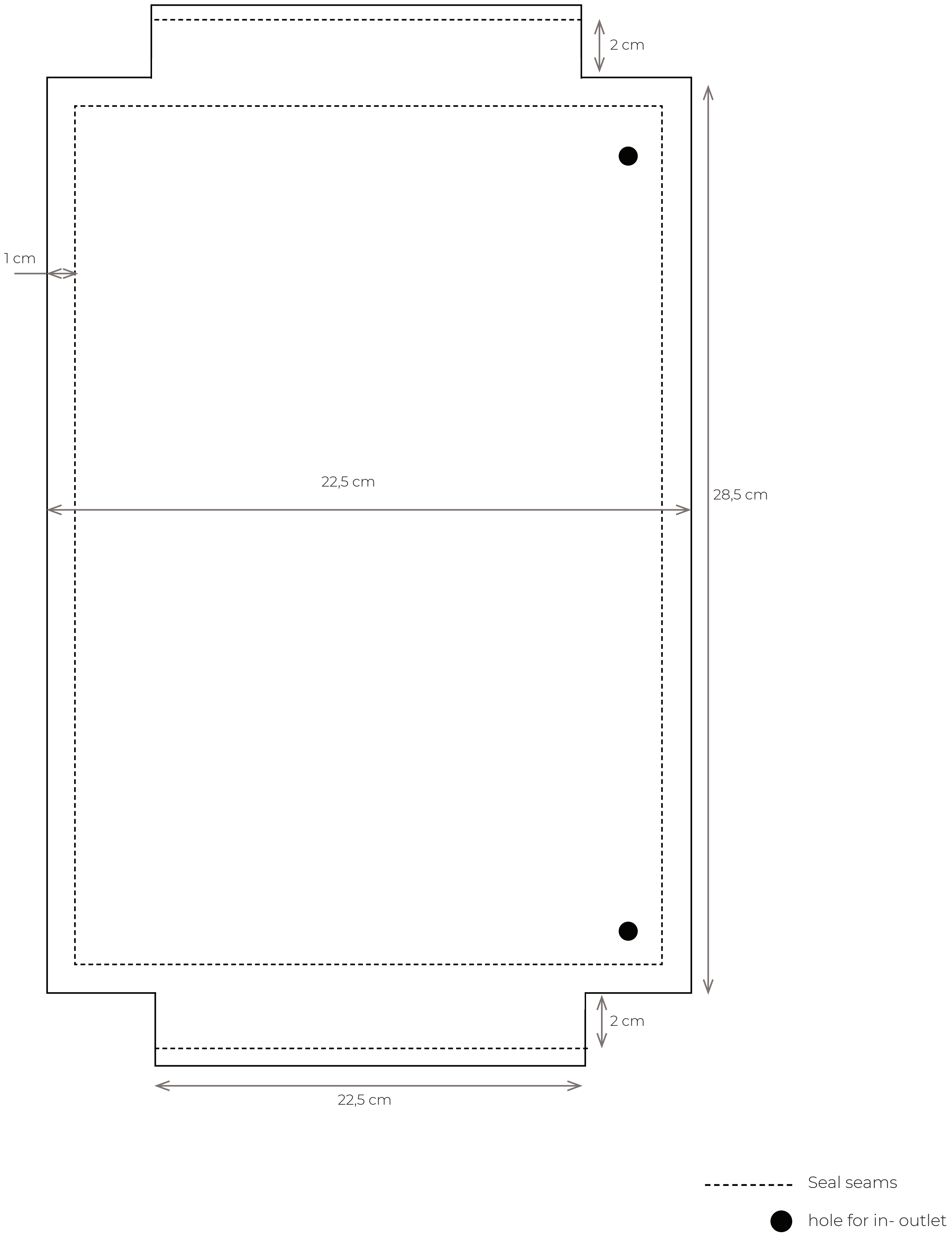

75 secs


80 secs


85 secs


90 secs

# APPENDIX D: OUTER FILM DIMENSIONS



# APPENDIX E: EVALUATION FORM 1

Name:
Function:

## Comfort

How would you rate the overall comfort of the water bolus?

| -- | - | +/- | + | ++ |
| --- | --- | --- | --- | --- |
| ○ | ○ | ○ | ○ | ○ |

## Pressure points

How would you rate the comfort regarding pressure points on your skin in the water bolus?

| -- | - | +/- | + | ++ |
| --- | --- | --- | --- | --- |
| ○ | ○ | ○ | ○ | ○ |

## Breathing

How would you rate the comfort of breathing in the water bolus?

| -- | - | +/- | + | ++ |
| --- | --- | --- | --- | --- |
| ○ | ○ | ○ | ○ | ○ |

## Material

How comfortable feels the contact between the material of the water bolus and your skin?

| -- | - | +/- | + | ++ |
| --- | --- | --- | --- | --- |
| ○ | ○ | ○ | ○ | ○ |

## Appearance

How friendly and reliable does the water bolus appear to you?

| -- | - | +/- | + | ++ |
| --- | --- | --- | --- | --- |
| ○ | ○ | ○ | ○ | ○ |

# APPENDIX F: EVALUATION FORM 2

Name:
Function:

## Connecting Effort

| Question | -- | - | +/- | + | ++ |
|---|---|---|---|---|---|
| How convenient is the velcro connection between water bolus A and the equipment? | ○ | ○ | ○ | ○ | ○ |
| How convenient is the sliding connection between the water bolus B and the equipment? | ○ | ○ | ○ | ○ | ○ |

## Connection durability

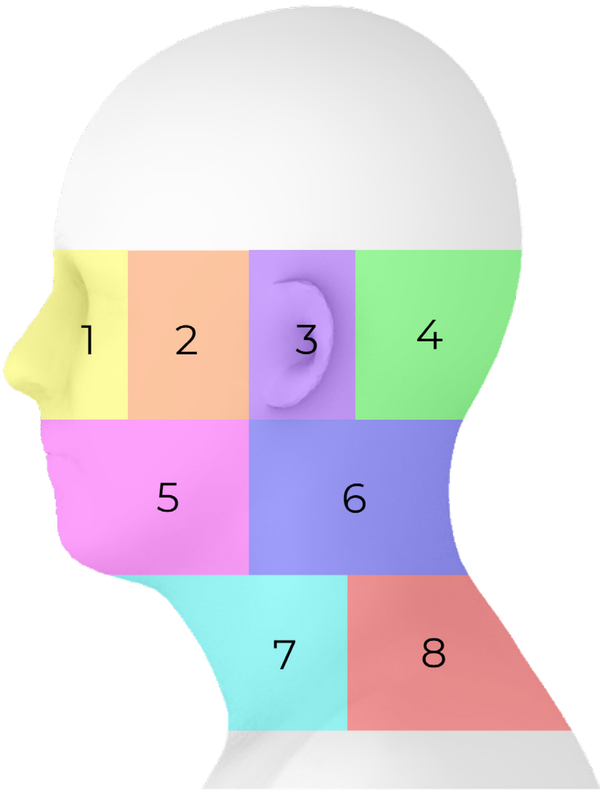
| Question | -- | - | +/- | + | ++ |
|---|---|---|---|---|---|
| How durable is in your opinion the velcro connection between water bolus A and the equipment? | ○ | ○ | ○ | ○ | ○ |
| How durable is in your opinion the sliding connection between water bolus B and the equipment? | ○ | ○ | ○ | ○ | ○ |

# APPENDIX G: LOCAL PERCEIVED DISCOMFORT

Name:
Function:

## How much discomfort do you feel?

| | | | | | |
|---|---|---|---|---|---|
| Zone 1 | ◯ No discomfort | ◯ | ◯ | ◯ | ◯ Extreme discomfort |
| Zone 2 | ◯ No discomfort | ◯ | ◯ | ◯ | ◯ Extreme discomfort |
| Zone 3 | ◯ No discomfort | ◯ | ◯ | ◯ | ◯ Extreme discomfort |
| Zone 4 | ◯ No discomfort | ◯ | ◯ | ◯ | ◯ Extreme discomfort |
| Zone 5 | ◯ No discomfort | ◯ | ◯ | ◯ | ◯ Extreme discomfort |
| Zone 6 | ◯ No discomfort | ◯ | ◯ | ◯ | ◯ Extreme discomfort |
| Zone 7 | ◯ No discomfort | ◯ | ◯ | ◯ | ◯ Extreme discomfort |
| Zone 8 | ◯ No discomfort | ◯ | ◯ | ◯ | ◯ Extreme discomfort |



# APPENDIX H: USER TEST RESULTS

**(DIS)COMFORT QUESTIONNAIRE RESULTS: MRCOLLAR**

| | Comfort | Pressure points | Breathing | Material | Appearance |
|---|---|---|---|---|---|
| **USER 1** | 4 | 4 | 4 | 4 | 3 |
| **USER 2** | 5 | 5 | 5 | 5 | 5 |
| **USER 3** | 4 | 4 | 2 | 5 | 4 |
| **USER 4** | 4 | 5 | 3 | 3 | 5 |
| **USER 5** | 4 | 4 | 4 | 3 | 4 |
| **USER 6** | 4 | 4 | 5 | 4 | 4 |
| **USER 7** | 4 | 5 | 4 | 4 | 4 |
| | | | | | |
| **AVERAGE MRCOLLAR:** | **4,1** | **4,4** | **3,9** | **4,0** | **4,1** |
| **AVERAGE H3D:** | **3,4** | **3,2** | **3** | **4** | **2,5** |
| **AVERAGE HONEYGRID:** | **3,8** | **3,8** | **4** | **3,6** | **4,3** |

**USABILITY QUESTIONNAIRE**

| | HC3D | | Mrcollar | |
|---|---|---|---|---|
| | Connection effort | Connection durability | Connection effort | Connection durability |
| **USER 1** | 2 | 2 | 4 | 4 |
| **USER 4** | 2 | 1 | 4 | 5 |
| **USER 5** | 2 | 2 | 4 | 4 |
| **USER 6** | 4 | 1 | 4 | 4 |
| **USER 7** | 4 | 4 | 4 | 4 |
| | | | | |
| **AVERAGE** | **2,8** | **2,0** | **4,0** | **4,2** |

**LOCAL PERCEIVED DISCOMFORT**

| | Zone 1 | Zone 2 | Zone 3 | Zone 4 | Zone 5 | Zone 6 | Zone 7 | Zone 8 |
|---|---|---|---|---|---|---|---|---|
| **USER 1** | 3 | 1 | 1 | 1 | 3 | 1 | 1 | 1 |
| **USER 2** | 1 | 1 | 4 | 1 | 3 | 1 | 1 | 1 |
| **USER 3** | 3 | 1 | 3 | 1 | 1 | 1 | 1 | 1 |
| **USER 4** | 3 | 1 | 3 | 1 | 1 | 2 | 1 | 1 |
| **USER 5** | 1 | 4 | 1 | 1 | 2 | 1 | 1 | 3 |
| **USER 6** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **USER 7** | 1 | 1 | 1 | 3 | 1 | 3 | 1 | 1 |
| | | | | | | | | |
| **AVERAGE** | **1,9** | **1,4** | **2,0** | **1,3** | **1,7** | **1,4** | **1,0** | **1,3** |

**REMARKS**

| | |
|---|---|
| **USER 1:** | Zeer gelijkmatige drukverdeling, niet onaangenaam, enkel aan de kaken licht oncomfortabel omdat ze worden samengedrukt |
| **USER 2:** | Linker oor oncomfortabel, kaken samengedrukt |
| **USER 3:** | Neus dichtgeduwd, wangen samengedrukt, niet heel erg vervelend/pijnlijk wel wat druk, materiaal voelt lekker op de huid, vorm veranderde soms, vooral vervelend aan de kaken |
| **USER 4:** | Algemeen niet erg oncomfortabel, enkel kaken samengedrukt, oor links meer druk |
| **USER 5:** | Kaken/jukbeenderen geklemd, oren geen last, schouders tegen de randen, buisjes in de weg, niet onprettig, voldoende zichtbaarheid is prettig, snel claustrofobisch maar niet in deze situatie |
| **USER 6:** | Geen drukpunten, gelijkmatige drukverdeling, wel strak |
| **USER 7:** | Voornamelijk de neksteun is oncomfortabel |

# APPENDIX I: PROJECT BRIEF

DESIGN FOR our future

TU Delft

## IDE Master Graduation

Project team, Procedural checks and personal Project brief

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

- The student defines the team, what he/she is going to do/deliver and how that will come about.
- SSC E&SA (Shared Service Center, Education & Student Affairs) reports on the student's registration and study progress.
- IDE's Board of Examiners confirms if the student is allowed to start the Graduation Project.

**USE ADOBE ACROBAT READER TO OPEN, EDIT AND SAVE THIS DOCUMENT**

Download again and reopen in case you tried other software, such as Preview (Mac) or a webbrowser.

**SUPERVISORY TEAM ****

Fill in the required data for the supervisory team members. Please check the instructions on the right !

** chair: Kaspar Jansen — dept. / section: Emerging Materials

** mentor: Toon Huysmans — dept. / section: AED

2nd mentor: G.C. Van Rhoon

organisation: Erasmus MC Cancer Institute

city: Rotterdam — country: The Netherlands

comments (optional)

Chair should request the IDE Board of Examiners for approval of a non-IDE mentor, including a motivation letter and c.v..

Second mentor only applies in case the assignment is hosted by an external organisation.

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

# Ergonomic Water Bolus Design for Treatment of Head and Neck Tumors

project title

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

start date 08 - 02 - 2021 | 03 - 07 - 2021 end date

## INTRODUCTION **

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

In Erasmus MC – Cancer Institute Hyperthermia unit, patients with cancer are being treated by raising tumor temperatures to the range of 40 - 44°C for 60-90 minutes. Around 150 new patients are being treated each year with hyperthermia to improve radio- or chemotherapy. Recently within the hyperthermia unit, a novel MR compatible head and neck hyperthermia applicator (MRcollar) were designed and developed. Electromagnetic energy is applied from this 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 tumor tissue. During this project a new water bolus will be designed to optimize cooling and patient comfort.

Stakeholders

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 tumors and deep pelvic tumors, this Hyperthermia Unit is the first institution worldwide to have developed a hyperthermia system specifically for treatment of deep head and neck tumors. The Erasmus MC asked for a graduate student to be involved in the development of a water bolus for this innovative hyperthermia system.

The design will be used for treatment of patients with neck and head tumors. By designing a comfortable and reliable water bolus, their hospital/treatment experience can be improved. The patients that are being treated with hyperthermia do not have the best prognosis. This treatment is only used for recurring tumors and when other treatments didn't work. Therefore it might become a challenge to approach them and involve them in the design process.

The clinician helps the patient to get onto the bed and positions the head on the neck support. Next, the clinician is responsible for starting and supervising the treatment. It would be beneficial for the clinician if it is as efficient and easy as possible to position and prepare the patient for treatment.

space available for images / figures on next page

introduction (continued): space for images

image / figure 1: Hyperthermia treatment

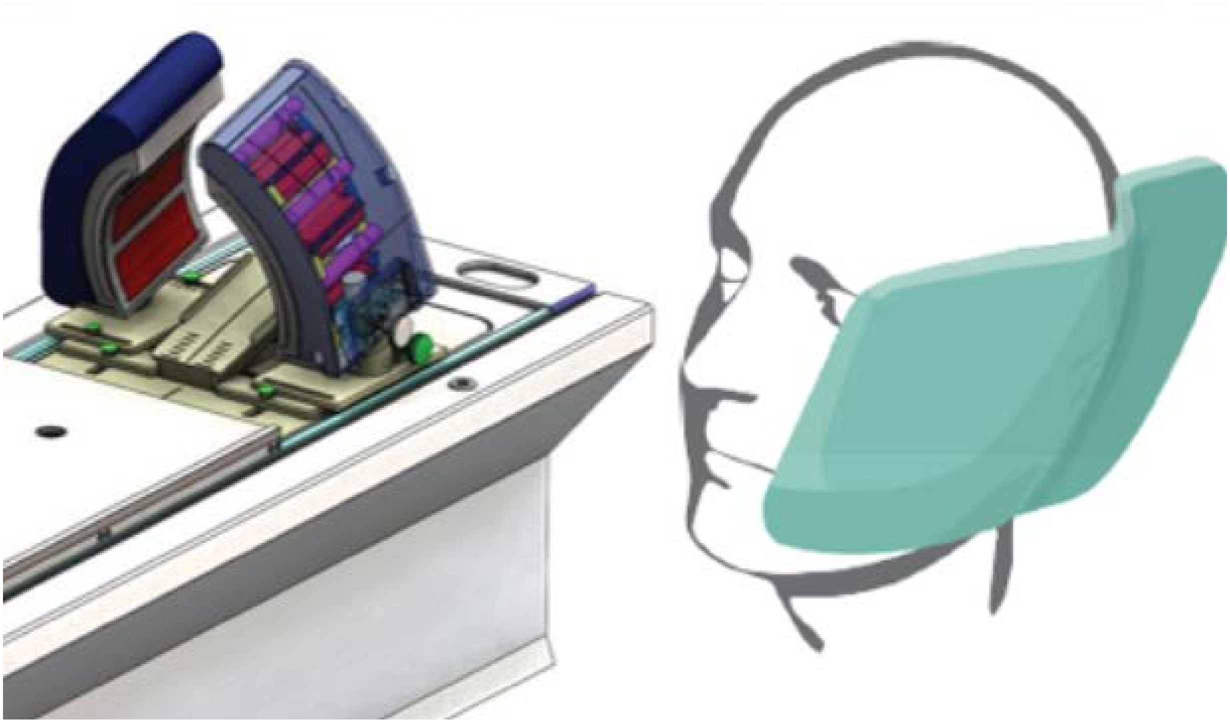


image / figure 2: Waterbolus

## PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

For effective treatment, we rely on an accurate, reproducible and stable positioning of the water bolus that provides cooling on the patient skin and energy conduction between the MRcollar applicator and the patient. Therefore, an ergonomic water bolus is crucial for successful hyperthermia treatment. The water bolus should ergonomically follow the patient's contours to ensure good contact with the skin of the patient for adequate cooling and power transfer. Further, equal thickness of the water bolus between the applicator and the irregular body surface is essential for good thermal contact to the skin. Furthermore, the design 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.

## ASSIGNMENT **

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... . In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

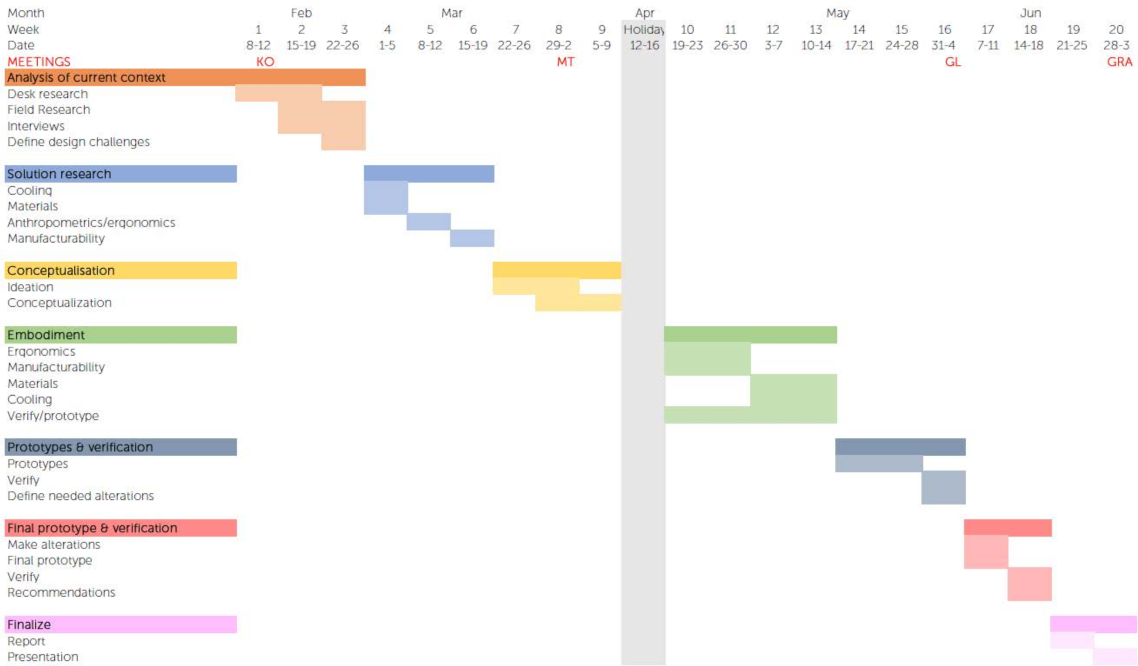
Design, manufacture and test an ergonomic water bolus for hyperthermia treatment of head and neck.

Output and deliverables
- Analysis of the current system design and formulation of the needs and constraints
- Conceptual design of a water bolus.
- Manufacturing and testing of proof-of-concept setups
- Assessment of improvements by volunteer experiments

## PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date 8 - 2 - 2021 3 - 7 - 2021 end date




During the first weeks of the project the current context will be analyzed by doing desk research, field research and carrying out interviews with clinicians, technicians and (if possible) patients who are involved in the hyperthermia unit. This will help to define the current issues and which challenges to tackle when designing the water bolus. Next, research for possible solution areas will be done; With a focus on ergonomics, suitable materials, benefits and limitations of possible production techniques and how to provide cooling.

With the knowledge of the previous phases in mind, different ideas can be generated and evolve into concepts. After the midterm evaluation these concepts will be developed in more detail while especially paying attention to materials, cooling, manufacturability and ergonomics and verifying these aspects with different prototypes or test set-ups.

During the last stages of the project a first full prototype will be made and tested. With the conclusions from this test, alterations can be made and implemented into the following protototype(s) to define the final product design and recommendations for future development.

The last two weeks will be used to finalize the report and prepare for the graduation presentation.



Initials & Name MLM Beljaars Student number 4545672

Title of Project Ergonomic Water Bolus Design for Treatment of Head and Neck Tumors

## MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... . Stick to no more than five ambitions.

This project fits very well to my personal interests and ambitions. Because it is a nice combination of medical, human centered and technical aspects.

I really wanted to do a health care related project, where I could gain some more insights and experience in the medical field. The collaboration with Erasmus MC will allow me to research the context on field and learn how the development of new medical equipment is approached in this setting. During the elective Biomechanics I already learned some basic anthropometrics tools and principles which will be very useful during this project.

Secondly, I really wanted to do a project with a focus on embodiment design. I like to think about product details, working principles, materials and manufacturability. In this design process I can explore all these features.

A big personal goal for this project is to further develop my prototyping skills and have a working prototype at the end, tested by users and altered to their recommendations. To do this I will broaden my knowledge about 3D printing possibilities and limitations.

## FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.