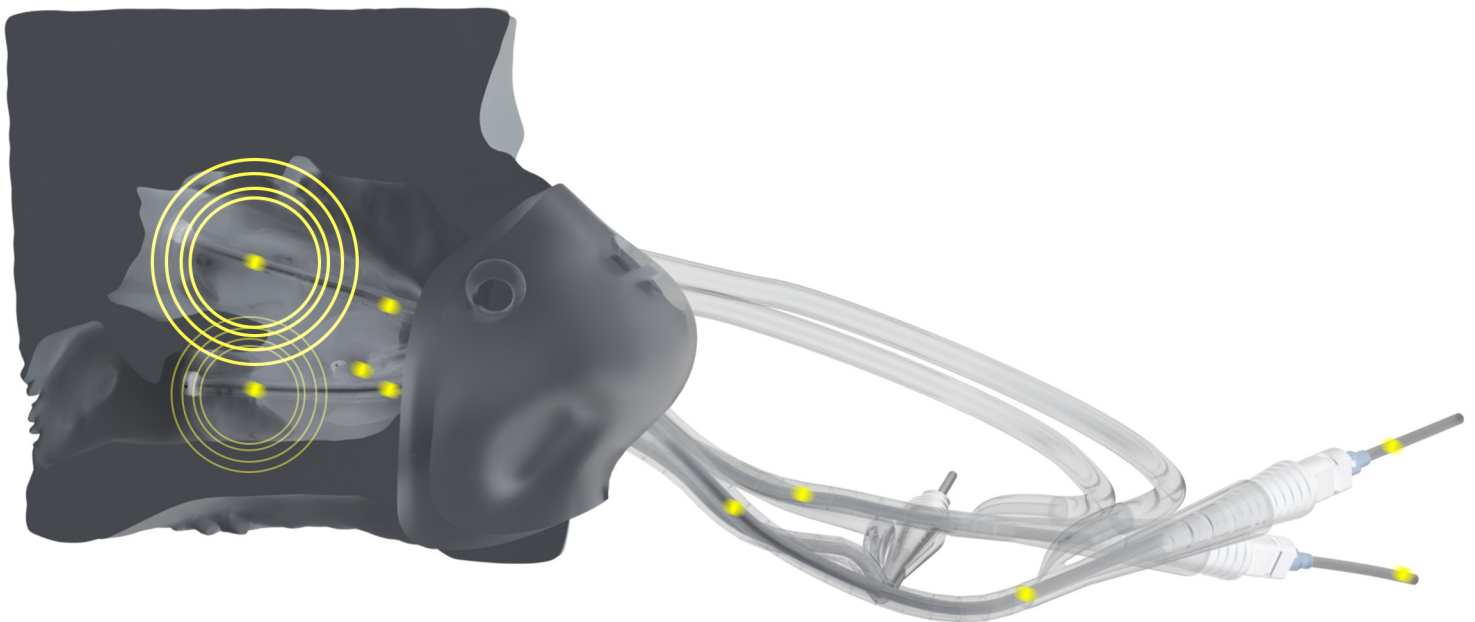


A.D.A.P.T.

Adaptive Deployment Applicator for Paranasal brachyTherapy



Designing a shape - adaptive
biocompatible HDR brachytherapy
stabilizer for carcinoma treatment
of the (para -)nasal cavity.

Preface

During my studies, I have often questioned what role product design should play in current society. Many of the projects I worked on in previous years of my Industrial Design Engineering study followed familiar consumer-driven patterns: developing new features, new forms or new conveniences without necessarily addressing a meaningful need. Although these projects strengthened my skills, they also left me with a growing frustration. I realised that I wanted to apply design in contexts where creativity, technical insight and resourcefulness contribute to something with tangible societal impact, rather than adding another layer to the stream of products already surrounding us.

Encountering this project therefore felt like a fresh breath of air. It offered a unique opportunity to engage with a domain where design is not an aesthetic accessory, but a practical instrument for improving medical practice. The complex anatomy of the paranasal sinuses, the precision required in radiation therapy and the clear unmet clinical need together form a challenge that demands both analytical skills and imaginative problem-solving. This combination is exactly what drew me toward industrial design in the first place.

This project has given me a sense of direction and purpose that previous assignments did not always provide. It allows me to bring together knowledge from an unfamiliar field, translate that knowledge into practical considerations, and shape it into early concepts that may one day support clinicians and patients. With this project I intend to show that industrial design can play a meaningful role in improving complex medical treatments, and to contribute to that possibility.

Acknowledgements

The key of a multi-disciplinary project such as the one you are about to read is first and foremost, multidisciplinary: The art of relating to multiple areas of study or work. Something that is only possible if the areas of study beyond that of your own, open themselves up to collaboration.

I am very grateful for the staff of the UMC Utrecht teaching and guiding me through the process of learning about anatomy, oncology, brachytherapy, radiation therapy and their own innovative 3D-printing practise.

The staff was always open for a short discussion or a quick question, even when their whiteboard was filled to the brim with patients that needed treatment. The availability of a quick CT-scan and even a test with the MRI felt very special and are experiences I will never forget.

A big thank you is due to Maarten Kastelijns, Mischa de Ridder, Petra Kroon, Milena Smolic and Renske van Noortwijk.

Secondly, I would like to thank my supervisors, Sepideh Ghodrat and Sonja Paus-Buzink for their guidance and clarity through a graduation project with this many facets. From formalities such as contracts, risk managements and consent forms to the integration of all the different topics discussed throughout this project. Thank you both for your critical views and supportive advice.

Lastly, I want to thank all the people in my personal environment: friends, house-mates, and family for thinking along and providing mental support. My colleagues at HANNO - Groots Cafe Delft for providing a bright place to write and incredibly coffee.

Summary

Paranasal sinus cancer in the present, is postoperatively treated with external beam radiation therapy (EBRT). This treatment method enables accurate high radiation dose delivery, it exposes surrounding organs at risk (OARs) to a low-dose radiation bath, contributing to significant negative side effects for overall patient health. High-Dose-Rate (HDR) brachytherapy could theoretically reduce this low-dose exposure due to its more direct dose fall-off ($\approx$ inverse square). However, this treatment method is currently infeasible, because no device exists that can be introduced in the target anatomy without overly invasive surgery and that can be reliably stabilized within the irregular sinus cavities.

This Industrial Design Engineering graduation project investigates the technical feasibility of a minimally invasive, shape-adaptive applicator capable of enabling postoperative HDR brachytherapy in the (para-) nasal sinus cavity. The core design challenge arises from the anatomical discrepancy between the narrow nasal vestibule entrance required for insertion and the larger, (sinus) cavity behind it where stable positioning is needed.

A stakeholder and workflow analysis in collaboration with UMC-Utrecht hospital staff, defined the primary requirements: atraumatic insertion, temporary stabilization, compatibility with existing workflows and protocols, reversibility, and avoidance of additional surgery. A review of the state-of-the-art materials, practises and mechanisms evaluated hydrogels, shape memory alloys (SMAs), shape memory polymers (SMPs), and pneumatic systems. The analysis demonstrated that no single mechanism or material satisfies all constraints. Leading to hybrid system strategies combining compliant deployment with more rigid stabilization elements.

Three initial concepts were developed, exploring the solution space of SMA's, Multi-chamber inflation systems and patient specific inflatables. During evaluation and synthesis, an existing medical device: The PORGES-14 Foley

Cystodrain Inflatable Catheter, inspired a revised design direction. Its manufacturing method and working principles opened interesting prototyping directions, which formed the basis of a redesigned applicator system tailored to head & neck (H&N) anatomy.

The PORGES applicators were used to develop a functional prototype, used in a 3D-printed anatomical phantom derived from anonymized patient data. CT-based dosimetric analysis was conducted in collaboration with the brachytherapy team. Compared to EBRT imaging, the applicator demonstrated:

- Improved conformity of 100% and 200% isodose lines to the clinical target volume (CTV)
 - Reduced exposure of healthy tissue to overall radiation
 - A visually reduced extent of the low-dose bath
- Using both the Conformity Index COIN and the Coverage Index CI in quantitative evaluation indicated that effective treatment could be achieved in a hypothetical scenario, whilst also highlighting the potential improvements in deployment accuracy, reliability, and repeatability.

The results demonstrate that a minimally invasive, shape-adaptive HDR brachytherapy applicator for intracavitary sinus treatment is technically feasible and clinically promising under controlled conditions. Phantom-testing supports the potential of reduction in low-dose exposure, but clinical validation remains necessary to reach conclusive evidence.

Key recommendations for further development:

To continue toward clinical implementation, the following research directions are recommended:

- Tissue-device interaction studies to assess deformation behavior, patient (dis-)comfort, and positional stability
- Expanded quantitative dosimetric validation across multiple anatomical models and repeated placements
- Mathematical validation model development to reach conclusive evidence
- Optimization of clinical workflow integration, especially focusing on surgical handling and placement

List of abbreviations

A-P:	Anterior–Posterior
Af:	Austenite Finish
AfT:	Austenite Finish Temperature
BT:	Brachytherapy
CT:	Computed Tomography
CTV:	Clinical Target Volume
DICOM:	Digital Imaging and Communications in Medicine
DVH:	Dose-Volume Histogram
EBRT:	External Beam Radiation Therapy
ENT:	Ear, Nose and Throat (Otorhinolaryngology)
HDR:	High-Dose-Rate (Brachytherapy)
H&N:	Head and Neck
IDE:	Industrial Design Engineering (TU Delft)
kPa / MPa:	Kilopascal / Megapascal (pressure units)
LDR:	Low-Dose-Rate (Brachytherapy)
MDR:	Medical Device Regulation (EU)
MRI:	Magnetic Resonance Imaging
OAR:	Organs at Risk
OR:	Operating Room
PDMS:	Polydimethylsiloxane (silicone)
PTV:	Planning Target Volume
RT:	Radiation Therapy
SMA:	Shape Memory Alloy
SME:	Shape Memory Effect
SMP:	Shape Memory Polymer
TPS:	Treatment Planning System
TV:	Tumor Volume
UMC-U:	University Medical Center Utrecht
VOI:	Volume of Interest

Table of contents

Preface	2
Acknowledgements	3
Summary	4
List of abbreviations	5
Table of contents	6
1. Project Introduction	8
Project timeline	10
2. Context introduction	12
Direct stakeholders	14
Stakeholder map	16
Brachytherapy: The basics	18
Brachytherapy: The complications	22
Anatomy: The (para-)nasal cavity	26
Anatomy:Size charts	27
3. Current clinical procedure methods	82
Current UMC Utrecht treatment journey	30
Current UMC brachytherapy specialism	32
A case study of current patient treatment and its inconvenience	34
Patient specific vs Standardized design	37
Synthesis: extracting the design implications, constraints, opportunities and contradictions	38
4. Current state of the art: A literature study	04
The recent developments in the field of brachytherapy and oncology	42
The (medical) use of shape morphing and smart materials	46
The (medical) use of hydrogels and smart polymers	48
Synthesis: A Design-driven material feasibility matrix	50
5. Project management and parameters	52
Problem statement	54
Assignment	55
Co-Creation: List of Requirements	56
Risk, safety and failure analysis	57
BHAG	57
Anatomy and target scope	57
The main limiting factor with current technology	57

6. Design	58
Concept 1:	60
Concept 2:	64
Concept 3:	68
7. Concept synthesis: A little piece of everything	76
Concept features: How does the design concept function	84
Prototyping	86
How multiple aspects of the concept would be manufactured for future testing	88
Concept accuracy versus testing capabilities	90
6-french vs 4-french, compromising size and functionality	92
Integrated design vs individual redesigns	94
Designing a new system	96
Testing	100
A scaled phantom	102
Segmented tests	104
Button-end design sprint	107
Target CTV's	108
3D printing the ideal environment	110
Phantom scans	112
Results	116
Phantom scans CTV_1	118
Phantom scans CTV_2	120
Result conclusions	122
Recommendations	126
Future medical device roadmap	129
Personal reflection	130
AI Declaration / Statement	131
Sources	132
Appendices A - J	139-157
Graduation Project Brief	

1

Project introduction

Annually, around 30 patients enter the hospital at UMC Utrecht with symptoms of a chronically blocked nostril, severe headaches, and frequent nosebleeds and exit with a (para-) nasal cavity carcinoma prognosis. This type of tumor often spreads to the nasopharynx, lymph nodes, and other regions in the head & neck (H&N) area where it can have deadly consequences. These cases of carcinoma are often identified at a late stage, because of the in-severity and commonness of the symptoms.

Fortunately, treatment options are already available. Patients currently undergo invasive surgery, where the cancer cells are mostly removed, accompanied by external beam radiation treating the rest of the cells accurately with high doses.

The unfortunate side effect of external beam radiation, especially in the H&N area is the low dosage bath that remains around the treated volume. The side effects of this low dosage bath leave lasting impact on parts of the brain, eyes, throat, and teeth.

A potential alternative radiation therapy is brachytherapy: internally placed radioactive sources for more direct and precise treatment, eliminating the low dose bath.

The UMC staff sees the emerging materials lab as an opportunity to investigate new materials and mechanisms for their innovative treatment plans.

They want to investigate new mechanisms for brachytherapy applications in the Head & Neck region, aimed to achieve new insights in the application of innovative materials, mechanisms and possibly the re-application of different techniques in the field of brachytherapy. By letting a graduation student fully focus on the topic with new and possibly unexpected insights, creative ideas for brachytherapy applicators could be generated and the UMC could have new concepts to further develop into actual products.

This project was introduced to me under the title: 3D printed biocompatible shape morphing device for innovative cancer treatment. (appendix I)

The brief proposes the problem of a low dose bath of radiation from external beam therapy and the benefits of eliminating this bath by employing brachytherapy would bring to the patient's overall health.

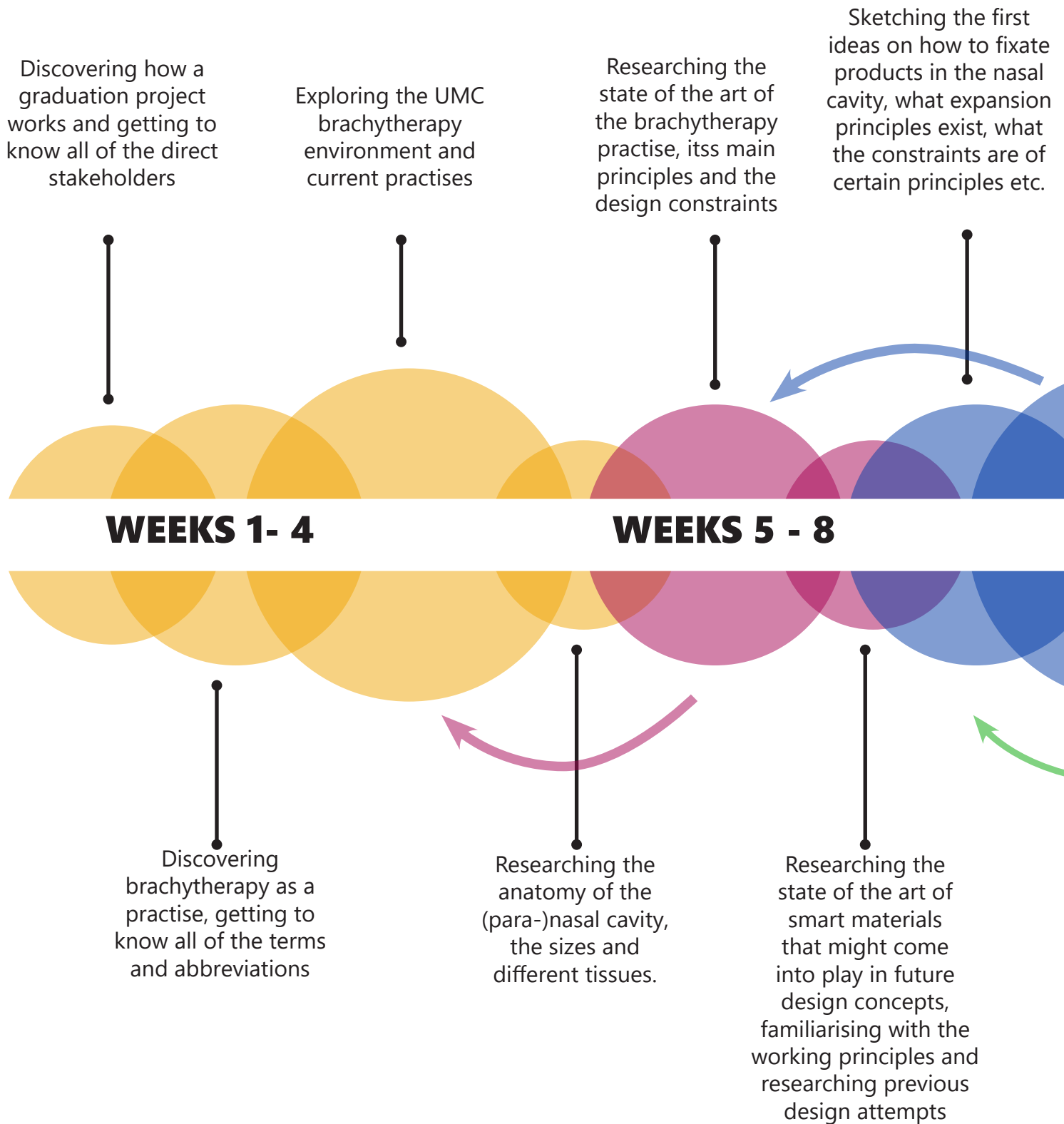
They propose that a device, capable of allowing BT applications in the paranasal cavity, could help at least half of the people with the current prognosis.

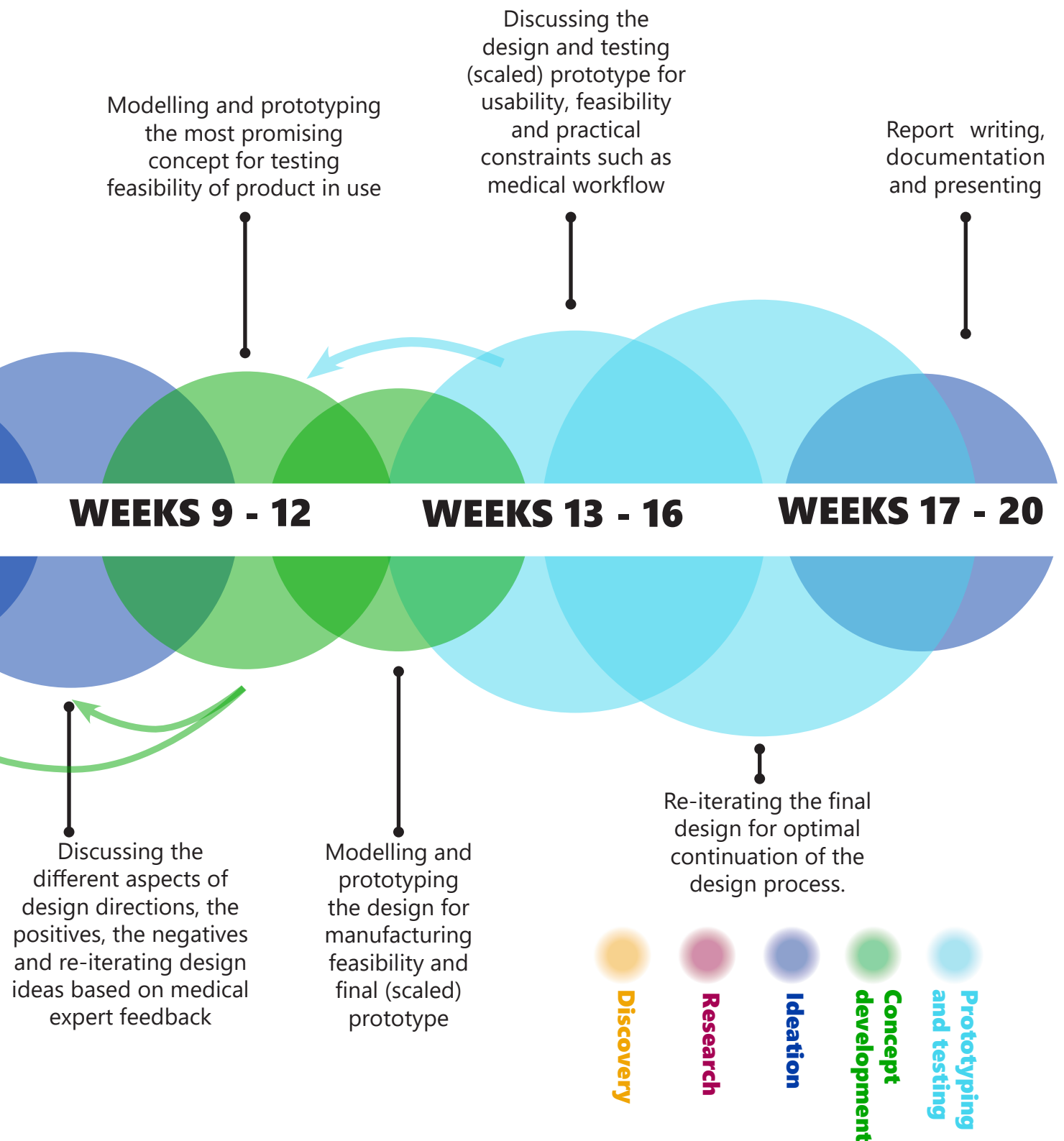
Resulting in the objective of
**creating a design that evaluates the
possibility of paranasal brachytherapy
application**

Project Timeline:

This graduation project follows a 6 phase process divided in:

Discovery, **Research**, **Ideation**, **Concept development**,
Prototyping and testing, **Documentation**





2

Context introduction

To get a full overview of the practical context, a preliminary research chapter will focus on what brachytherapy treatment entails, its optimal conditions for application, common pitfalls and limitations of brachytherapy and a short brief on the UMC's applications of brachytherapy. Next, an overview is made on the anatomy of the nasal cavity and the paranasal sinuses through both literature research and anonymized case studies from the UMC.

This chapter functions as an overview of the background that is needed to grasp the broad nature of the design environment.

The chapter will end with an overview of all gathered information that highlights the key takeaways for the final design.



Figure 1: A concept render of the UMC Utrecht main hall (Bouwenuitvoering.nl)

Direct stakeholders:

Coordinators of the TU Delft and supporting medical staff of UMC Utrecht

This graduation project was presented as an individual project, but turned out to be the most interdisciplinary project I have encountered yet. From working with the incredibly helpful medical staff at the UMC Utrecht, to the material experts from Mechanical Engineering and Industrial Design Engineering.

I am also very grateful for my supervisors Sepideh Ghodrat and Sonja Paus-Buzink.

As chair, Sepideh helped me with sticking to the (sometimes daunting) faculty guidelines of a graduation project, whilst also helping me get in contact with her broad network of material specialists and granting me the ability to test in the faculty laboratory. She also helped me keep my priorities straight within this project and to focus on the right subquestions to get the optimal result.

My mentor, Sonja, took on the responsibility of questioning every assumption made in this project, keeping me aligned with the academic level that is required for a graduation thesis. Her experience with designing for the medical industry has prevented me from overlooking critical clinical, technical, and academic considerations, and consistently pushed the project toward a higher level of rigor and relevance.

Chair:

Sepideh Ghodrat

Assistant professor
Emerging materials

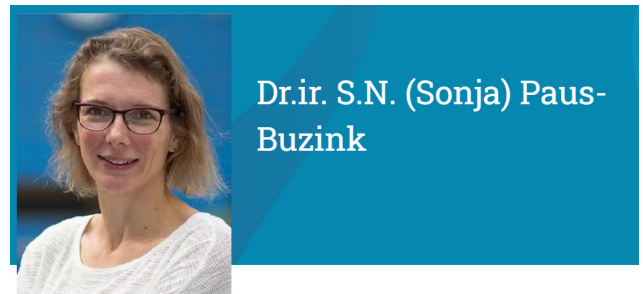


Dr. S. (Sepideh) Ghodrat

Mentor:

Sonja Paus-Buzink

Assistant professor Human
factors, Medisign



Dr.ir. S.N. (Sonja) Paus-Buzink

**Maarten
Kastelijns:**

Researcher and
laboratory technician
brachytherapy UMC
Utrecht



Mischa de Ridder:

Radiotherapist and
Oncologist at UMC
Utrecht



The original source of this project, the brachy- and radiotherapy staff of the UMC Utrecht were all a critical part of the multidisciplinary team that made this project feasible. The weekly meetings providing feedback on all my thoughts and ideas, their flexibility to make some time for me when their agenda's were filled with treatments and their enthusiasm on ideas we co-created.

Without them introducing me to the complex infrastructure behind the innovative treatment they facilitate for patients from all around the country, I would have lacked the clinical context necessary to make informed design decisions, and the resulting outcomes would have been disconnected from real-world brachytherapy practice.

Milena Smolic:

Fysicus
Brachytherapy UMC
Utrecht



Petra Kroon:

Klinisch fysicus
RadiotherapieUMC
Utrecht



**Renske van
Noortwijk:**

Junior Researcher
Radiotherapy UMC
Utrecht



Stakeholder map

To get a complete overview of the indirect stakeholders that would be involved with a project like this one Mendelow's Matrix (Barrington & Barrington, 2024) is employed to analyse stakeholders by dividing them in categories according to their power and direct interest in the project. This method determines which groups require engagement, need to be (kept) satisfied, should be (kept) informed or only require monitoring for effective stakeholder management. It is important to gather insights into the roles and opinions of the different stakeholders, to abstract wishes and requirements and their importance .

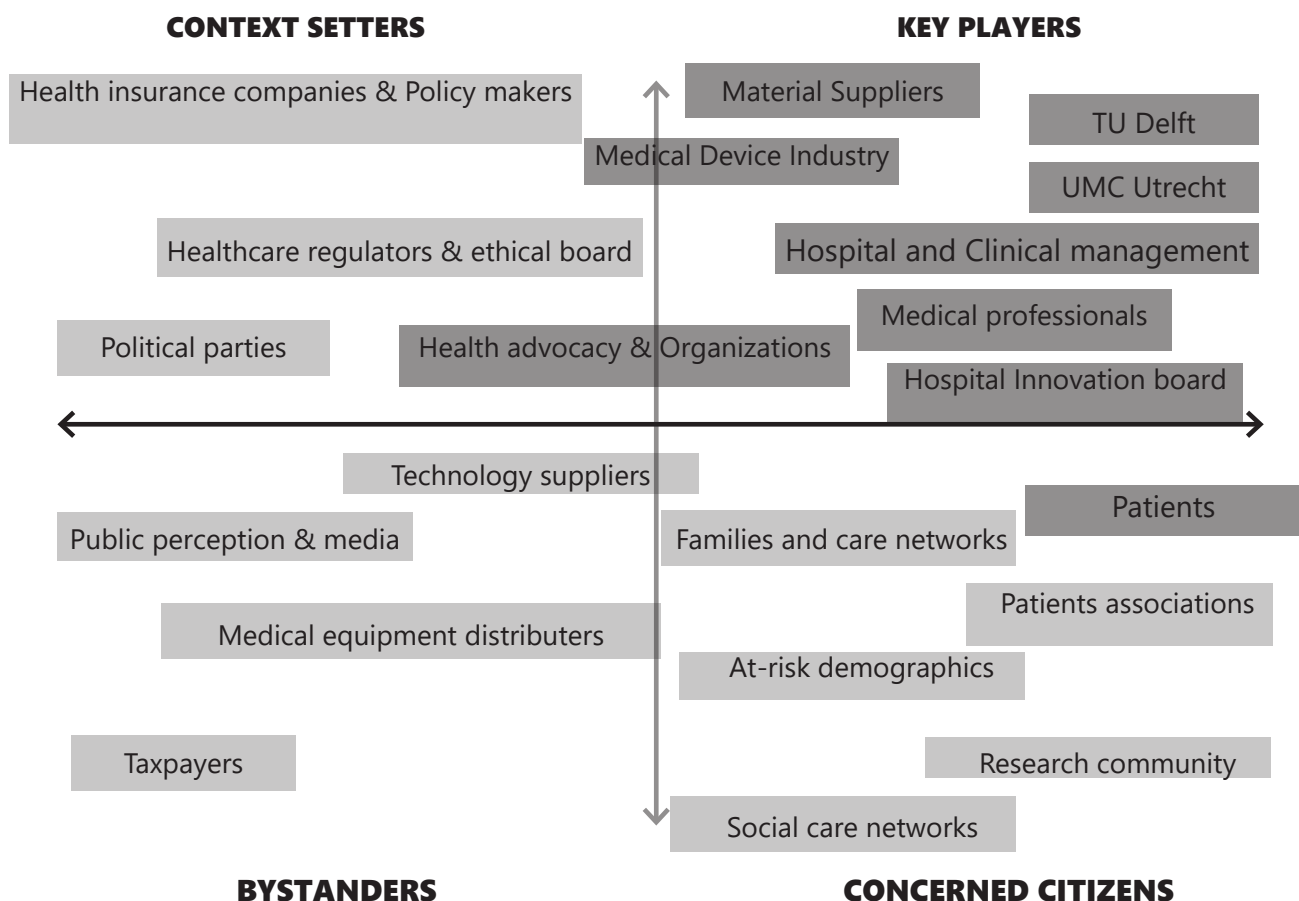
The **short-term stakeholders** impact the project mostly in aspects of direct design decisions **Long-term stakeholders** will mainly impact development, marketing and manufacturing strategies.

Bystanders will need minimum effort and have relatively little influence on the project.

Context setters will need to be kept satisfied about the workings of the product. As long as they are satisfied they will not go looking for issues.

Concerned citizens, although lower in power, might have a lot of interest and need to be ensured no major issues are arising. These audiences can also help point out any areas that could be improved or have been overlooked.

The key players need to be managed closely as they are well involved in the project and have the power to change it. According to Mendelow's theory these individuals need to be at the top priority of being kept satisfied.



The stakeholder map already provides brief insights into some conflicts of interest and ethical dilemma's which are not uncommon in the medical design department. Questions such as risk acceptance and accountability could be shared with multiple stakeholders, which could lead to tensions or disagreements.

The OR-staff could disagree with the radiation staff on the inefficiencies that placement checkups of a device like this could cause.

Manufacturing parties, the In-House manufacturing staff and the MDR regulators could get into disagreements on how the device is made and what aspects need to be checked. Just like how in-house development might be faster and more patient-tailored, but less regulated and therefore possibly less safe.

As with all arguments around the design and manufacturing of medical devices the same rule of thumb should apply: Do the medical benefits outweigh the risks?

Table 1: Conflict overview between stakeholders

Conflict	Stakeholders involved	Underlying tension	Design implication
Precision vs Safe Insertion	Radiation oncologists, Surgeons and nurses	Stability requires rigidity, but the human tissue requires softness and compressibility	Device must be compliant during insertion and structured after deployment.
Workflow simplicity vs Adaptive geometry	Radiation Therapy technicians vs On-site surgeons	Adaptive systems tend to increase complexity while workflows must remain predictable and quick	Adaptive behaviour should be passive, mechanical and possibly self-contained
Anatomical variability vs Manufacturing feasibility	UMC R&D team / in-house development team vs surgeons and manufacturing companies	Cavity geometry varies a lot, while fabrication is likely more tailored to consistent and predictable parts	Use adaptable geometries instead of fully patient-specific (rigid) prints
Short procedure time vs Controlled deployment	Radiation oncologists vs RT technicians	More adaptability of a device, likely needs more application/activation steps, while shorter procedure times lead to more efficient treatment and less pressure on hospitals	Deployment must be accurate, predictable and controlled. Within those limits, deployment should be as fast as possible (UMC staff states: No longer than 1h)
Minimising clinical risk vs Promoting innovation	UMC Utrecht vs TU-Delft	Risk is minimized by working with proven principles and mechanisms. However, daring to let go of the existing technology might encourage new and innovative ideas.	Due to the limited time-frame of the project, taking inspiration from existing technology is inevitable. However, as a personal ambition I aim to keep an open mind to new and innovative solutions

Brachytherapy: The basics

To understand the clinical context of the to be designed product, a brief insight into brachytherapy is needed.

Brachytherapy is a type of internal radiation therapy for cancer treatment. Its first treatments dating all the way back to 1903 after Curie's discovery of Radium. (Kemikler (2019)) First only treating skin-contact tumors, later treating cervical and endometrial tumors up until the 1960's where the use of Iridium-192 and remote after loaders made brachytherapy in more complicated body parts possible.

The limited use of brachytherapy in comparison to external radiotherapy is presumed to be due to its invasive nature. Sometimes requiring high-risk surgeries. The practise has technical difficulties and a relatively steep learning curve. In today's medical environment, with newly developed imaging techniques and dose planning,

brachytherapy's success is increased (De Ridder et al. (2024)) and in certain situations is preferred to external radiation due to its direct proximity to the tumor, allowing more precise treatment plans.

How it works

In its premise, modern brachytherapy revolves around the use of Iridium and Platina 'pellets' of around 4mm in length and 0.5 to 0.8 mm in diameter (figure 2). The radiation of these pellets is measured using a dosimeter; to determine the exposure time a pellet should have near the targeted tissue.

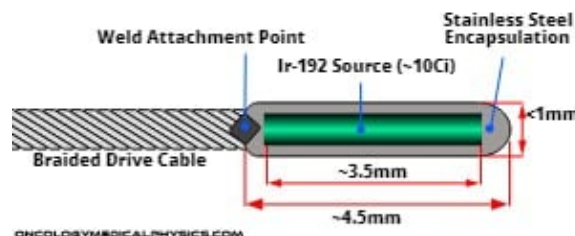


Figure 2: A technical drawing of the Ir-192 source welded to a drive cable ((Oncology Medical Physics LLC, 2022))with a visualisation of the source passing through a catheter (tube) to radiate a designated area

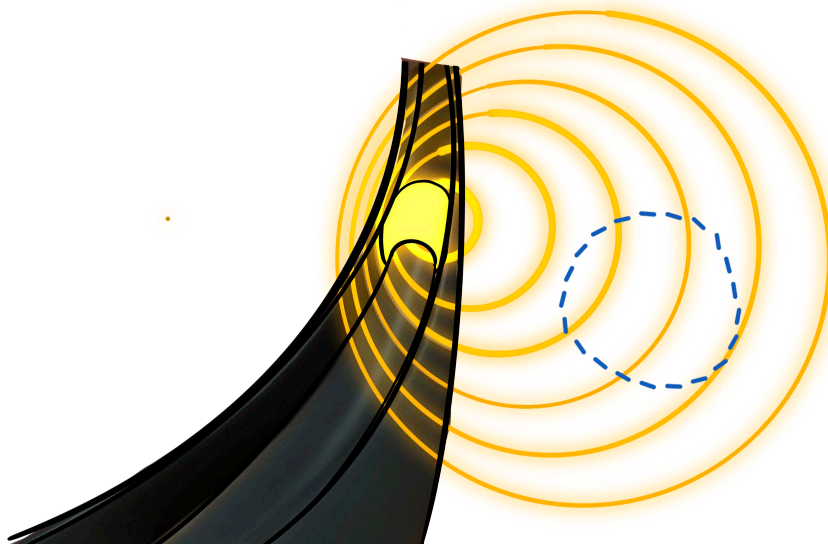




Figure 3: An image of the Elekta flexitron afterloader <https://ir.elekta.com/investors/press-releases/2023/elek-tas-flexitron-has-benefitted-cancer-patients-with-millions-of-brachytherapy-treatments/>

The pellets (also called sources) are sent through specialized catheters and held at calculated distances from the targeted area to radiate this area as effectively as possible without (over-) radiating the surrounding (normal) tissue. The device controlling the position of the sources is called an afterloader (figure 3).

Submethods

These radiation periods can differ based on various circumstances such as tumor size, location and overall patient health concerns. The locations and time periods are planned by radiation oncologists as so called 'dwell points and dwell times'.

The three commonly used radioactive sources in remote afterloading devices are: cobalt-60, cesium-137 and iridium-192. Currently, the most commonly used source for afterloading is iridium-192, because of its medium average gamma-ray energy (~400 keV) and its high specific activity. However, its relatively short half-life is a distinct disadvantage requiring frequent replacement of sources (typically 3 to 4 times per year). (Podgorsak, 2005)

Brachytherapy: The basics

To understand the clinical context of the to be designed product, a brief insight into brachytherapy is needed.

There are mainly two types of brachytherapy treatments:

- **Intracavitary**, where the sources are placed in body cavities close to the tumour volume.
- **Interstitial**, where the sources are implanted within the tumour volume.

Intracavitary treatments are always temporary, of short duration, while interstitial treatments may be temporary or permanent. The temporary implants are carried out using either manual or remote afterloading procedures.

Other less common forms of brachytherapy treatments include surface plaque, intraluminal, intraoperative, and intravascular source applications, and for these treatments either gamma-emitting or beta-emitting sources are used. (Podgorsak, 2005)

The two main intracavitary therapy methods are Low Dose Rate (LDR) (between 0.4 and 2 Gy/h) and High Dose Rate (HDR) (greater than 12 Gy/h) therapy. In interstitial cases Pulse Dose Rate (PDR) therapy is also used but has become less relevant for head & neck brachytherapy (Van Noortwijk, Kroon, Kastelijns, et

al. (2025)). The different methods of radiation are basically determined on the cancer type and location, a prominent factor that determines this is the presence or absence of so-called Organs at Risk (OAR), which are organs that are vulnerable to radioactive intoxication.

LDR therapy is typically used by implanting permanent radioactive 'seeds' that stay in the Clinical Target Volume (CTV) or the to-be radiated area.

HDR therapy implements the aforementioned method of guiding sources through catheters and retracting them after each session.

The advantages of using HDR when compared to LDR are:

- *Optimization of dose distribution*
- *Outpatient treatments*
- *Elimination of staff radiation exposure*

However, there are some disadvantages in the use of HDR such as:

- *Uncertainty in biological effectiveness*
- *Potential for accidental high exposures and serious errors*
- *Increased staff commitment* (Podgorsak, 2005)

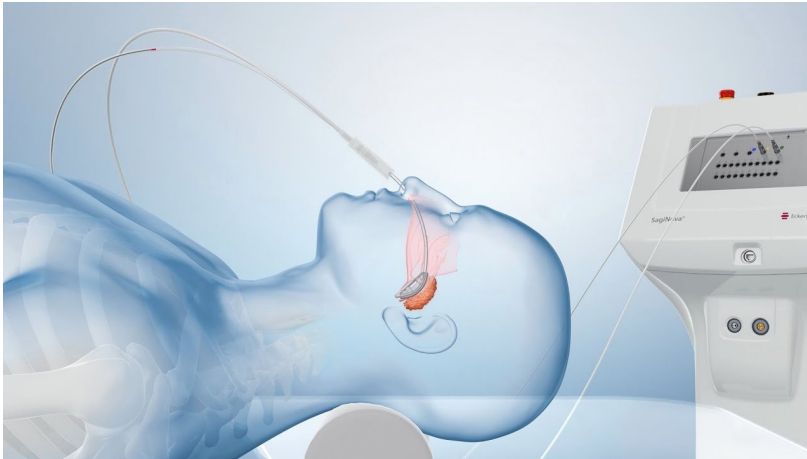
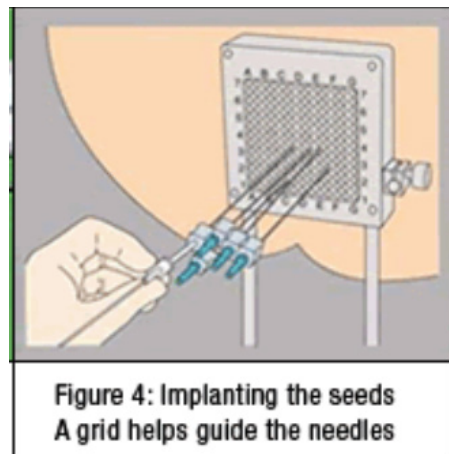


Figure 4: A digital visualisation of a brachytherapy treatment (Gebrüder Betz Medical Animation, 2021)

Figure 5: A visualisation of interstitial seed implantations via a guiding grid. <https://bxta.com/uk/patient-information/what-is-ldr-brachytherapy/>



UMC brachytherapy

At the UMC, the current brachytherapy state of the art treatment is done with patient-specific 3D-printed molds designed for HDR therapy, which keep the catheters in place with external and internal guides. For areas such as the nasal vestibule, eye sockets, mouth, and throat this method is proven to be effective and prevents large surgical interventions in the patient's facial tissue or overradiation of OARs.

Other brachytherapy treatment methods for, for example breast cancer, make use of expanding mechanisms that are surgically placed once and designed to stay in place for the entire radiation period. The catheter ends are then coupled for individual sessions, removing the necessity of multiple surgeries. Both are discussed in later chapters.

LDR

Low dose rate (0.4 - 2 Gy/h)
2 - 6 days treatment duration
Radiation hazard = High

HDR

High Dose Rate (>12Gy/h)
10 - 14 days treatment duration (split X minute sessions)
Radiation hazard = Low

PDR

Pulse Dose Rate (varying Gy/h)
2 - 10 days treatment duration (split X minute sessions)
Radiation hazard = Medium

Table 2: The difference between LDR, HDR and PDR treatment

Brachytherapy: The complications

What are the limitations that brachytherapy puts on how our product should operate?

Volumes

Brachytherapy is an exact practice and radiation that exceeds the target volume could have lasting effects on a patient's safety and overall health. A system set up for categorizing how radiation doses need to be calculated is that of the target volumes (Sahdev and Reznick (2009)):

- Gross Tumor Volume
- Clinical Target Volume
- Planning Target Volume
- Treated Volume

Planning

These volumes are the first steps into creating a plan for brachytherapy radiation. Of importance is the way in which the sources are positioned relative to the volume to be treated. There have been several models developed for this purpose providing the advantage published results giving leeway into how a similar target volume would be planned. Podgorsak, (2005) explains it as follows:

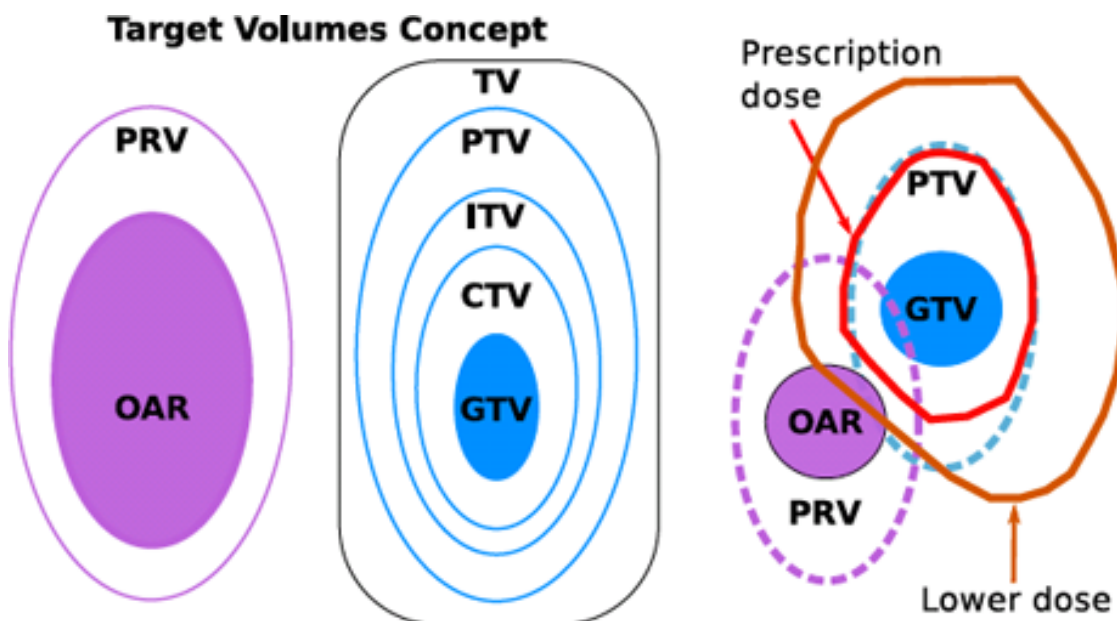


Figure 6: A visual representation of the different tumor and target volumes Schlachter et al. (2019)

"The advantage of using a well-established model is that one benefits from the long experience associated with such models and that one can take advantage of published results. The use of uniform models and methods in brachytherapy treatments simplifies comparison of treatment results. Typical treatment in which a model may be used is, for instance, the treatment of cancer of the cervix where the dose is given to a specific point A or in case of Low Dose Rate (LDR) treatments of head and neck cancers using iridium-192 wires. In this latter case the so-called Paris model provides suitable guidelines for the calculation of treatment dose and time. For treatments in which dose optimization techniques are used, the treatment times depend on how the sources are positioned relative to the dose calculation points and on the source strength. In situations where the system to be used is not obvious, the scientific literature should be consulted in order to take full advantage of already existing experience. With the use of a specific method for brachytherapy treatment and model for dose distribution calculation, the comparison of results is simplified. The use of a well established dosimetric system for treatment of cancer gives a common point for such comparisons. However, the use of a model alone is not sufficient to validate results; it is necessary to have a reliable method for the determination of the source strength in order for the dose calculation to be accurate. This means that it is necessary to have the brachytherapy sources calibrated, with a calibration traceable to the international measurement system."

UMC Utrecht methods

One person involved with validation of methods and models employed at the UMC's brachytherapy section is Renske van Noortwijk, doing her PhD on standardizing practical methods which at the moment rely heavily on expert intuition and previous experiences.

What this means for this project is that a good understanding of the planning methods & models could result in certain design directions or restraints to take into account. For example: the GTV is calculated at around 200% of the radiation value of the PTV. This is done because the applicator around the source catches a lot of the radiation which should not reach the targeted tissue.

If the design would not shield off the first half of the radiation dose, the radioactivity of the source would either need to be lower or a new HDR-plan needs to be set up for this specific applicator.

Furthermore, the catheters that are used during brachytherapy also have their limits. At the UMC, Elekta 6-french catheters are used. Elekta provides safety regulations with these catheters and the accompanied afterloaders (Elekta, 2019). They mention the bending limit of this setup being around 15mm (Elekta, 2019). Exceeding this minimum bending radius causes damage to the afterloaders' system and parts.

Brachytherapy:

The complications

Radiation theory

One of the most prominent topics, as we will come across later in this report, is the unpredictability of radiation energy around different materials. Radiation falls off due to attenuation of the energy of individual photons which is very closely related to the density of the material the photons pass through.

Therefore, one could presume that radiation energy at 1 cm distance from the source will be lower when photons pass through water than when the photons would pass through air (as water has a higher density than air). However, this is not entirely true due to a phenomenon called Compton scatter (Baltas et al. (2006)) (along with other effects) which is particularly relevant to Ir-192 radiation patterns. This effect can be best described as the photons colliding with other elements in their environment causing them to change their direction of travel.

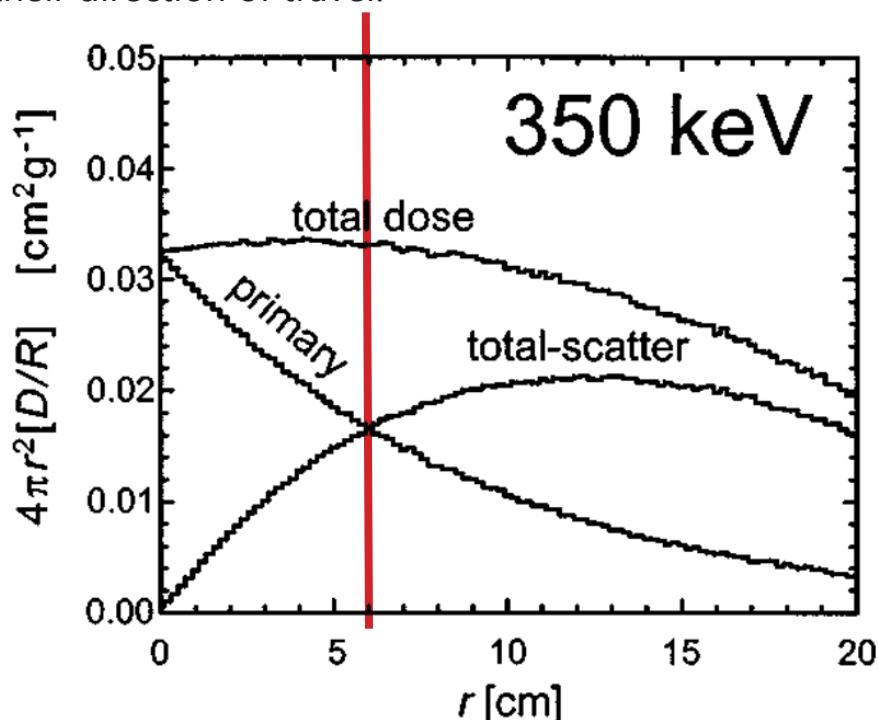


Figure 7: A graph showing the influence of primary dose, total-scatter dose and the combined doses Carlsson and Ahnesjö (2000)

Next to that, they occasionally cause the release of an electron, further complicating the calculation of energy doses at different distances from the source.

As can be seen in figure 7: closer to the source, the primary attenuation has the most prominent effect on calculating radiation energy levels. When we look further from the source the scatter effects are larger and the cause for most of the radiation on that point (often referred to as Voxel).

Method discussion

A study done at UMC Utrecht under supervision of Petra Kroon has shown an active debate on the best calculation methods for radiation predictions in various environments. However, a clear consensus is yet to be found. Which is why my conclusion from this segment (for now) is to design the applicator in such a way that the environment around the radioactive source remains as homogeneous as possible, to allow predictable calculation of the CTV.

Absorption

$$\left(\frac{\mu_{\text{en}}}{\rho}\right)_{\text{Water}} = 0.0328 \text{ cm}^2/\text{g}$$

-11%

$$\left(\frac{\mu_{\text{en}}}{\rho}\right)_{\text{Lucht}} = 0.0295 \text{ cm}^2/\text{g}$$

Attenuation

$$\left(\frac{\mu}{\rho}\right)_{\text{Water}} = 0.106 \text{ cm}^2/\text{g}$$

-10%

$$\left(\frac{\mu}{\rho}\right)_{\text{Lucht}} = 0.095 \text{ cm}^2/\text{g}$$



Figure 8: The difference of water and air absorption and attenuation Van Heijst et al., 2021

An UMC overview of the absorption and attenuation rates through water and air. Accounting for just the primary radiation. Confirming the assumption that primary radiation lowers in energy faster through water than through air. With the short distances the device will operate in, this will be the primary rule of thumb

Anatomy:

The nasal and paranasal sinus cavities

Tumors in these paranasal sinuses are difficult to reach with brachytherapy catheters that need to remain fixed for a prolonged amount of time. Therefore, with current technology invasive surgery in the facial structure is needed to properly reach the tumors and fix the catheters in place.

With current procedures the nose needs to be moved out of the way to properly place and fixate brachytherapy catheters, which leaves scars in the face and can not be comfortably held in place for 10 days. Because of the invasiveness of this surgery, most of the time beam radiation therapy is preferred over brachy.

It is important for the catheters to be fixated with a certain accuracy in relation to the CTV for efficient treatment and lower risk of toxicity in the patient (Rangarajan, 2018).

Organs At Risk

One of the complications with the selected anatomical context is the presence of nearby organs at risk (OARs), such as the eyes, teeth, pharynx, temporal and frontal lobes in the brain (where the prefrontal cortex, amygdala and hippocampus reside).

Health risks

Intoxication of these OARs could cause structural and synaptic damage to long-term cognitive and executive dysfunction (Zhang et al., 2020), emotional well-being deficits (Hardy et al., 2023), (partial) loss of sight, and irritation & swelling in the throat, nose and mouth.

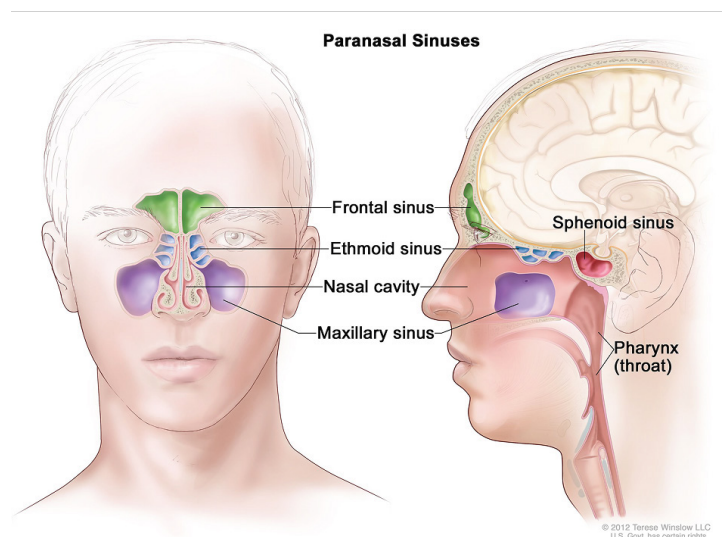


Figure 9: The anatomy of the paranasal sinuses
<https://www.cancer.gov/publications/dictionaries/cancer-terms/def/paranasal-sinus>

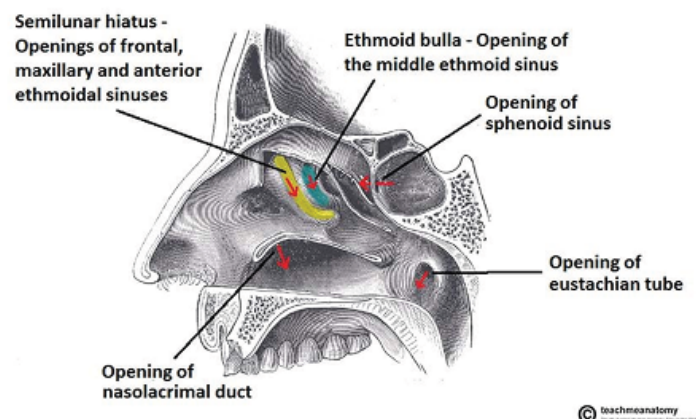


Figure 10: The anatomy of the paranasal sinus openings
<https://teachmeanatomy.info/head/organs/the-nose/paranasal-sinuses/>

Anatomy:

Size charts

A study by Ranzeetha et al. (2023) examines anatomical variability in the nasal cavity and paranasal sinuses, offering clinically relevant reference dimensions. Although the study primarily compares differences across gender and age groups, its reported mean values provide a useful baseline for understanding the spatial constraints within which the proposed design must operate. These averages will therefore be used to establish preliminary size boundaries for the target cavity.

Sinus	Average Volume (cm ³)	Notes & Variation
Maxillary	12–31 cm ³	Typically the largest sinus; ranges from 14–15 cm ³ in most adults, but males can reach over 30 cm ³ .
Frontal	2.6–9 cm ³	Highly variable and often asymmetric; males tend to have larger volumes.
Ethmoid	3.3–3.5 cm ³	Consists of ~9 small air cells per side; volume remains relatively stable across ages.
Sphenoid	4.5–10 cm ³	Shows sexual dimorphism; often between 4–6 cm ³ on imaging studies, but some morphometric data report up to 11 cm ³ .

Parameter	Average Value (mm)	Source
Length	55–61 mm	Measured from nasal spine to choana.
Width	25 mm	Measured at the inferior turbinate level.
Height	38–41 mm	From nasal floor to cribriform plate.

Sinus	Average Ostium Diameter (mm)	Notes
Frontal sinus ostium	5.6–8.5 mm	Typically sandglass-shaped, with narrow central section in the frontal recess.
Maxillary ostium	3–6 mm (approx., various imaging studies)	Drains into the middle meatus; often oval-shaped.
Sphenoid ostium	2–5 mm (typical radiographic range)	Opens posteriorly near superior turbinate.

Table 3a, 3b, 3c, Provided by (Ranzeetha et al., 2023)

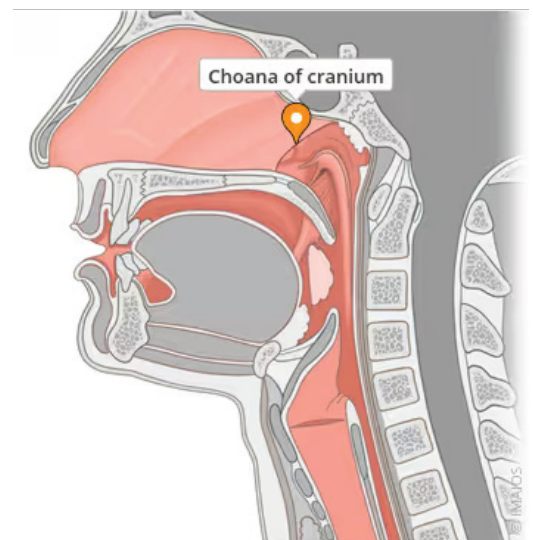


Figure 11: The location of the choana
<https://www.imaaios.com/en/e-anatomy/anatomical-structures/choana-of-cranium-1536890588#>

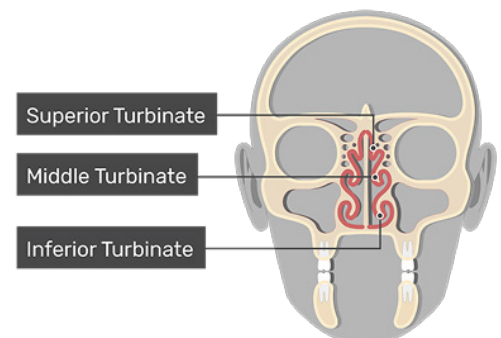


Figure 12: The anatomy of the three turbinates
<https://www.getbodysmart.com/nasal-cavity/turbinate-nasal-conchae/>

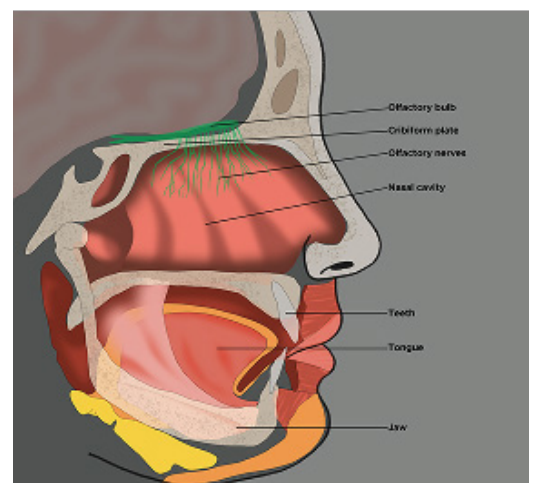


Figure 13: The nasal cavity anatomy
<https://mdsearchlight.com/joint-muscle-and-bone/cribriform-plate-fractures/>

3

Current medical procedure method

This chapter will translate the knowledge from the previous chapter to the practical applications at the UMC. Starting with mapping the treatment journey of current nasal vestibule applications where 3D-printed applicators are commonly used. A step by step description of the procedure should further highlight the environment, the design will function in, whilst also explaining which safety precautions are already in place and to which the design will likely also need to be tailored.

Furthermore, an insight will be given into the specialism of UMC practitioners, why they make the choices that they make, how they see the procedure and possibly what their current visions are for other applications regarding their specialism.

A short discussion will be given on the pro's and con's of patient specific design versus standardized designs.

Lastly, a case study will be investigated regarding a situation relevant for our future design in which a patient was now treated with beam radiation, also highlighting the downsides of beam radiation opposed to brachytherapy.



Figure 14: The Elekta Unity 2: MR-Linac
<https://www.elekta.com/products/radiation-therapy/unity/>

Medical:

Current UMC brachytherapy specialism

At the brachytherapy section for head and neck cancers at the UMC Utrecht, 3D printing specialist M. Kastelijns has made previous casts/molds for fixing brachytherapy wires in the back of the throat (nasopharynx), eye socket and nasal vestibule. All of which have seemed effective in both time and surgical interventions making treatment easier for both patient and surgeon. (De Ridder et al. (2024)).

Paris model

The treatment plans they make are done with the aforementioned Paris model as a baseline:

" The Paris system is used primarily for single and double plane implants and does not address other types of volume implants. It is necessary to follow a set of general rules for the selection and placement of the sources in order to achieve the desired dose distributions.

General rules are as follows:

- Sources must be linear and their placement parallel.*
- Centers of all sources must be located in the same plane (central plane).*
- Linear source strength (activity) must be uniform and identical for all sources.*
- Adjacent sources must be equidistant from each other.*
- Spacing between sources should be wider when using long sources.*

The stated (reference) dose-rate is a fixed percentage (85%) of the basal dose rate.



Figure 15: The current mould placed over the patients nose for treatment of the nasal vestibule

The basal dose rate is the average of the minimum dose rates located between the sources inside the implanted volume. The individual minimum dose-rates should be within $\pm 10\%$ of the average (basal dose rate), thus restricting the number of sources to be used.” (Podgorsak, 2005) .

Practical methodology

As previously mentioned, a 3D-model of the volume of the nose together with coordinates for the catheters are extracted from CT-scans and imported in CAD software (currently Fusion360).

Here they align 8mm diameter cylinders along the catheter paths, import and align the twist lock slots for the coupler and import and place stitch guides for when the entire orthosis (figure 15) needs to be placed.

The procedure has been proven to be efficient (De Ridder et al. (2024)) at treating tumors in the nasal vestibule and the front of the nasal cavity.

Material-radiation interaction

The material used for the applicator (Biomed Clear) has a relative electron density of 1.1 and a CT number of 100 Hounsfield units (HU).

Therefore, it is presumed water equivalent when it comes to radiation attenuation and absorption meaning it does not perturb the dose calculations.

The same applies for the material that is used when applying amore techniques, where the 3D-printed catheter guide is surgically placed inside the body. These applicators are printed in medical grade PEEK FDM filament and require a separate printer. (Dallal et al. (2025))



Figure 16: A photo of the FormLabs printer at the UMC in Utrecht

Medical:

Current UMC Utrecht procedure journey

Pre treatment assessment.

Intake where a 1mm layer CT-scan is done in combination with an MRI scan to determine where the tumor is situated and how large it is. With this information a decision is made by the oncology specialists on whether brachytherapy or beam radiation therapy is most effective.

Treatment mapping

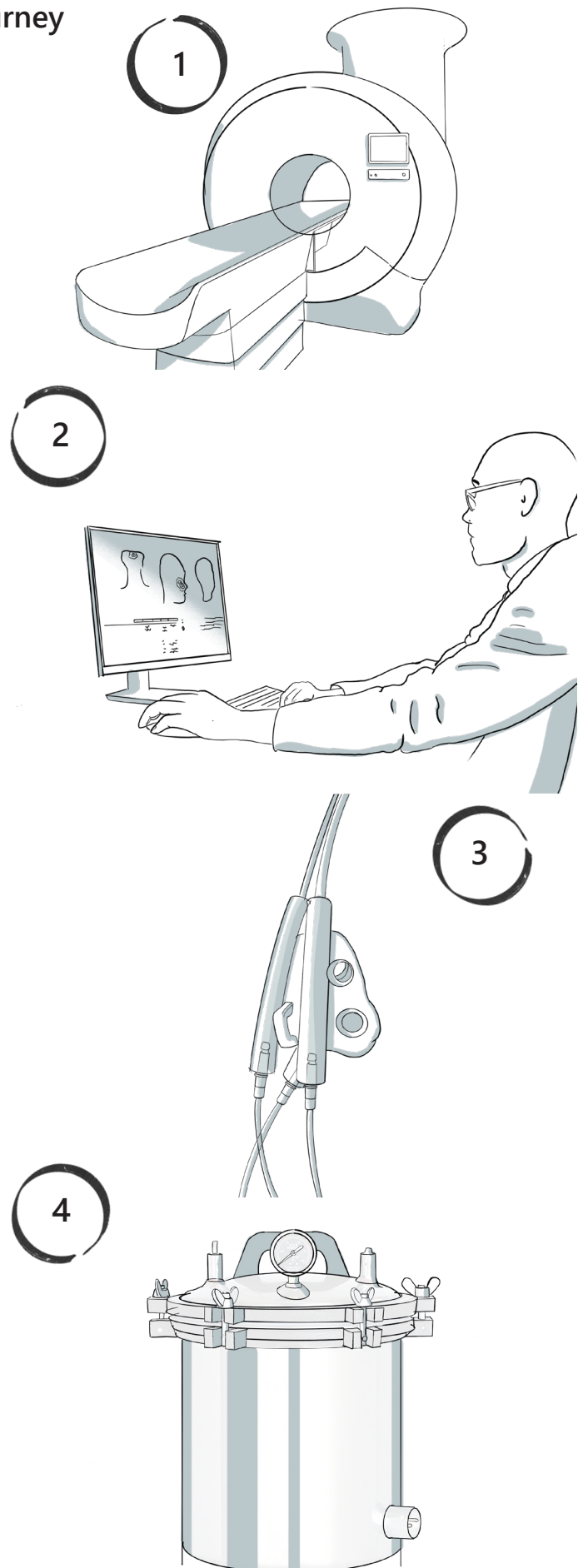
When the decision is made for brachytherapy, a treatment and dosing pre-plan is made. The catheter placement is drawn in the scans and dwell points are added to overlay dosage patterns with the CTV.

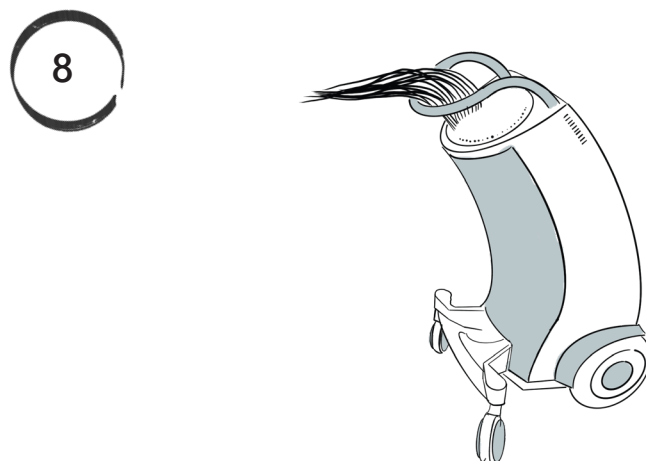
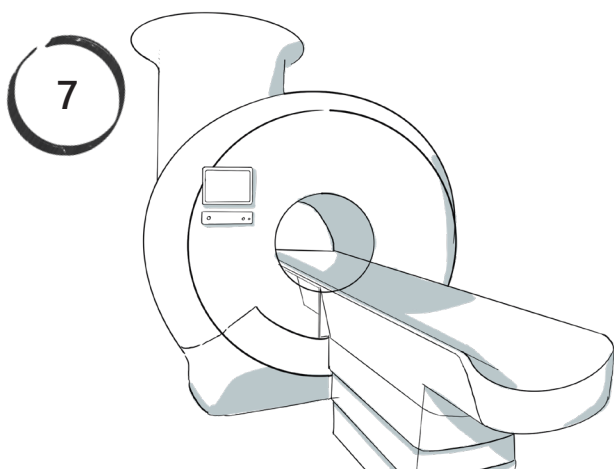
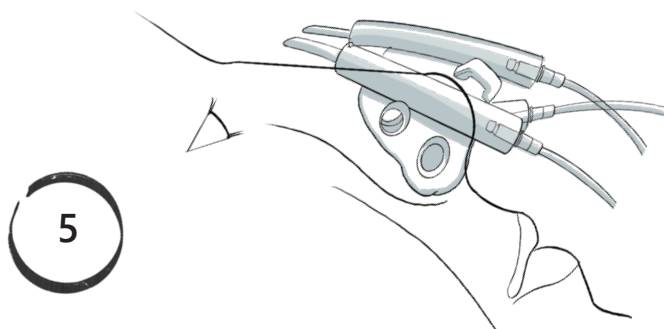
Optimal treatment plan

Based on the coordinate points of the catheters and the outline of the nose on the scans a 3d model is set up by the radiotherapy 3D specialists. In this model the guides for the catheters are drawn together with the anchor points on the nose. After completion and validation of the 3D model it is printed in-house.

Validation and sterilisation:

The 3D print is fitted on the patient by surgeons, without permanent fixation. After confirmation of an adequate fit, the print is cleaned and sterilized using an autoclave machine.





Pre-treatment surgery

During surgery the mold is placed and stitched into place. The catheters are put through the guides and locked into place with twist-locking fits. In some cases catheters need to be stuck inside of the tissue (called interstitial placement), in these cases a guide is made in the print that helps the surgeon interstitially place the catheter and lock it in place the same way as the others.

Placement check

The placement of the applicator is checked with CT and/or MRI scans. Copper wires are used to locate the catheter placement which can be easily identified on said scans.

Dosage

The patient receives 96 doses of radiation over a 10 day period with at least 1 hour intervals. The mold and catheters stay in the same place and therefore need to be designed to accommodate for the patient eating, drinking and sleeping during the therapy.

Post-treatment surgery & aftercare

After all doses have been delivered, the orthosis is removed including all the catheters and the patient is examined one final time to validate results. Afterwards the patient's stitch wounds and radiated tissue are treated to prevent long-term side effects as much as possible. The patient stays for multiple days in the hospital for aftercare.

Medical:

A case study of current patient treatment and its inconveniences

Pre-surgery

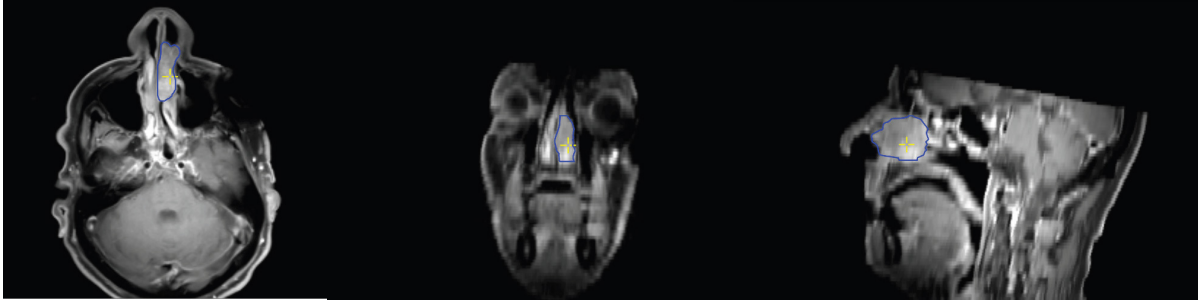


Figure 17:
Pre-surgery
scans of a
patient with
a GTV along
the nasal
septum

In figure 17 we can see an example of a scan of 1mm slices of an anonymized patient with a tumor in the septum of the nasal cavity.

The tumor has been able to grow this large, because the symptoms of (para)nasal sinus cancer are very close to a long cold or a blocked nostril.

Post-surgery



Figure 18:
Post-surgery
scans of a
patient with
a GTV along
the nasal
septum

In figure 18 we can see the same patient but after surgical removal of most of the tumor and surrounding tissue. This way the core of the GTV is exposed as much as possible so that radiation doses can be kept lower to prevent unnecessarily over-radiating surrounding tissue.

External Beam Radiation Therapy (EBRT)

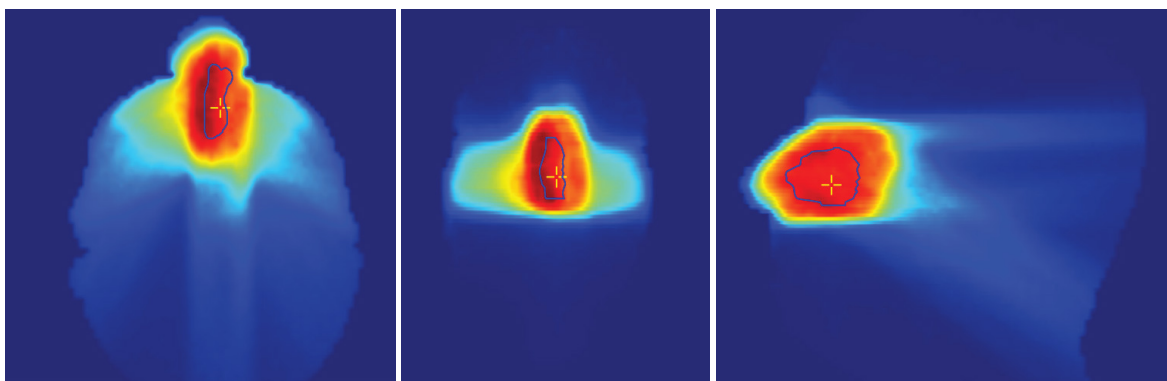
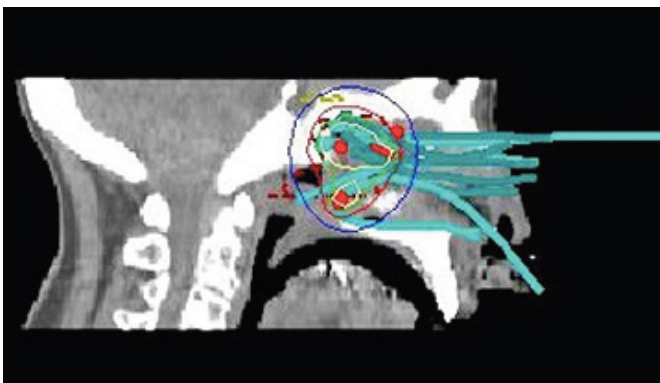


Figure 19:
Monaco
treatment
plans of
external beam
radiation
on the GTV
from figures
17 & 18

In figure 19, images created using Monaco (Clements et al., 2018) at the UMC Utrecht, the radiated area is highlighted. The dark blue line is highlighting the target area, as can be seen the radiation bath is much larger than the necessary area indicates. Radiation reaches the eyes, teeth, upper throat, temporal and frontal lobes. This can lead to irritation and irreversible damage.

The reason this type of treatment is chosen is mainly because current brachytherapy applications with 3D-printed molds were not able to fixate the brachytherapy catheters with enough precision and confidence without performing overly invasive surgery on the face of the patient.



As can be seen in figure 20 by Tagliaferri et al. (2015) where a patient with similarly placed tumors undergoes the procedure with brachytherapy. Catheters are interstitially placed and stitched to the nose of the patient.

Figure 20: An interstitial brachytherapy treatment plan by Tagliaferri et al. (2015)

Dose calculations

As discussed earlier, achieving accurate dose predictions in heterogeneous environments is challenging, and current UMCU protocols accept an approximate 3% calculation uncertainty for brachytherapy. In external beam radiotherapy, however, the dose distributions delivered to the paranasal sinuses often exceed this margin by a considerable amount, primarily because beams must pass through multiple tissue interfaces, air pockets, and irregular bony structures.

If a dedicated applicator enabled brachytherapy in these regions, the radioactive source would be deployed inside a more homogeneous and predictable local environment, rather than across the heterogeneous pathways encountered in external beam treatments. Theoretically, this would reduce dose calculation uncertainty and substantially decrease the amount of healthy tissue exposed to unintended low-dose baths.

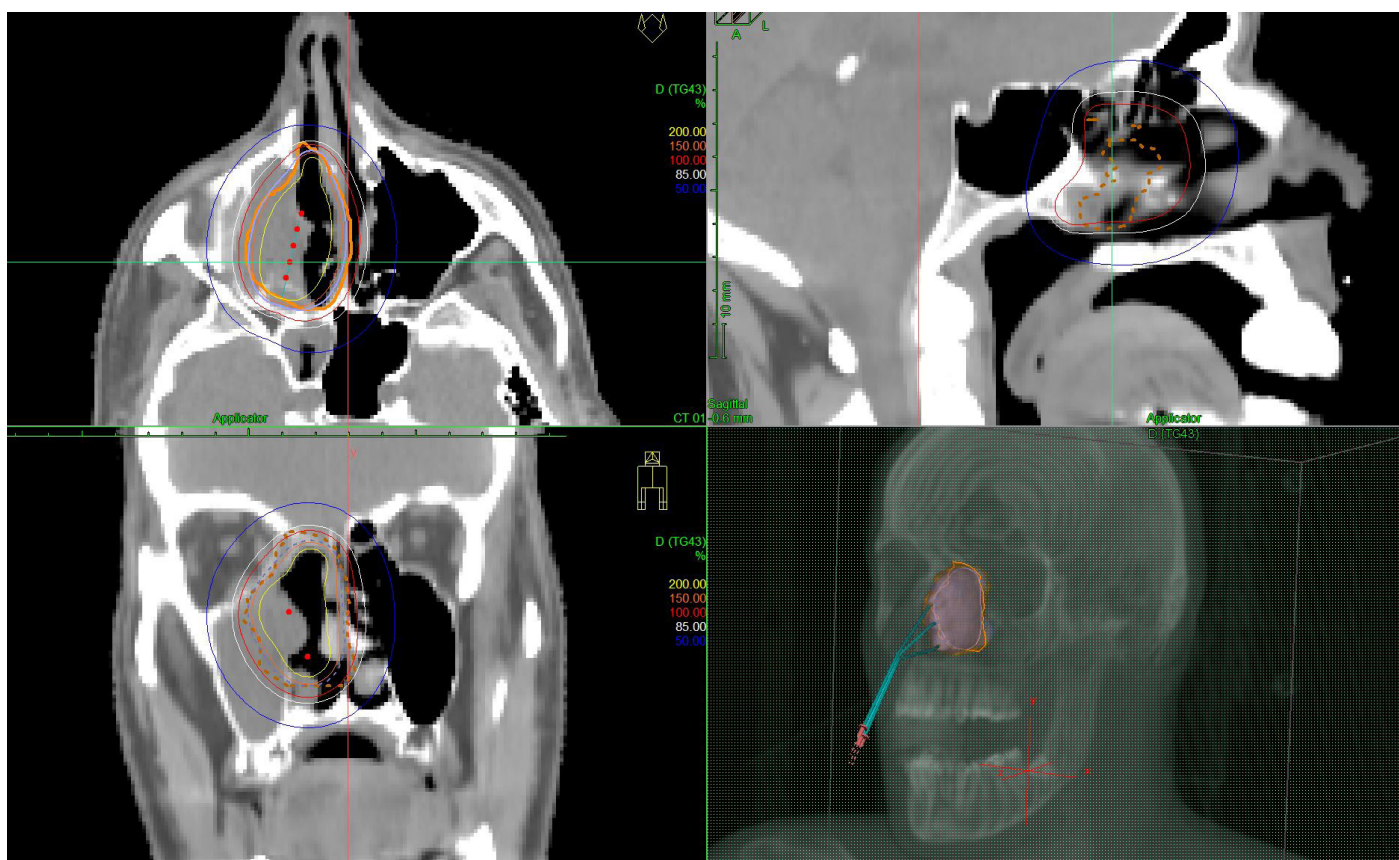


Figure 21: Another potential case provided by the UMC Utrecht

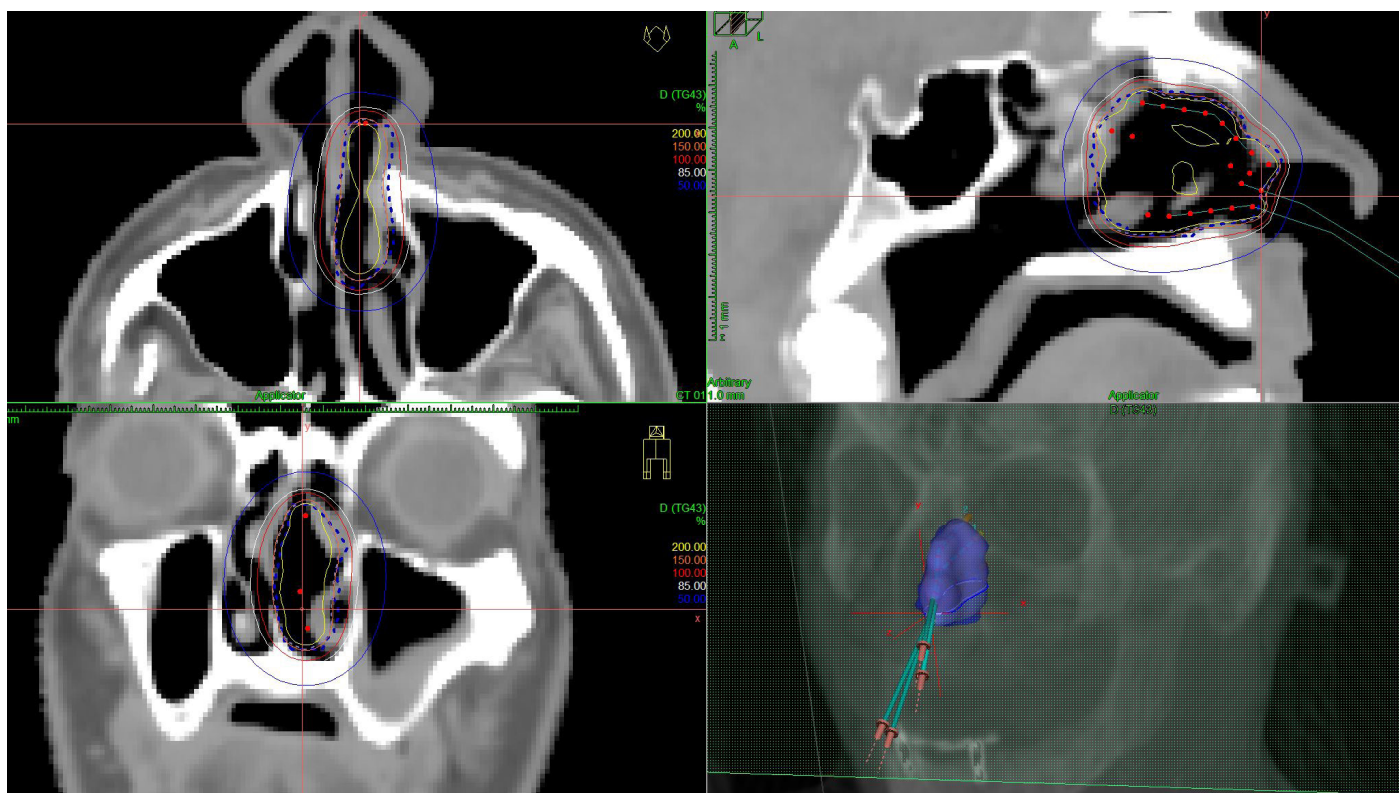


Figure 22: Another potential case provided by the UMC Utrecht

Medical:

Patient specific production vs standardization

The current methods employed by the experts at the UMC, encompass a patient specific design approach. Mainly to ensure a perfect fit for each patient without overcomplicating the design to make it adjustable for each specific patient. The fact that this type of treatment is used on adults and children alike, also supports the use of patient specific designs as the volume of the nose is vastly different from person to person.

However, as the study by Ranzeetha et al., 2023 discuss, not all sizes in the (para-)nasal cavities grow equally with age. Hinting at a possibility of standardized size ranges. This could also mean the possibility of designing a (para-)nasal cavity applicator that can be adjustable for specific cases, or anatomies.

Sinsky et al. (2021) highlight the different costs and benefits from a patient specific design approach versus a standardized adjustable design approach. They argue the efficiency and cost-effectiveness (basically the commercial value) of standardization against the flexibility and improved clinical outcomes of customization in the medical product design domain.

For standardization the article argues:

- The creation of efficiencies by developing routines through consistency
- It facilitates quick staff training and cross coverage
- Allows for more predictable patient care
- Lowers costs of having to design a product for each individual patient

However it also:

- Disempowers clinical expertise and creative approaches
- Restricts clinicians in optimal treatment
- Flawed standards and metrics may harm people or cause burn-outs
- The standards may have been established without sufficient input from those directly impacted
- Complicates the MDR guidelines, as it requires predefinition, validation and risk mitigation across a broad range of scenarios

For customization the article argues:

- The possibilities for optimisation for clinical outcomes
- The accommodation for patient needs and preferences
- The encouragement for innovation
- Proof of reduction in hospitalization, surgical interventions and costs

However it also:

- Can result in chaotic design processes
- Is time-consuming and uncontrolled
- Quality of the final outcomes relies on adequacy of the medical staff at hand
- Increases cognitive workload for clinicians
- Needs new care pathways and workflows, and time-management regulation systems
- Relies more on expert clinical judgement, mitigating MDR extensiveness

Synthesis:

Extracting the design implications, constraints, opportunities and contradictions

The findings from the clinical workflow, anatomical analysis and material exploration together outline the boundaries within which a workable concept must operate. While the research is still ongoing, several patterns recur consistently enough to translate into early design implications. These do not define the final direction yet, but they clarify the conditions that any solution will need to accommodate.

Design Constraints

The most dominant constraint is the dimension difference between the narrow nasal passage and the larger, highly variable sinus cavity behind it. Any system must therefore be introduced in a compact state, with a predictable and reversible transition into its functional configuration once inside the cavity. The mucosal surfaces and proximity to critical structures limit the allowable forces during this transition. At the same time, catheter placement requires a degree of structural stability that soft tissues alone cannot provide. Sterilisation, imaging compatibility and integration in existing UMCU workflows further restrict material selection and manufacturing options.

Design Opportunities

This anatomical constraint also creates the main opportunity. The sinus cavity offers more space for controlled expansion, anchoring or structural deployment than the vestibule does. Post-operative cavities frequently present enclosed or semi-enclosed volumes, which could support temporary fixation without surgical attachment. Shape-changing materials or multi-stage structures may use this difference in available volume to achieve insertion, deployment and eventual removal through the same pathway. The variability between patients also makes adaptive or self-adjusting behaviour potentially valuable, reducing reliance on fully patient-specific parts.

Contradictions

Across the explored options, several contradictions become apparent. The device needs to be soft enough to pass a-traumatically through sensitive tissue, but stiff enough after deployment to guide or stabilise a catheter. High deformation ratios are required during insertion, and the deployed geometry must be precise and repeatable. Materials that offer controllability often introduce activation triggers or thermal considerations that are undesirable in a clinical setting. These opposing demands cannot be met by a single property or material; they point toward a combination of functions rather than a single-material solution.

The transition between these states must be passive, predictable and reversible, without depending on complex tools or activation procedures. These insights will guide the upcoming prototyping phase, in which the focus shifts from identifying what is possible to testing how these combined behaviours can be achieved within clinically realistic geometries.

Design Implications

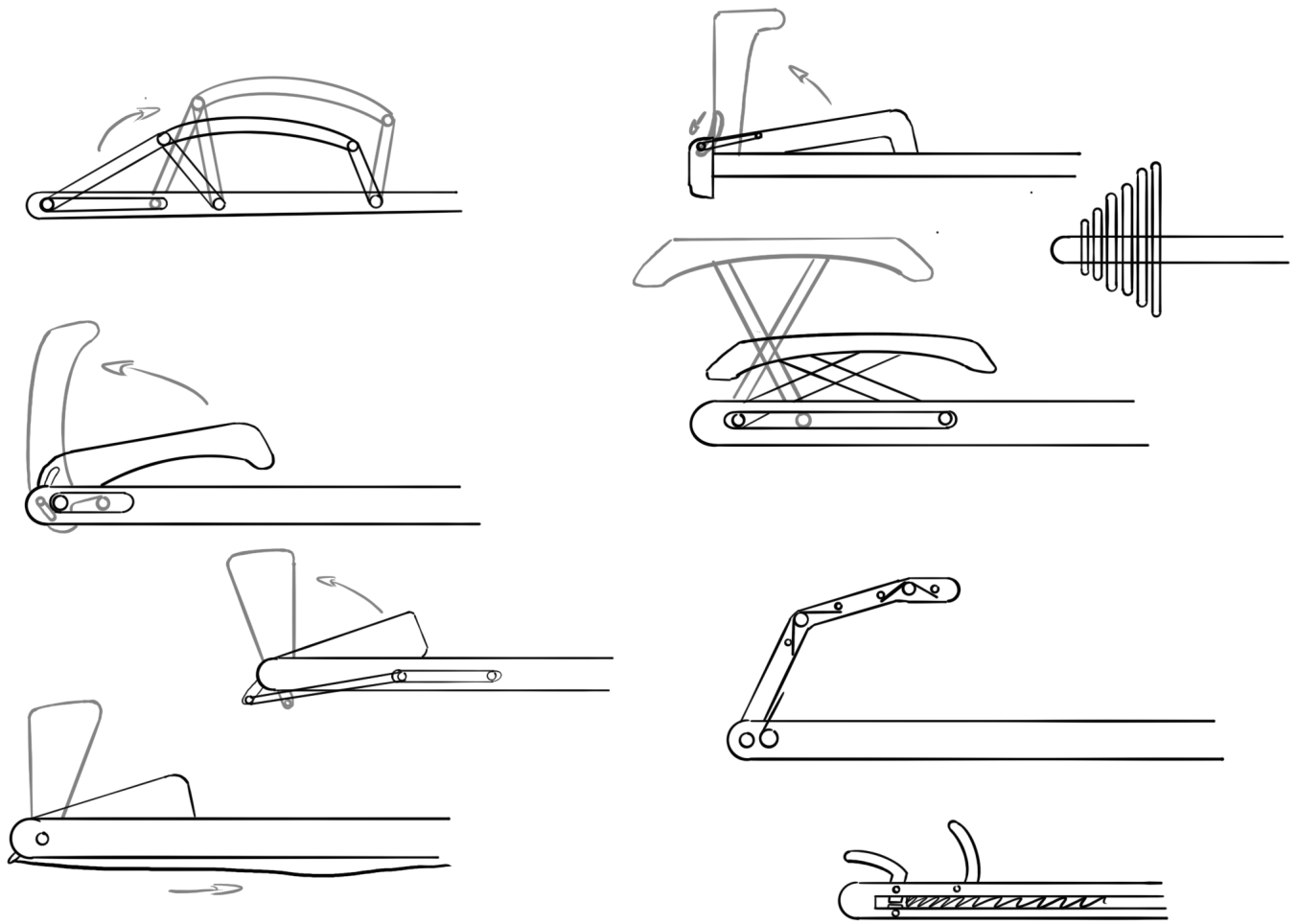
From these constraints and contradictions, several implications for the next phase follow. Purely compliant systems are unlikely to meet the positional requirements of brachytherapy, while fully rigid solutions cannot navigate the nasal cavity. A feasible concept will therefore need to combine compliant external behaviour with localised structural elements that provide stability after deployment.

4

Current state of the art: A literature study

With the insights from the introduction and context research, it is time to dive a little deeper into topics that could be of influence on the design and its constraints.

Investigating the state of the art in a research fields such as brachytherapy and head & neck oncology could give insights into what has already been tried and why it was (un-)successful. Next to just the state of the art in the medical research fields, the material science will also be further investigated. The original brief of this project stated: "You will design a prototype using smart materials capable of shape morphing and shape retention.". To fully grasp what smart materials are and how shape morphing and shape retention works. A literature study needs to be deployed.



This chapter will therefore focus on a comprehensive overview of what innovations can be found in the fields of brachytherapy, head & neck oncology, Shape Memory Alloys, and shape morphing materials. Of the latter two an overview will be made on their properties to identify possible mechanisms or constraints more easily.

The literature is collected iteratively and through multiple domains. The initial literature was identified through papers authored or recommended by the UMC Utrecht staff directly involved in this project, including their cited references. For materials-focused publications, the chair supervisor, Sepideh Ghodrati provided the primary entry point into relevant material science literature.

Building on the insights from the primary literature research phase, additional studies were consulted through search-engines such as Pubmed, Google Scholar, and Perplexity.ai

Current state of the art:

A literature research on the recent developments in the field of brachytherapy and oncology

This chapter will dive deeper into the literature research that already exists on the topics: brachytherapy innovations and practices, Smart materials in the medical field and brachy- applicators in other practices than the head and neck oncology.

BT innovations and practices

A literature review by Cua et al. (2024a) shows a broad view of how brachytherapy has evolved since the 2017 GEC-ESTRO (Groupe Européen de Curiethérapie – European Society for Therapeutic Radiology and Oncology) convention.

They divide the innovations in the following relevant subcategories:

- 3D printing
- Applicator designs
- Shielding
- Implant techniques
- Definitive, post-/peri-operative 3D printing in brachytherapy

3D printing

For as long as 3D printing exists, the medical adaptations have as well. Starting from prototypes of certain tools to guides for incisions in orthopedic surgery to now guides for catheters around the human body. With bio-compatible materials such as PEEK or Biomed Clear among a few others (Mourya et al. (2025)) the applications of 3D-printed patient specific orthoses have become a common application of the manufacturing method.

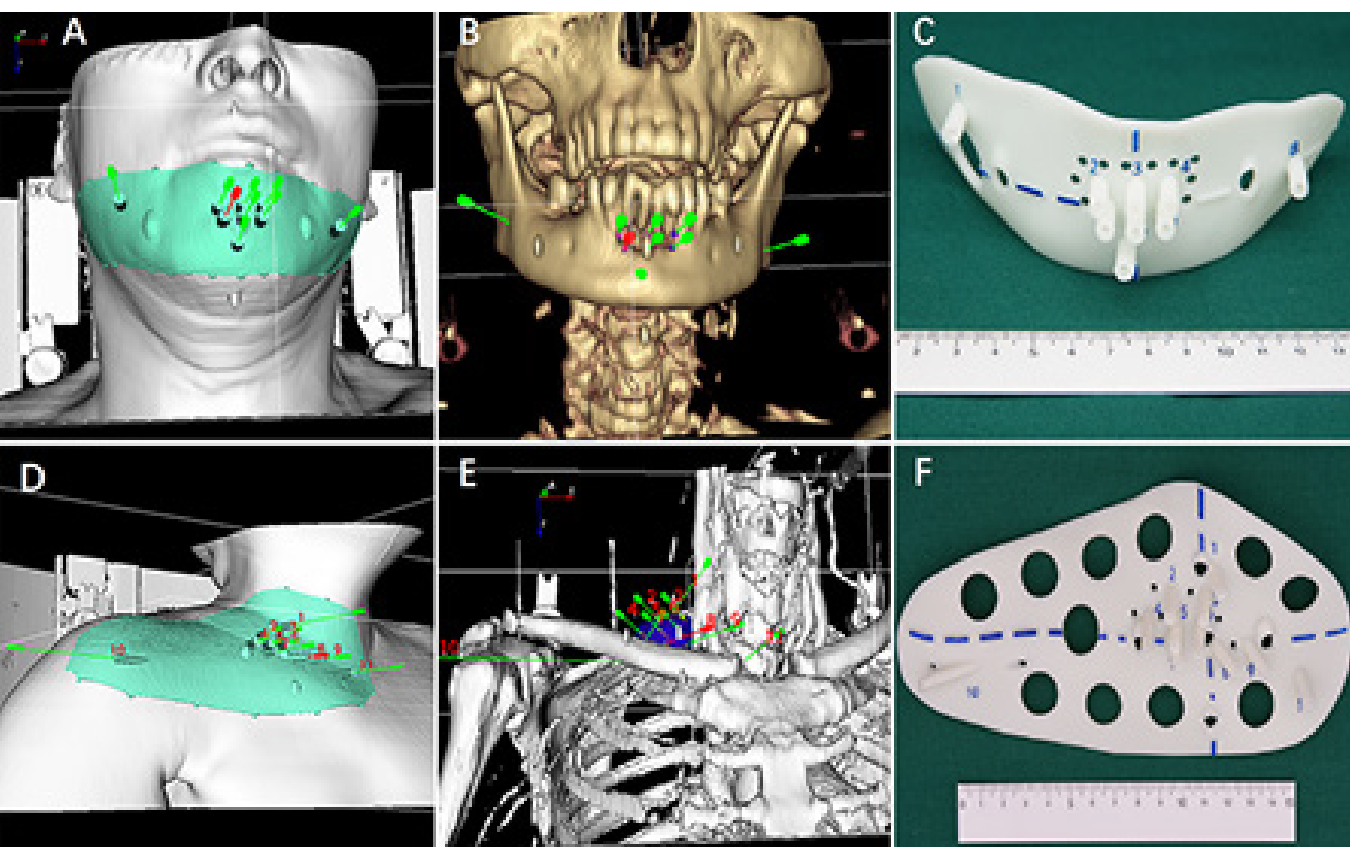


Figure 23: An example of 3D-printing being used for interstitial brachytherapy by Qui et al.

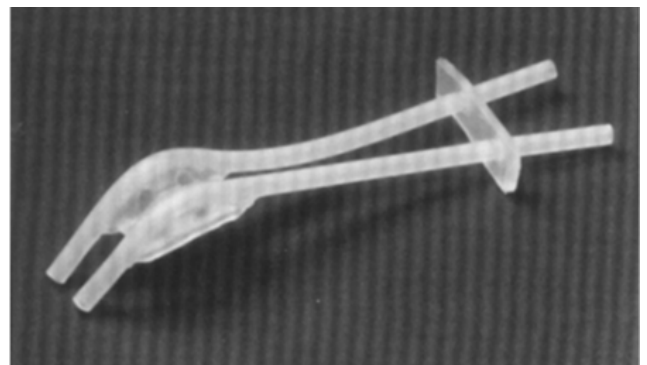
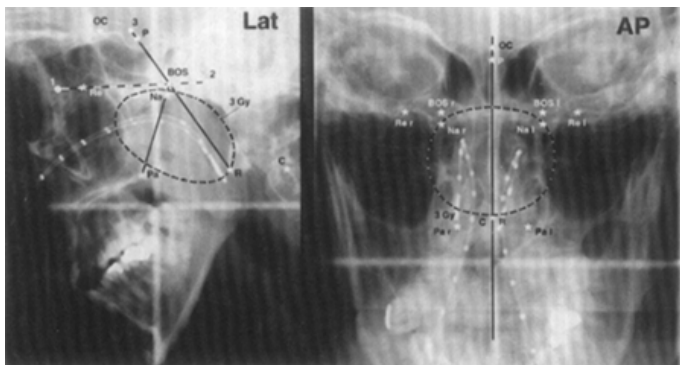


Figure 24: Imaging scans of the nasopharynx applicator provided by Levendag et al.

Some examples are the 3D printed radiotherapy templates by Chen et al. (2021) & Qiu et al. (2021), directed at creating guidance for surface-level brachytherapy treatment in the head and neck area.

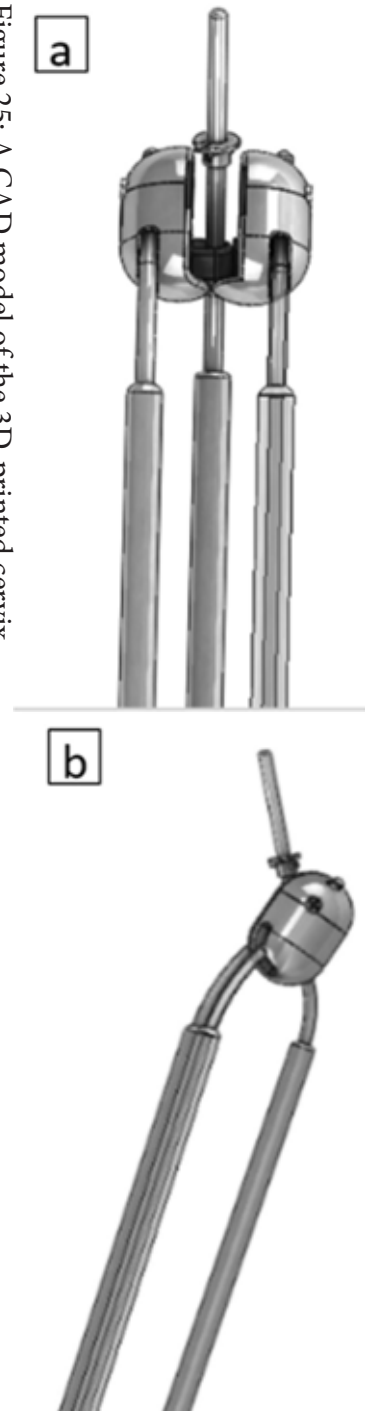
Reports like that of Mourya et al. (2025) show examples of new biomedically cleared printable materials that specifically fit the design of a new brachytherapy applicator in the cervix.

McGrath et al. (2024) show examples of different 3D-printable steel types and their influences on radioactive shielding in brachytherapy applications.

H&N applicators

An older study by Levendag et al. (1997) is one of the few examples where an intracavitary approach to brachytherapy is applied to the nasopharynx area. (figure 24) The applicator, made out of silicone is fixated on the nose and guides 2 catheters to the target area, placed farther away into the throat. The catheters were fixated by hooking the guides on the sharp corners of the nasal cavity to the throat. This way it would be fixated on the nose and on the throat, allowing secure placement. The doses however are relatively high for this treatment, which is now done fully with beam therapy as tumor spread is higher in the nasopharynx as well (M. de Ridder, 2025).

Figure 25: A CAD model of the 3D-printed cervix applicator by Mourya et al



Current state of the art:

A literature research on the recent developments in the field of brachytherapy and oncology

Component limitation studies

A nasopharynx applicator designed by Jean-Joseph et al. (2025) has previously tested the integrity and behavior of catheter bending under tension with an Euler Buckling test (compressing the catheter, making it bend until it buckles) and with non-linear finite element analyses to discover the physical limits of the BT catheters they were using. They showed the limits of 6 French nylon catheters which buckled at a bending radius of 28mm.

A limit to this theory is the fact that they did not test if the radioactive pellet actually was able to turn the corner of 28mm as well, with a length of around 4mm this could be a problem and should be tested, if bending radii come into play in the design concept.

The study by Straathof et al. (2024), show the possibilities with bended catheters and radio-source passage through the curves.

Shape-adaptive Brachytherapy applicators

Founded in 1987, Merit Medical Systems, Inc. is a leading manufacturer and marketer of proprietary disposable medical devices. Merit serves client hospitals worldwide. In 2017 they released the Savi Brachytherapy applicator (figure 26), a so called: Strut Adjusted Volume Implant (SAVI) is a single-entry device which delivers a short course of radiation for early stage breast cancer. The aim of the device is to reduce patient interactions during brachytherapy treatment where previously catheters needed to be placed surgically and oftentimes every day.

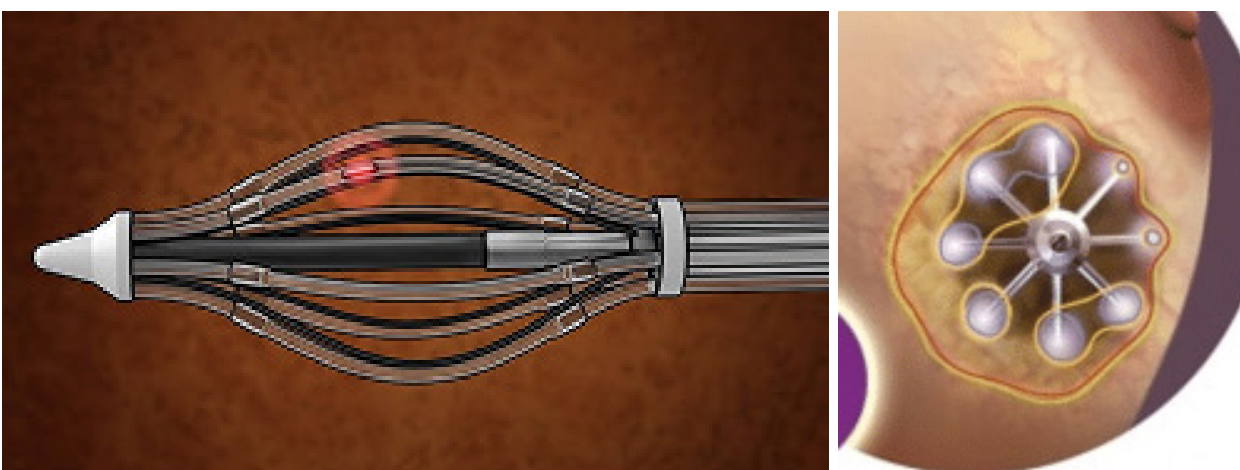


Figure 26: SAVI applicator from Merit Medical Systems

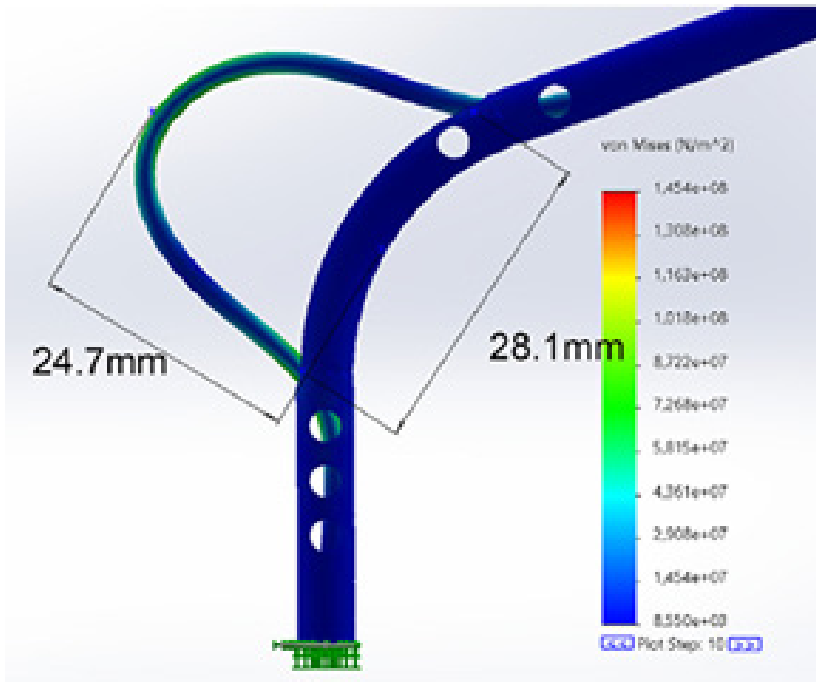


Figure 27: The maximum curvature test by Jean-Joseph et al.(2025)

Inflatable applicators

Another inspiration from the current field of brachytherapy is the use of inflatable foley applicators like the PORGES applicator, primarily used for stabilizing in the urinary tract. The applicator is manufactured using a molding technique for the catheter guide. After that is completed, the tube is dipped to create an outer layer of silicone, and a shrink sleeve is glued to the top of the applicator. By guiding an air path through the silicone layer which exits in between the glued top and bottom of the shrink sleeve, the ability to inflate the shrink sleeve is created.

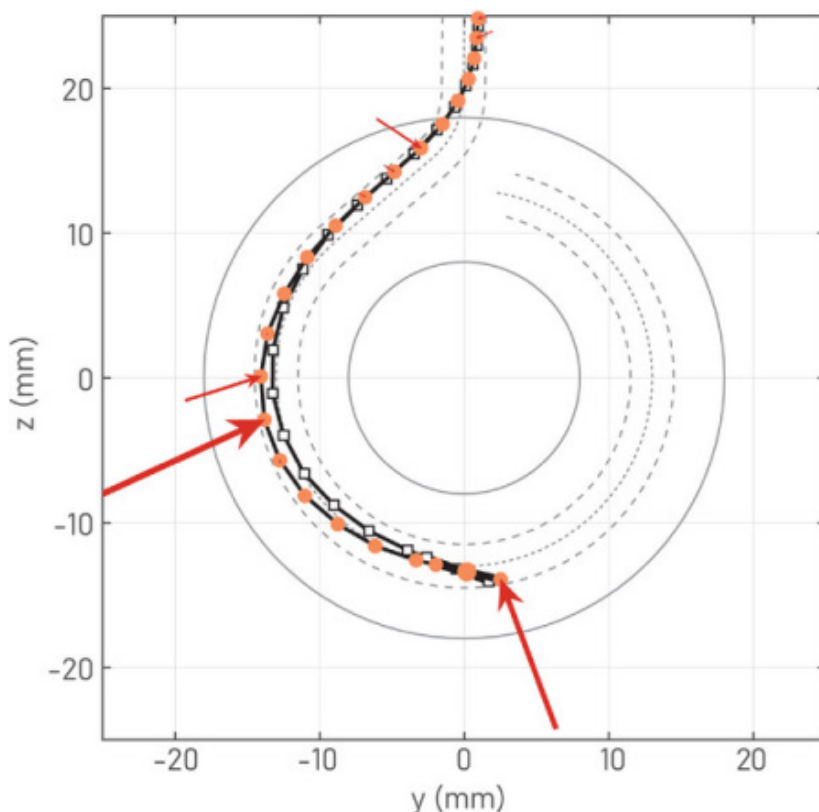


Figure 28: The curvature test by Straathof et al. (2024)



Current state of the art: Shape memory alloys

Researching the medical use of shape morphing and smart materials to investigate the possibility of low-profile expansion mechanisms through these materials

Superelastics and Shape Memory Alloys

One of the key elements of smart material sciences especially within the scope of this project is the development of superelastic- and shape memory alloys. Such as NiTi(Cu) (also referred to as NiTiNol (Wang et al., 1965))

The unique property of this material and its variations is that it can be trained in a certain shape by heating it thoroughly. After returning to room temperature the shape can be deformed into whatever shape one would like. After heating it again (ΔT depends on the material ratio) the material goes back to its trained shape. This unique property allows the material to be used in innovative ways to create smaller hinges or actuators.

Superelastic materials (SEM) are also shape memory alloys (SMA's) which have to be trained in the same way. However, they return to their trained shape (Austenite) at room

temperature. Practically, this means they remain in their shape almost permanently. Deforming these materials closely resembles putting tension on your everyday spring.

Programming these SEM in a certain shape at inner body temperatures could allow the application of a mechanism under tension that releases when inserted to remain in situ.

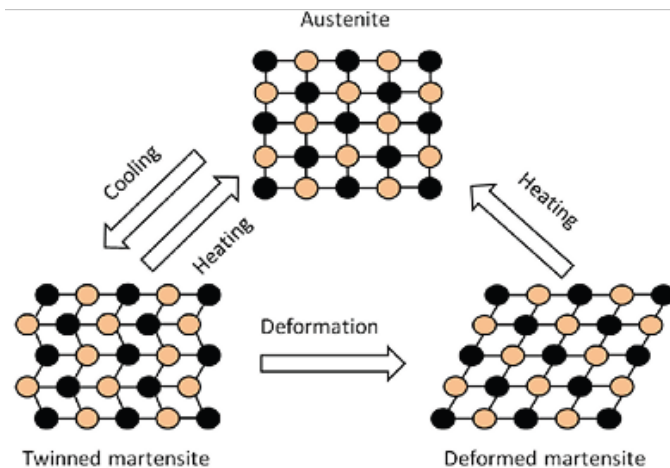


Figure 29: The different SMA states (Bengisu & Ferrara, 2018)

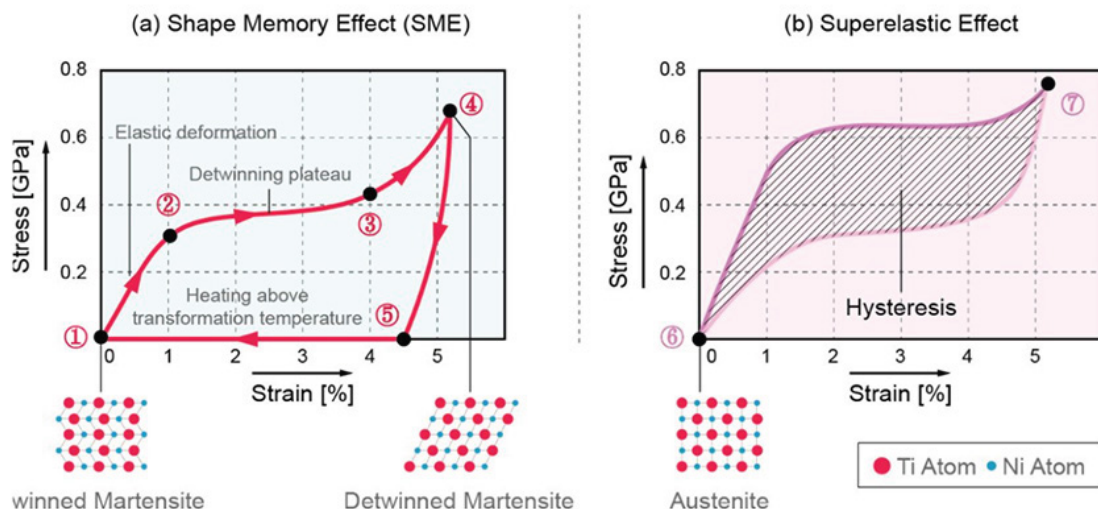


Figure 30: The different stress-strain curves bewteen SMA's and superelastics (Bengisu & Ferrara, 2018)

SMA applications

Studies like those of Gangadhar et al. (2015) show the possibility of using NiTi wires to create low-profile hinges and linear actuators which act on temperature differences.

Figure 31: the design of hinges with SMAs (Gangadhar et al., 2015)

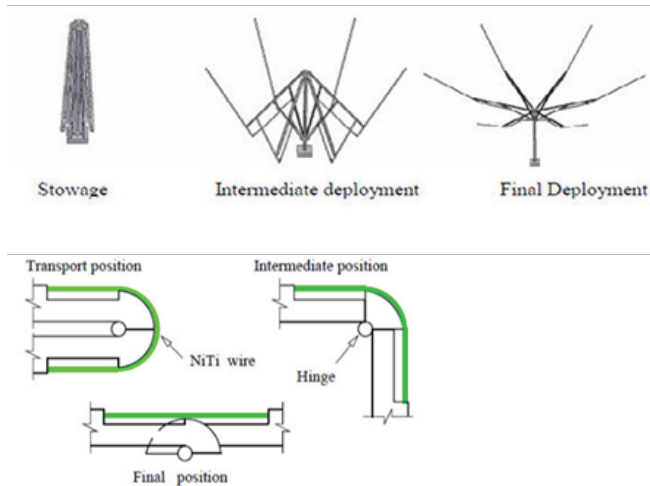


Figure 3: SMA hinges (From Likhachev, et al 1994[4])

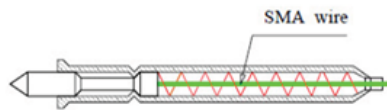


Figure 4: linear motion SMA actuator (From Moorlegheem 1993[5])

One of the most common clinical examples of Shape Memory Alloys in medical applications are NiTiNol blood vessel Stents (Pelton et al. 2007). Mesh structures made from a Nickel Titanium alloy that function as an expander for blood vessels and arteries which are too narrow.

These stents are expanded in the arteries with use of an inflatable balloon, which sets them in place until the temperature of the stent is high enough to be self-sufficient in expansion force to remain in situ.

The use of other SMA materials in medical context has proven to be effective and is practiced in publications such as: Mirzababaei et al. (2024)

Where shape morphing polymers are used to dig into tissue and fixate themselves by gripping surrounding tissue. Nickel is again the element that allows the shape morphing element to exist. Microgrippers were applied to retrieve cells from a porcine liver.

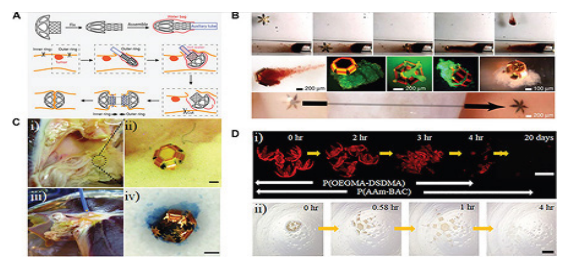


Figure 32: The application of microgrippers Mirzababaei et al. (2024)

At 4° C, these structures were open, while upon being heated to 37° C, they reached complete closure in 10 min. They applied these microgrippers in vivo to showcase their ability to retrieve biopsies in areas that are not easily accessible.

One problem with the above studies was that the actuation was irreversible, increasing the difficulty of retrieval of cells or tissue. In contrast, Breger et al. (2015) developed microgrippers that could undergo reversible actuation.

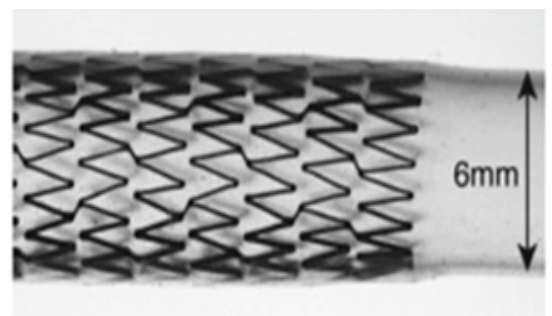


Figure 33: the Nitinol stent's by Pelton et al. (2007)

Current state of the art: Smart polymers

Researching the medical use of hydrogels and smart polymers to investigate shape morphing and retention principles

Injectable systems offer minimally invasive methods for in situ fixations. Fluids change in situ into solid or gel-like structures, eliminating the necessity of surgical fixation / intervention.

Rossi et al. (2021) mention the use of hydrogels in prostate application to enlarge the distance between the targeted radiation area and the healthy rectum tissue.

By inserting a fluid hydrogel in the designated area and letting it solidify through body temperature the radiation dose is absorbed and therefore less intrusive in the healthy tissue.

Vaggers et al. (2020) review similar procedures with the use of polyethylene glycol (PEG) hydrogel spacers. In this study an average spacing of 7.7 to 16 mm resulted in a reduction in radiation of 21.6 to 52.6%. With low doses being almost completely shielded.

However, these studies only mention the use of hydrogels injected in tissue to expand or even create cavities.

The use of hydrogels for filling up existing cavities with multiple openings such as the nasal cavity is yet to be found. And would therefore, likely have to be tested.

Hydrogels such as the SpaceOAR consist for 90% out of water and polyethylene glycol (PEG) that when combined, form a soft gel material that can be injected in a volume to solidify said volume (figure 35).

Physical cross-linked gels → Are reversible
Chemically cross-linked gels → Are irreversible

Lower critical solution temperature (LCST) and upper critical solution temperature (UCST) behavior are important terms when describing thermo-responsive polymers (see figure 34)

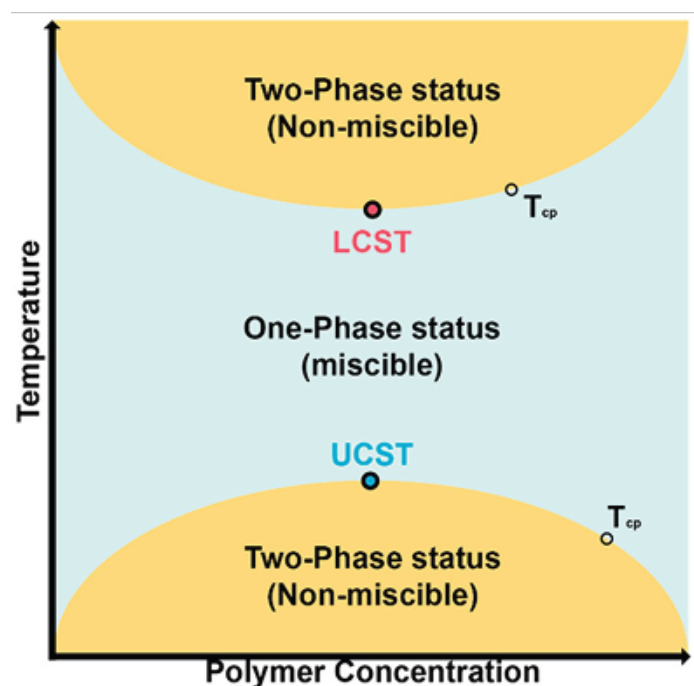


Figure 34: the different states of shape morphing hydrogels (K. Zhang et al., 2021)

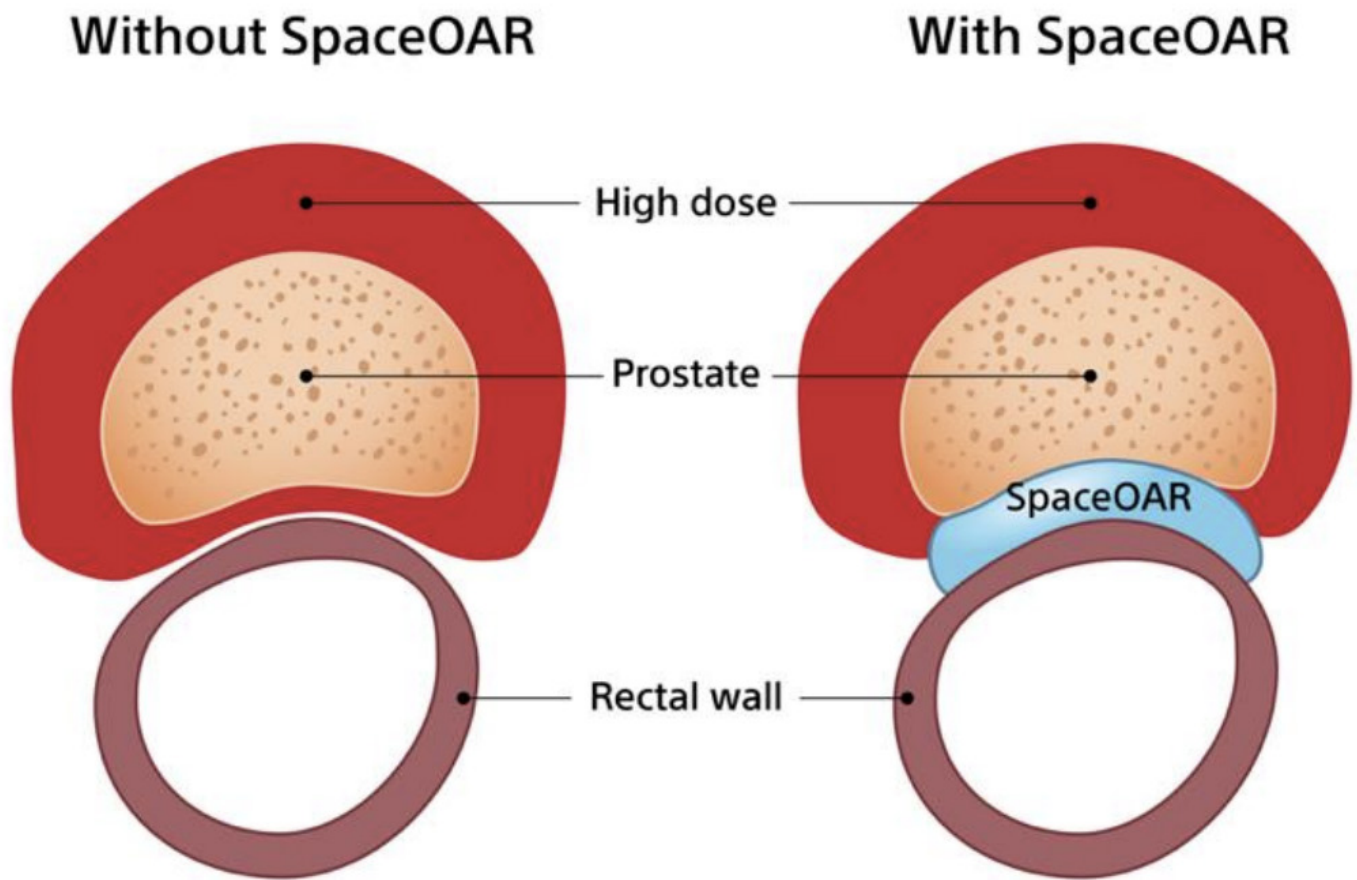


Figure 35: Rossi et al. (2021) The difference in application with and without hydrogels

PEG hydrogel spacers are safe to insert. Gel insertion is easy, fast and has a low rate of failure.

These studies convincingly demonstrate a significant reduction in rectal dosimetry.

Synthesis:

A Design-driven material feasibility matrix

All aforementioned options are listed on their different properties for the project.

Criterion	Hydrogels/soft elastomers	SMA (Nitinol)
Mechanical stiffness (kPa–MPa)	Very low stiffness (kPa). Safe interaction with mucosa but insufficient for directional control.	High stiffness in austenitic state (MPa). Enables steering but risks pressure peaks and if designed incorrectly could harm soft tissue.
Deformation ratio (insertion → deployment)	Very high swelling/deformation potential. Expansion uncontrolled and iso-tropic.	Limited recoverable strain ($\approx 6\text{--}8\%$). Predictable shape return in mm. Might need to be retrained after a number of cycles.
Radiation stability	Generally stable at clinical doses. Minimal degradation.	Limited evidence; base properties stable, but long-term phase-shift effects unclear. Metals tend to influence radiation patterns.
Manufacturability at IDE	Can be cast in 3D-printed molds. Low geometric precision. Or 3D printed themselves, however considered possibly too expensive and complex for in-house manufacturing.	Can be integrated manually into prototypes; printable, but not yet commercially available.
Manufacturability at UMCU	Not part of validated workflows. Would need custom processes and machinery.	No established workflow; integration into printed models possible but new.

Table 4: The different discussed materials divided by performance criteria

SMP's	Pneumatic / Hydraulic inflatables	Printed Medical Polymers (Biomed Clear / PEEK)
Intermediate stiffness; tunable. Lower forces during recovery.	Very low stiffness when deflated; moderate when inflated. Poor inherent directional stability.	High stiffness (depending on print quality and layer orientation). Excellent geometric stability but combination of bio-safe and compliant materials are not widely available.
Higher recoverable strain (10–400%) but slow recovery.	Very high (collapse → inflation). Expansion easy but geometry difficult to constrain apart from wall thickness variety.	Very low deformation. Requires insertion in final shape or mechanical expansion methods.
Susceptible to degradation depending on chemistry. Requires validation.	Fluids stable; membrane materials require verification, but medical grade silicones and latex already in use.	Known radiation stability; already used clinically, performs predictably.
Is printed in research fields, but not commercially available.	Simple (scaled) prototyping with silicone membranes; low resolution and wall-thickness control.	Fully printable with existing machines, but rigid results only.
Needs to wait until commercially available print methods arise.	Could potentially be integrated in the printing methods already performed at UMC, however commercial manufacturers are preferred regarding safety.	Fully validated workflow at UMCU; excellent patient-specific manufacturability.



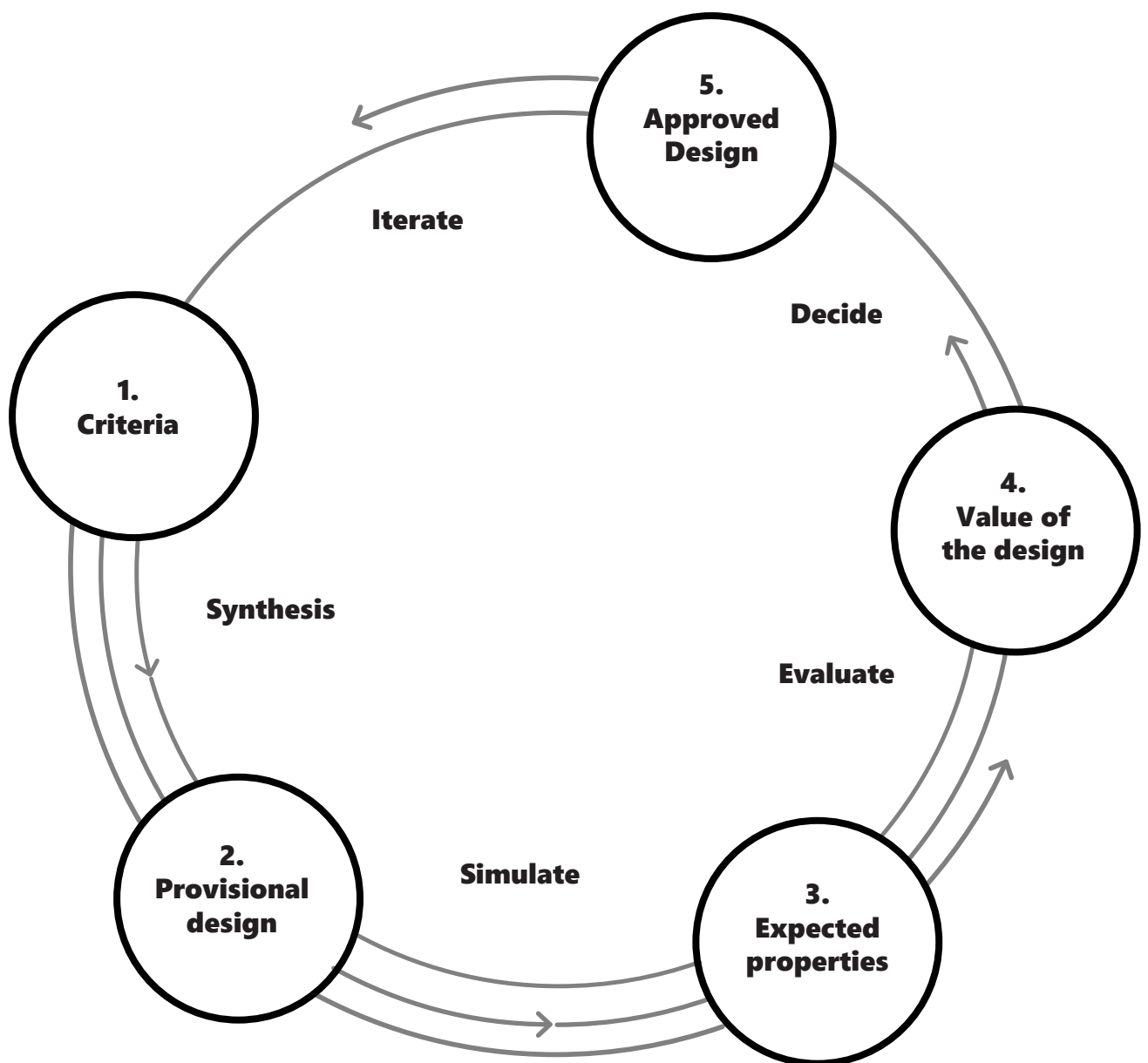
Project management and parameters

Now that all current innovations and state of the art have been mapped, the focus can shift back to the design aspect of the project.

It is important to clear up the project parameters (Van Boeijen et al. (2014)) such as the problem statement ("what is the problem I am trying to solve? why is it a problem? Why has the problem not been solved?"), the assignment set up to solve the aforementioned problem ("To solve problem X, we need to create/design Y").

When all of that has become more clear. It is time to look at the requirements, listing everything that you know you need to create "Y". This also gives insights into what criteria exist to validate when the design has failed or succeeded in its task in the form of Risks and Goals.

Lastly, it is important to set a clear scope (in this case anatomically) of where the design should be functioning and what cases will be left out of scope.



Delft Design Guide (Van Boeijen et al (2014).

Problem statement

The problem statement originates from a discrepancy in the complex anatomy through which the brachytherapy catheters should be navigated. The paranasal sinus entries are small and relatively difficult to navigate. After entry the catheters are difficult to fix in place as a large cavity needs to be filled.

With current (available) technology the most safe and time & cost efficient option is to perform beam radiation therapy, leaving a large low dose radiation bath on the eyes, brain and mouth. Brachytherapy is only considered on the front of the nasal cavity (vestibule) as the other cavities are too unstable to reach with current technology and without large interventional surgeries.

Assignment

"Create a design to evaluate the possibility of paranasal brachytherapy without large surgical interventions for more effective and less intrusive paranasal cancer treatment for both patient and hospital staff through iterative prototyping"

List Of Requirements

ID	Requirement	Type	Source
1	Catheter flexibility needs to be identical to present radii	Technical	UMC-Staff
2	The CTV will be patient specific. The applicator must be adaptable to patient specific anatomies	Medical	UMC-Staff
3	Catheter orientation must be predictable meaning it can be planned beforehand	Medical	UMC-Staff
4	The applicator must be biocompatible	Medical	Regulations
5	Must resist high radiation doses	Technical	UMC-Staff
6	All materials must be MR-safe (non-magnetic)	Technical	UMC-protocol
7	Radiation must not be in direct contact with tissue	Medical	UMC-Staff
8	Tolerances for swelling must be taken into account	Technical / Medical	UMC-Staff
9	Electronics are a no-go during radiation (possibly placement / removal at low power)	Technical / Medical	UMC-Staff
10	The device needs to be able to remain in situ for 2 weeks	Medical	UMC-protocol
11	Must be applied non-invasively	Medical	UMC-Staff
12	Must remain within stable margins (1mm total (Tiong et al. (2009) -> 3mm. With H&N this margin will be smaller)	Medical	Medical assumption
13	The applicator must be sterilizable	Technical / Medical	UMC-protocol
14	Application must take no longer than 1 hour	Medical	UMC-Staff
15	Must be visualizable on CT and MRI scans	Medical	UMC-Staff
16	Needs to be removable without invasive surgery	Technical / Medical	UMC-Staff
17	Needs to facilitate complex patient-specific dosimetry plan (>1 line of dwell points)	Technical / Medical	UMC-Staff
18	The expansion ratio of the design should be within the range of 1 : 5 and 1 : 10.	Technical	Assumption

Risk, safety and failure analysis

Based on the requirements and our newly gathered insights on the medical context, the device operating next to brain tissue and eyes needs to perform safely.

To determine what is safe in this situation a few aspects are assessed of which the complete overview can be found in Appendix C:

- Maximum allowed pressure on mucosa
- Risk of misplacement
- Thermal hazards from shape-memory activation
- Placement shift risks during the 10-day treatment window
- Sterilization & degradation behavior of (smart)-materials

Big Hairy Audacious Goal (BHAG)

“ Be able to create and execute a patient specific brachytherapy dosimetry plan for a case where beam radiation is the current preferred therapy”

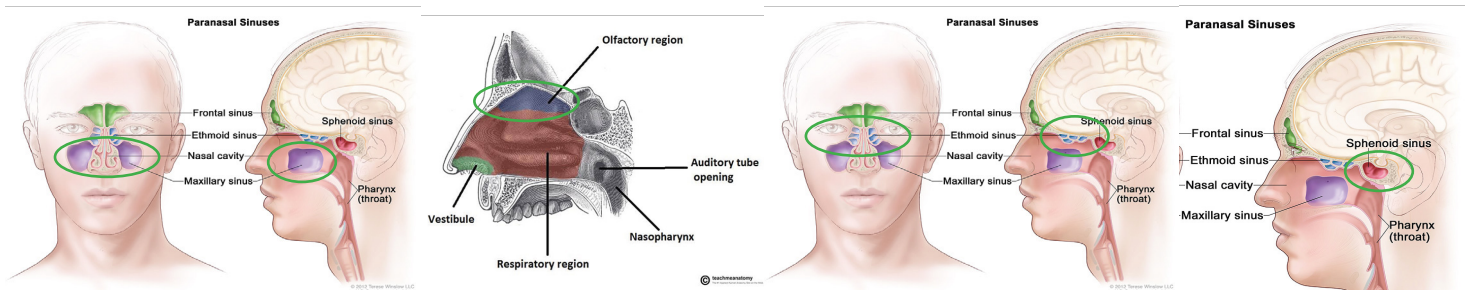
Anatomy Target Scope

The maxillary sinus

The upper nasal cavity

The ethmoid sinus

The sphenoid sinus



The frontal sinus is excluded as little to no carcinoma has been previously identified and the target area overly complicated the applicators requirements

The main limiting factor with current technology

“The current methodology of treating the nasal vestibule does not match the size discrepancy of the nostril entrance and the cavity behind it. Therefore it would not be able to facilitate complex intracavitary dosimetry plans, meaning that without invasive surgery the patient is better off with beam radiation therapy”



Design concepts

From the previous chapter we are able to extract the following insights and their accompanying design implications which will be integrated in the concepts:

Insight

1. Anatomical mismatch is the primary constraint

Design Implication

Device must enter in a compact state and expand only after passing the nasal valve; requires high deformation ratios with a predictable deployed geometry.

2. Catheter stability cannot rely on soft tissue

Deployed configuration needs local structural support or guiding features to ensure reproducible catheter positioning without damaging mucosa.

3. Sensitive anatomy requires atraumatic behaviour

Insertion state must be compliant, smooth and low-profile to minimise friction and force during navigation and removal.

4. Workflow constraints limit activation methods

Deployment mechanisms must be simple, passive and reversible, avoiding heat, solvents, or specialised equipment not present in standard clinical settings.

5. No single material satisfies all requirements

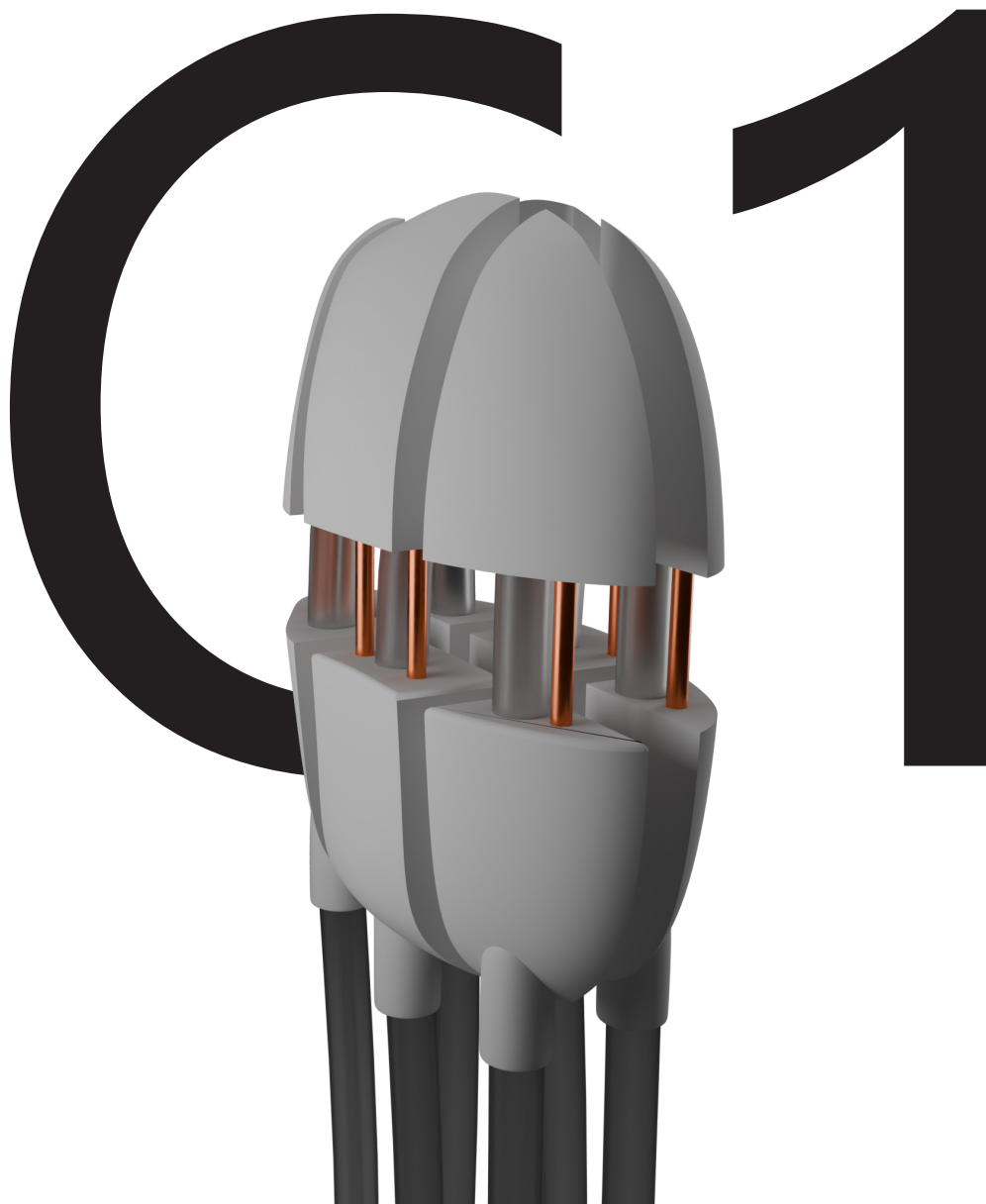
A hybrid approach is more feasible: compliant outer elements combined with internal structures that provide stability or directional behaviour.

6. Postoperative variability reduces suitability of fully patient-specific parts

Device should adapt to irregular geometries through shape-morphing or self-adjusting behaviour rather than relying solely on customised printing.

7. Core contradiction defines the design direction

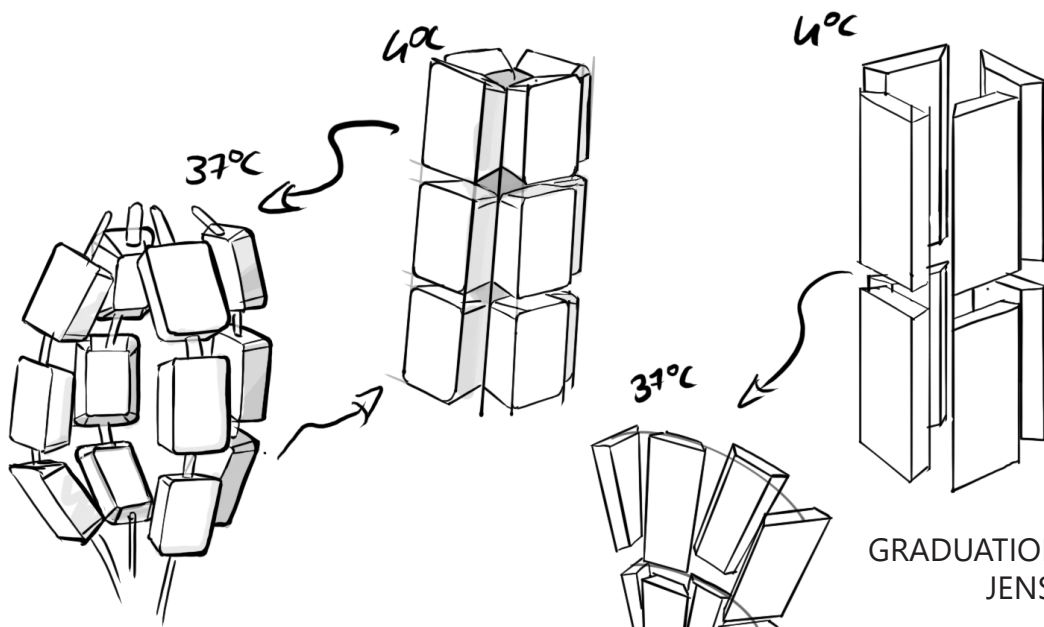
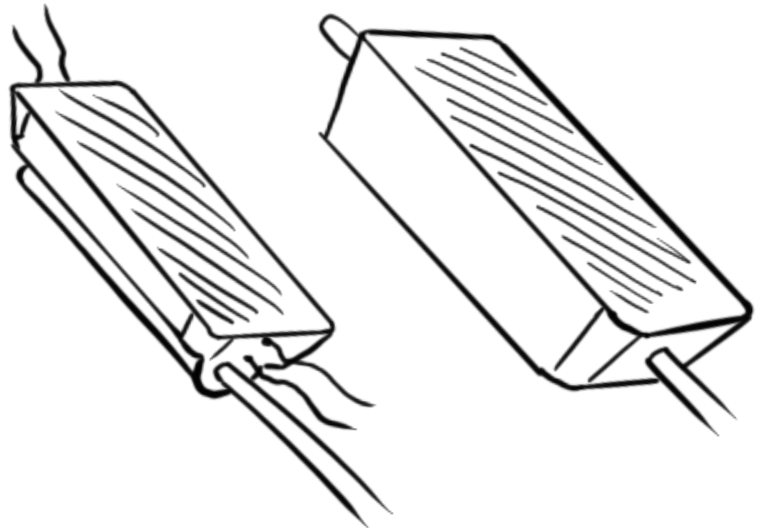
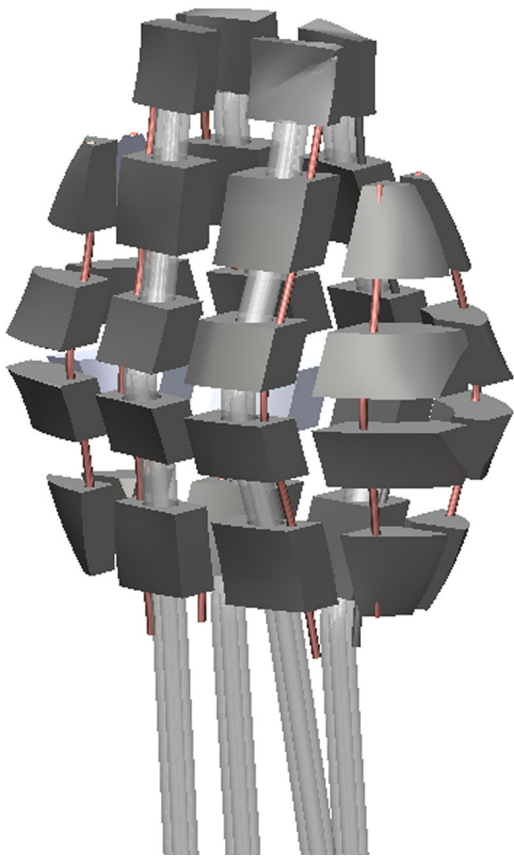
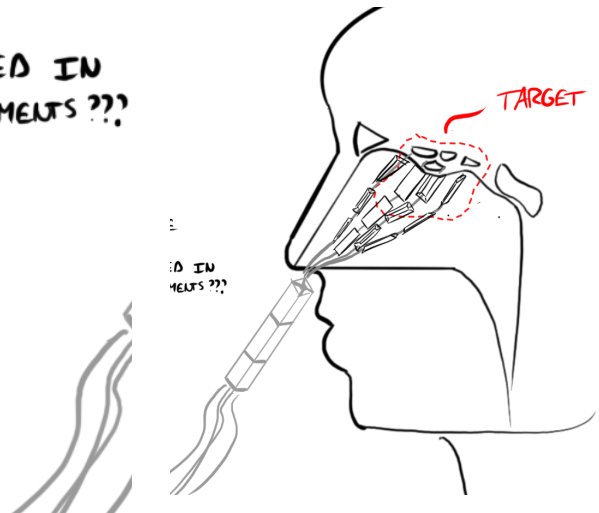
The design must remain soft for insertion, structured for stability, adaptable to different cavities, and predictable/safe in operation driving the need for combined mechanisms.



Rigid SMA expansion mechanism

Making use of the shape morphing properties of NiTiNol wire by allowing it to navigate a skeletal structure of the amore which ultimately provides the expansion mechanism we are looking for.

The concept consists of 3D printed blocks, or as I like to call them: 'vertebrae' with dedicated holes for both the catheters they keep in place and for the NiTiNol wire that connects the vertebrae to each other.



Working principles

- The NiTiNol wire has an Austenite Finish Temperature (T_{Af}) of around 30 to 37 degrees C. We program the shape of the NiTiNol to be in the orientation of the expanded assembly.
- When we cool the NiTiNol, it becomes easier to deform, meaning that we can shape the assembly to fit through the nostril by compressing the vertebrae to each other to elongate the assembly as much as possible.
- After placing the deformed set of vertebrae in the nasal cavity with an endoscope. The assembly is allowed to heat up to body temperature (around 37 degrees). The result of this heat is the NiTiNol moving towards its programmed shape, dragging the vertebrae outwards until they are pushed against the tissue walls of the nasal cavity.
- The catheters (also linked to the vertebrae) are put into the designed locations and should be ready for treatment.

The concept is designed by extracting the shape of the desired amore from the DICOM files (made in OCB) and put into a modelling software. The desired coordinates of the catheters are overlayed on the 3D file and the holes needed for their placement are modelled in.

After the amore's shape and catheters are put into the modelling software it can be cut up into the vertebrae to make sure it eventually should fit inside the nostril.

Once the individual vertebrae are identified, the splines for the NiTiNol wires are drawn and cut from the vertebrae. These splines are used to guide the programmable shape of the NiTiNol wire.

For prototyping the individual vertebrae are 3D printed and post-processed. The NiTiNol will be programmed by printing out the shape of the splines in 2D and using those as a guide for the stainless steel programming sheets.

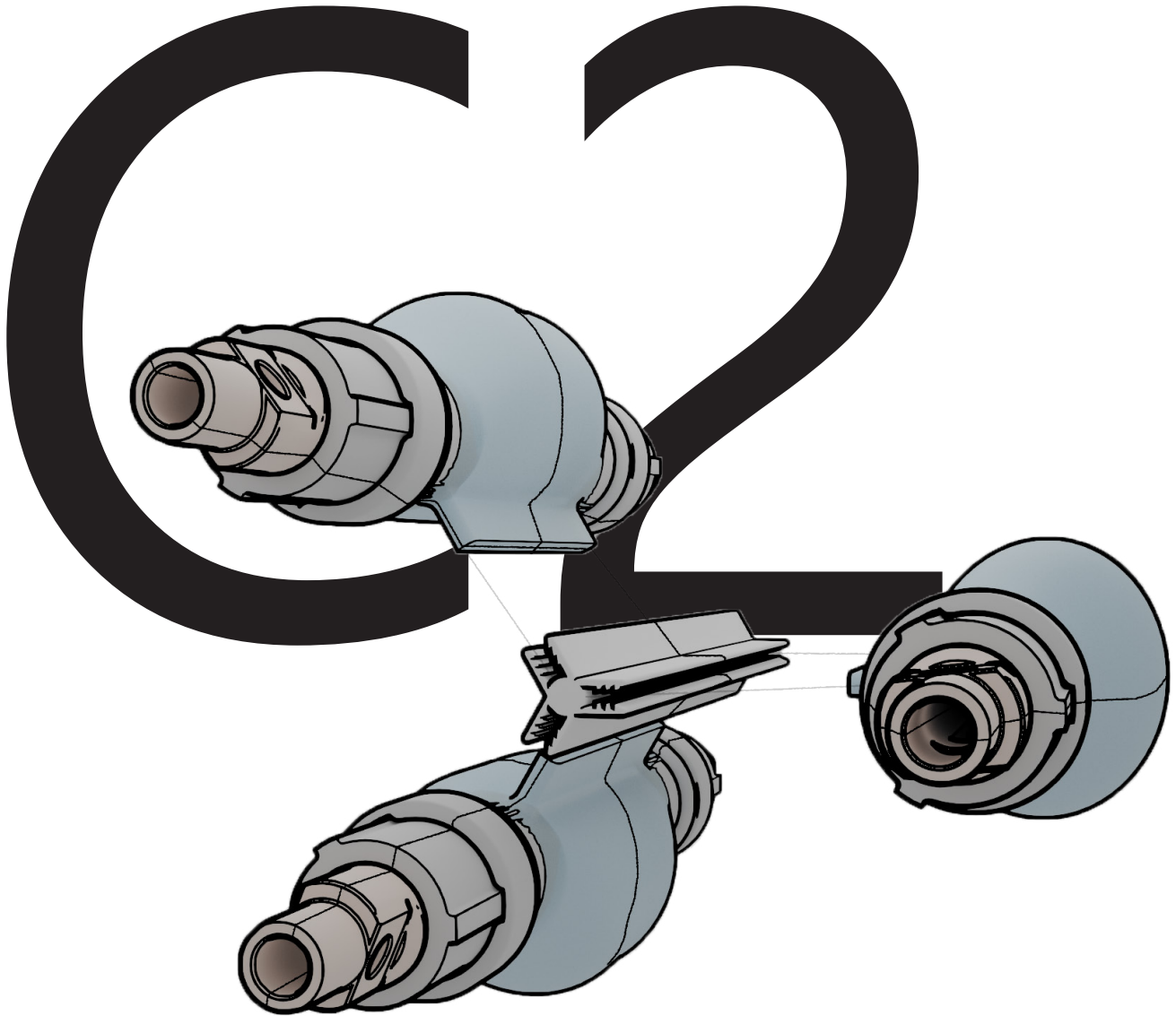
The NiTiNol is fixed in the to-be programmed shape and tempered in the ceramic oven.

Meets	Does not meet
A high deformation ratio (mainly determined by how small the vertebrae can be designed)	Predictable and controlled radiation plans (Influence of Nitinol on radiation attenuation has insufficient evidence)
Predictable and plannable deployment geometry	Activation concerns (body temperature is an relatively unreliable metric, especially through the nostrils where air constantly passes through)
Reversible deployment with cooling fluids	Direct integration in UMC workflow (training facilities such as a dedicated ceramic oven would be necessary.
Controlled, 3-dimensional expansion (determined by in-house training facilities and expertise)	The device would likely not easily adapt to a changing environment, such as healing or swelling tissue.

Technical depth chart:

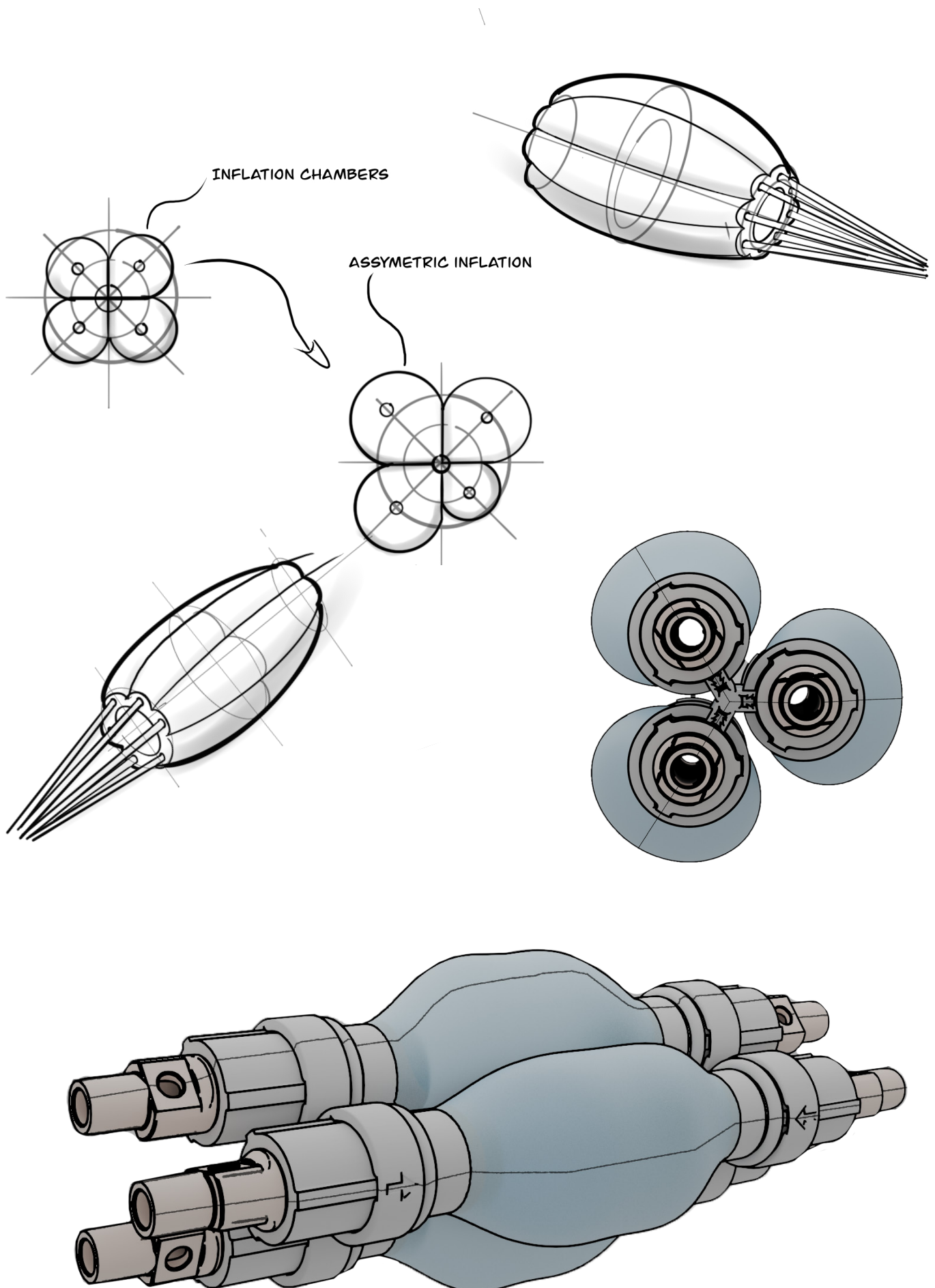
Activator	The mechanism is actuated by changing the nitinol temperature. When using nitinol wire with an austenite finish temperature of around body temperature, the optimal option would be a superelastic - cold drawn wire. For this concept 0.5mm is considered the most suitable diameter(Nickel Titanium Wire - Superelastic and Cold-drawn - Ø0.5mm, n.d.)
kPa / MPa	As the aforementioned vertebrae are printed in PEEK, which has a tensile strength in the range of 96.5MPa, the contact areas with the targeted tissue will be hard-to-hard. Meaning less expansion force is needed to fixate this rigid structure in place, also because too much force would likely cause the tough PEEK material to cause trauma to the patients tissue. In conclusion the expansion force will likely be in the kPa range for this concept.
Cycle repeatability	Nitinol has ranging cycle repeatability after training. Depending on the force put on the material the cycles can vary from 100s to 1000s of cycles (Rebelo et al., 2011) (A. R. Pelton et al., 2007/2007). As the device will likely remain in the 100 cycles for placement and testing before application, this is considered adequate.
Sustainability	The nitinol wire itself can be re-trained almost infinitely as long as the material remains intact. Therefore it can be reused after sterilisation. The printed vertebrae however can not be reused or repurposed after use.
Radiation attenuation & absorption	In a study by Özen (2024), the clinical effects of Nitinol in brachytherapy applications with Ir-192 radiation are tested. The attenuation levels are presumed clinically insignificant. However, the exact case with multiple Nitinol wires and plastics around them should be tested for attenuation and absorption influences. The material PEEK has proven to be water-equivalent in earlier applications at the UMC and will therefore be assumed to have little influence on radiation plans
Sterilisation	PEEK has already been sterilized in previous cases. As has been done with Nitinol in heart stent manufacturing. It would however be wise to test the full assembly for sterilisation feasibility.
Maximum strain	Both PEEK and Nitinol have maximum strain values of well in the MPa range, which for the environment the device will be functioning in is assumed adequate. However, the print-quality of PEEK is something that should be well considered from case to case in the development of the device at the UMC

Table 6: Presumed technical properties of Concept 1



Multi-chamber inflation mechanism

This concept was created by taking inspiration from the previously mentioned SAVI-applicator, used for breast cancer. However, the critiques from medical staff were the perfect radial expansion and the gaps of air this applicator would leave. The first problem was tackled by drawing up an idea with asymmetrical expansion chambers. This resulted in the idea of creating separate balloons which would be centrally fixated. By having the balloons individually inflatable, we theoretically would be able to create patient specific fixation mechanisms. Furthermore, it could lead to the possibility of letting the catheters follow the centerpoint of the inflatable which would ideally give the option of creating patient specific catheter paths for complex radiation plans.



One of the first questions upon presenting this concept to the medical Staff of the UMC Utrecht was the feasibility of making a reliable connector between the balloon and the lock-insert for the 6-french catheters from Elekta (Clinical Brachytherapy | Products | Cancer Treatment | Elekta, n.d.).

Which is why a short design sprint is done to prototype a connector piece that ensures a more reliable connection to the balloon than just a tight fit, all the while incorporating the tried and tested lock-insert female topology (Appendix D). By sandwiching the balloon between the connector piece and a rubber ring and then sliding a locking mechanism over the rubber ring to squeeze it fixed, the balloon sleeve should be fixed airtight without introducing glue or other adhesives. The rest of the concept revolves around the principle of placing multiple balloons in a radial pattern. By using multiple inflatables instead of one, custom shapes can be achieved to accommodate for different patient specific needs and anatomies. These different inflatables will have relatively simple shapes, therefore they can very likely be ordered with custom dimensions tailored to the needs of the individual patient). Next to that the connector pieces can likely be 3D-printed in the formlabs resin printer available at the UMC's facilities. An alternative (possibly cheaper and more reliable) option would be to find a mass-manufacturing facility for injection molding.

The only variable then remains: the amount of balloons and their orientation. For this, a simple divider can be made in various shapes with ribbed slots for the balloons to fit in. If necessary, the slots could possibly be redesigned to clamps which grip onto the balloon.

Improvement after discussion with UMC experts:

The UMC staff had a lot to say about this concept as they definitely recognize the potential of controlling the catheter orientation by inflating multiple balloons in respective amounts. However, they also saw bottlenecks in the placement of the connector pieces and weren't able to imagine the inflation principle much yet with the current concept developed. To make the concept more abstract we discussed trying to configure the concept more in the fashion of the aforementioned PORGES inflatable catheter. By taking inspiration from their manufacturing techniques, we might be able to design a device that has multiple inflatable chambers without the silicone coming in direct contact with the catheters (which would drastically increase friction), and while being able to inflate the chambers individually for patient specific catheter placement. This way we would also avoid the necessity of complex custom lock-insert connectors to the balloons which need to accommodate both air-/water-tightness and the Elekta lock inserts. By making use of existing connectors, the development time could be decreased and safety more guaranteed.

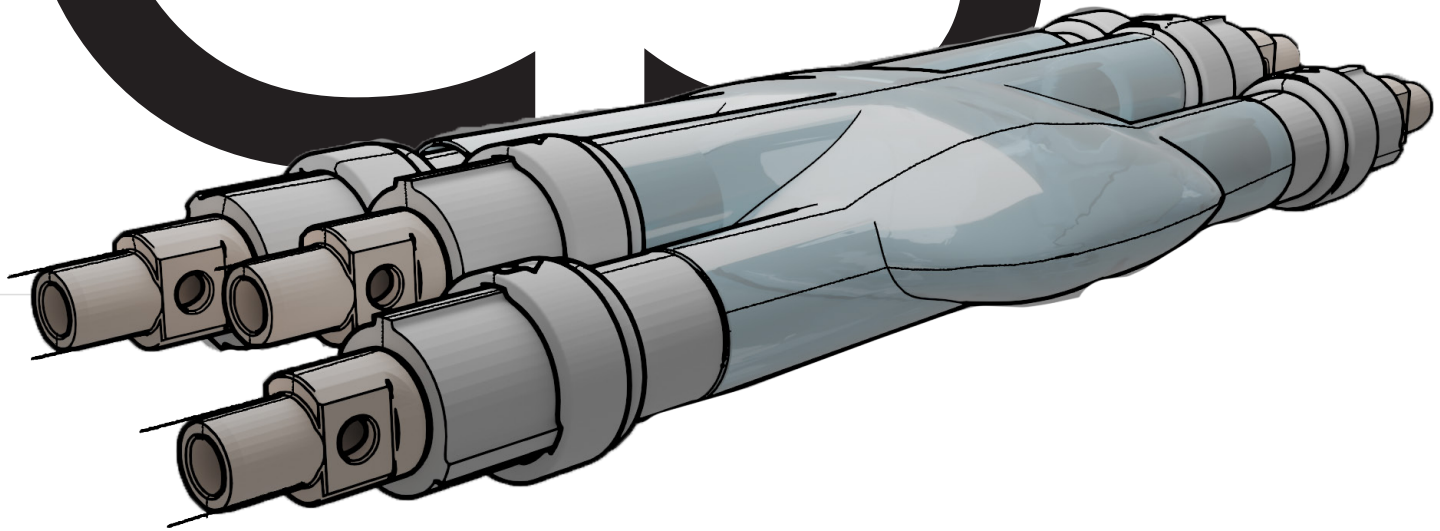
Meets	Does not meet
Soft a-traumatic insertion materials	Relatively little catheter stabilization (suspended from two fixations on flexible material)
Theoretically high expansion ratio	Risk of unpredictable deformation under uneven cavity geometry
Smooth surfaces	Connector pieces untested for reliability and would need additional MDR-approval
Adaptable to different patient anatomies	Inflatables do not reach all the way to the back of the nasal cavity because of the design of the connector pieces. Leaving for example the ethmoid sinus or nasopharynx untreatable

Technical depth chart:

Activator	The mechanism is actuated by the increase of pressure through a syringe filled with NaCl solution (potentially a more viscous solution could be applied for more reliable shape retention). The pressure can be manually increased or decreased by simply adding or removing solution.
kPa / MPa	As the silicone (or in the future latex) material is flexible and needs to form to the shape of the cavity to fully fixate itself. An estimated maximum pressure of 200kPa is needed for secure fixation.
Cycle repeatability	For the cycle repeatability of medical grade silicone, the accuracy of the correlation between volume and expansion pressure needs to be taken into account. This type of silicone has the tendency to act differently the first cycles of inflation than the many cycles after that. This phenomenon is called stress softening, briefly explained by Cooper (n.d.).
Sustainability	Silicones used in the medical industry have a high temperature resistance and can therefore be autoclaved relatively easily. Unfortunately this process is still not widely applied on silicone products, meaning the gross of the products are disposed (Wolf & Stammer, 2024).
Radiation attenuation & absorption	With enough pressure, the creases of the outer wall would seamlessly fit onto the tissue of the nasal cavity. When filled with NaCl, the entire planar environment should be homogenous and water equivalent, allowing easy dose calculations.
Sterilisation	As previously mentioned, medical grade silicones are sterilizable through autoclave methods. However, Kuruoğlu et al. (2024) mention the microscopic damage that is done to catheters in sterilization processes. Combining that with the fact that silicone applicators are relatively cheap compared to the costs of sterilization and the accompanied labor, leads to the conclusion that the infrastructure is not completely equipped for sterilizing silicone applicators for multi-use purposes. This concept will therefore be likely assumed as a single-use device with future prospects of becoming multi-use.
Maximum strain	Rjc (2025) among with other sources highlight the mechanical properties of multiple variations of medical grade silicone. All of them show a tensile strength in the 1 to 10MPa range with elongation at break ranging from 100% to 800%. In conclusion, the maximum strain with medical grade silicone should pose no problems for the specific cases of this design.

Table 7: Presumed technical properties of Concept 2

C3



Patient specific inflatable

The third concept focuses more on the patient specific application of concept one, with the material flexibility (and security) of concept 2, by taking the amore from OCB (Appendix E) and creating a patient specific balloon out of it.

This way, more complex catheter configurations could be reached as opposed to concept 2 without having to program and print materials in unison like concept 1.

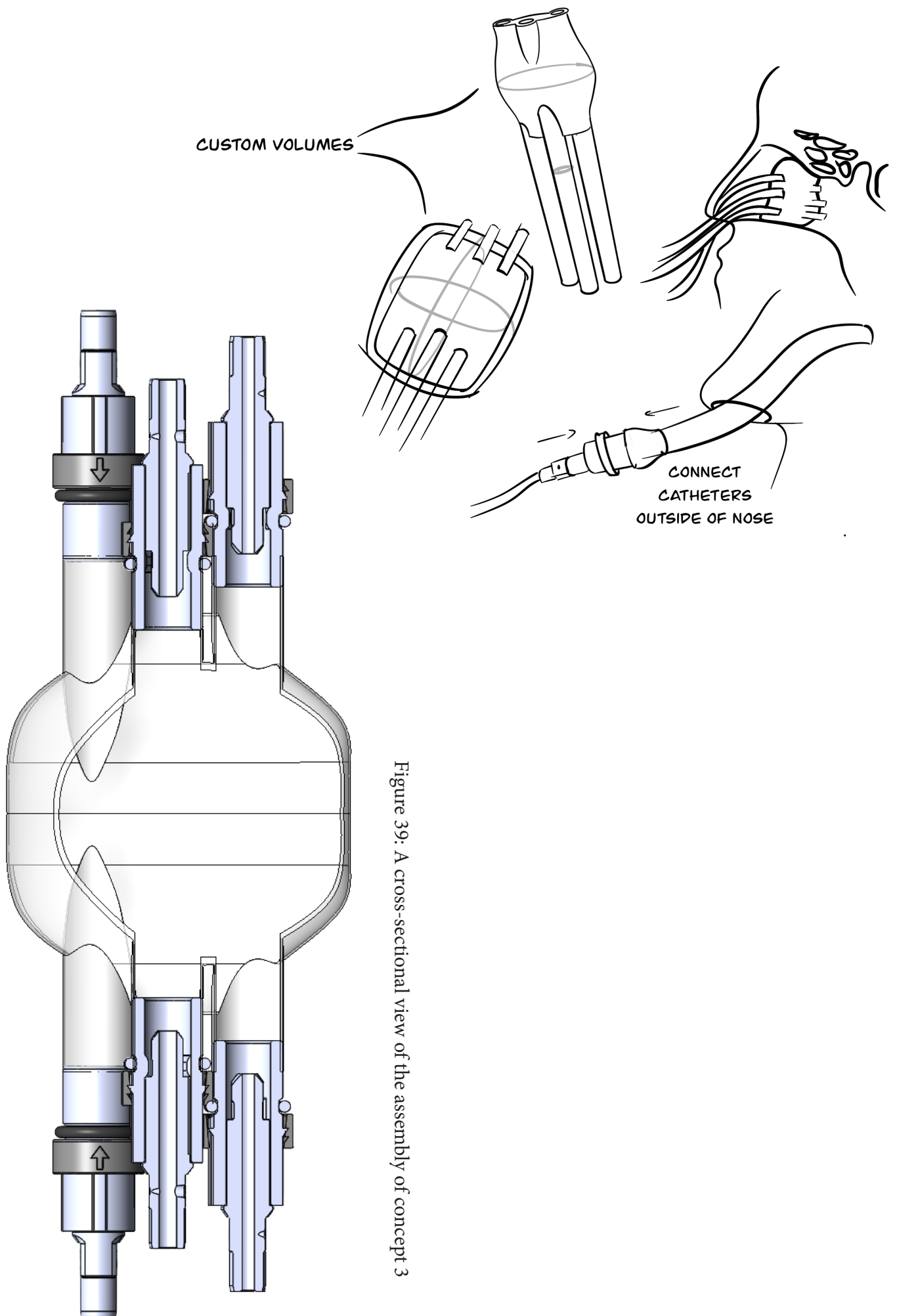


Figure 39: A cross-sectional view of the assembly of concept 3

Assembly:

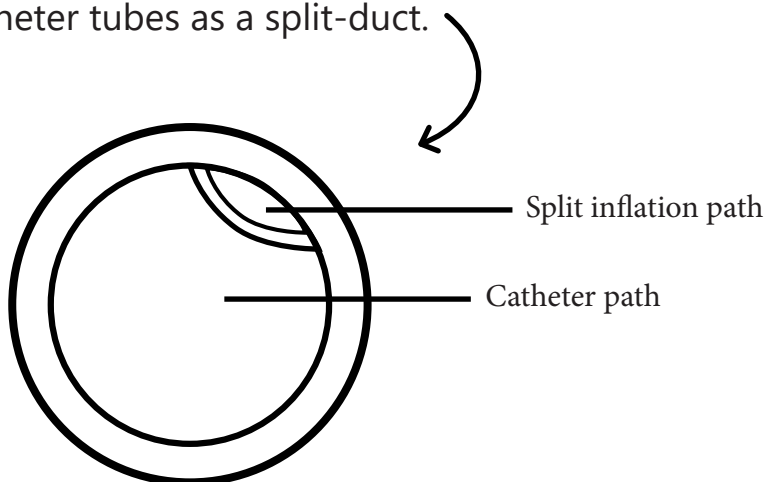
A short design sprint on creating a connector piece between a balloon and the elekta lock-insert

The design of concept 3 closely follows the assembly process of concept 2.

However, after discussing the design flaw of the connector pieces being too large for application on the beginning and the end of the applicator surfaced. Leaving the deep areas of the nasal cavity untreatable as the catheters are no longer covered by the inflatable.

Therefore a quick redesign is made where the connector pieces would ideally be outside of the nostril, leaving the catheters covered with silicone sleeves up until the inflatable where the catheters are suspended from shorter sleeves at the end of the inflatable.

An additional tube for inflation would be needed, or could be introduced through one of the catheter tubes as a split-duct.



The balloon could be made using multiple manufacturing methods ranging from casting to vacuum-forming or flexible resin printing.

The possibility of being able to order custom medical grade inflatables like the concept model in question does also exist (for example at: (Medical Balloon Designer, n.d.)), but is not preferred by UMC staff as, in their experience manufacturing their devices in-house is more efficient and more accurate than having to order patient specific devices from external companies.

This is mainly because of the healing and swelling of tissue post-surgery, which can make timing a delicate matter.

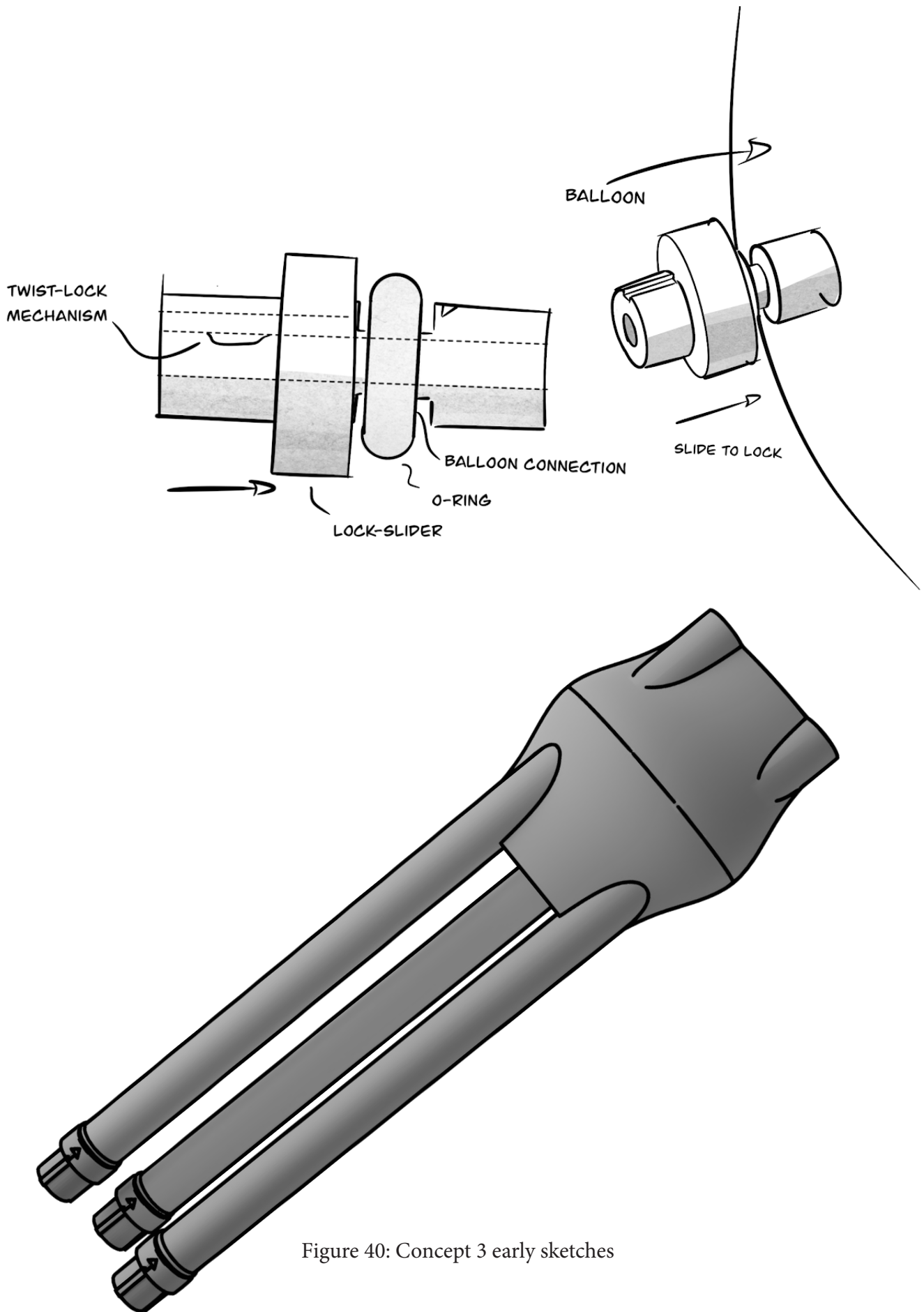


Figure 40: Concept 3 early sketches

Prototyping:

How the third concept was quickly prototyped and how it resulted in new design directions

As for manufacturing methods, a prototype has been cast by 3D-printing the negative shape of the first iteration balloon and casting it with ecoflex 0030 silicone (Appendix F). Insights from this first iteration of prototyping were as follows:

- The catheters being in direct contact with silicone cause too much friction for operation, the catheter paths need to be isolated from the silicone with a different material, therefore double walls or another material will likely be needed. More rigid silicone or latex could suffice.
- To create double-walled balloon structures multiple manufacturing methods are needed, likely using a coating of some sorts with a dipping technique or with overmolding.

The first prototype also raised a productive discussion. New questions arose on the optimal shape of the design, how far the catheters should protrude after the inflatable and putting the connector outside of the nose, which of course is more logical than the first iteration where the connectors were narrowly placed inside the nasal cavity as well.

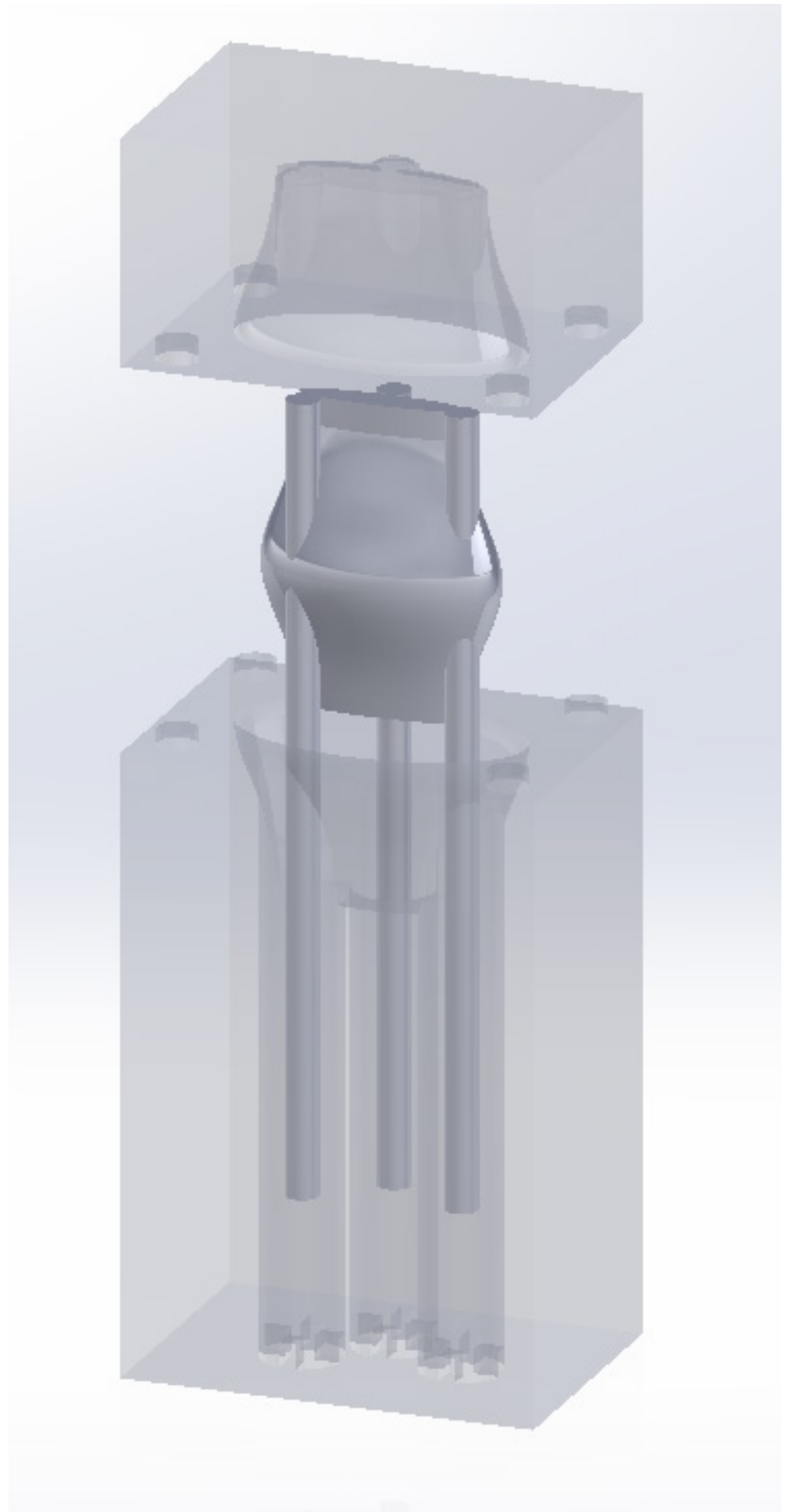


Figure 41: CAD visualisation of the moulding cast and process

Figure 42: The moulding process at the TU Delft emerging materials lab

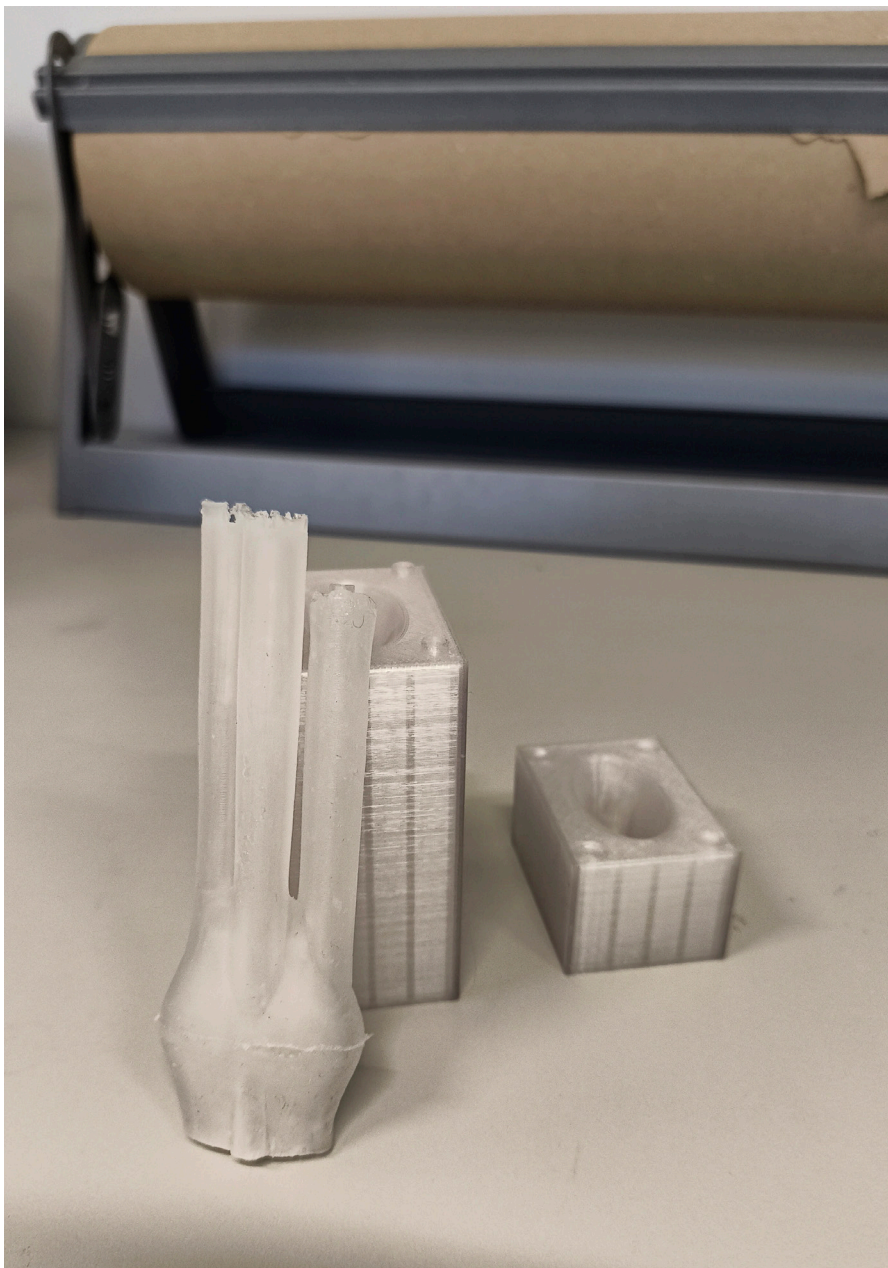


Figure 43: The first result of the moulding process

Meets	Does not meet
High positional precision (patient-specific geometry)	Ease of insertion: No rigid central line to guide insertion (flexible materials might fold or buckle unpredictably)
Potentially excellent pre-determinable catheter positioning	High friction materials could cause struggles with catheter and applicator insertion
Possibly smooth integration with UMC 3D-printing workflows if in-house silicone casting gets MDR-approved	Complex when cavity shape changes between planning, surgery and application (think of healing or swelling tissue)
Geometric stability once deployed	
Custom-balloon manufacturing facilities exist, if design is too complex they could be possibly be founded	

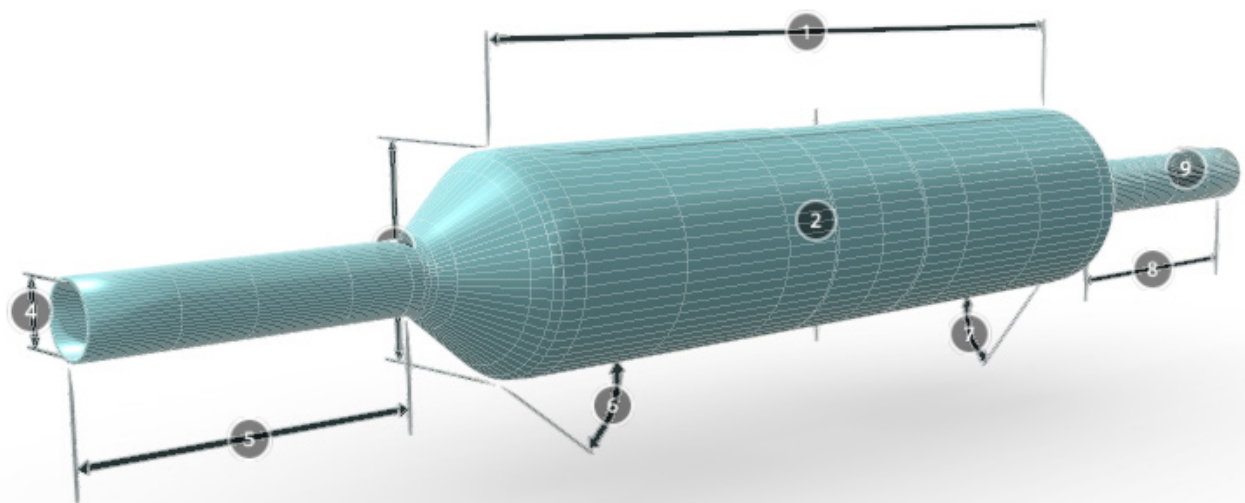


Figure 44: Medical Balloon Designer, n.d.

Technical depth chart:

Activator	The mechanism is actuated by the increase of pressure through a syringe filled with NaCl solution (potentially a more viscous solution could be applied for more reliable shape retention). The pressure can be manually increased or decreased by simply adding or removing solution.
kPa / MPa	The shape of the inflatable is tailored to the patient-specific anatomy, meaning it would likely need less pressure for secure fixation as opposed to Concept 2. The required pressure would however still need to be tested, but is estimated to be in the kPa range
Cycle repeatability	For the cycle repeatability of medical grade silicone, the accuracy of the correlation between volume and expansion pressure needs to be taken into account. This type of silicone has the tendency to act differently the first cycles of inflation than the many cycles after that. This phenomenon is called stress softening, briefly explained by Cooper (n.d.).
Sustainability	Silicones used in the medical industry have a high temperature resistance and can therefore be autoclaved relatively easily. Unfortunately this process is still not widely applied on silicone products, meaning the gross of the products are disposed (Wolf & Stammer, 2024).
Radiation attenuation & absorbtion	With enough pressure, the creases of the outer wall would seamlessly fit onto the tissue of the nasal cavity. When filled with NaCl, the entire planar environment should be homogenous and water equivalent, allowing easy dose calculations.
Sterilisation	As previously mentioned, medical grade silicones are sterilizable through autoclave methods. However, Kuruoğlu et al. (2024) mention the microscopic damage that is done to catheters in sterilization processes. Combining that with the fact that silicone applicators are relatively cheap compared to the costs of sterilization and the accompanied labor, leads to the conclusion that the infrastructure is not completely equipped for sterilizing silicone applicators for multi-use purposes. This concept will therefore be likely assumed as a single-use device with future prospects of becoming multi-use. Especially when accounting for the patient-specific nature of the design.
Maximum strain	Rjc (2025) among with other sources highlight the mechanical proerties of multiple variations of medical grade silicone. All of them show a tensile strength in the 1 to 10MPa range with elongation at break ranging from 100% to 800%. In conclusion, the maximum strain with medical grade silicone should pose no problems for the specific cases of this design.

Table 8: Presumed technical properties of Concept 3

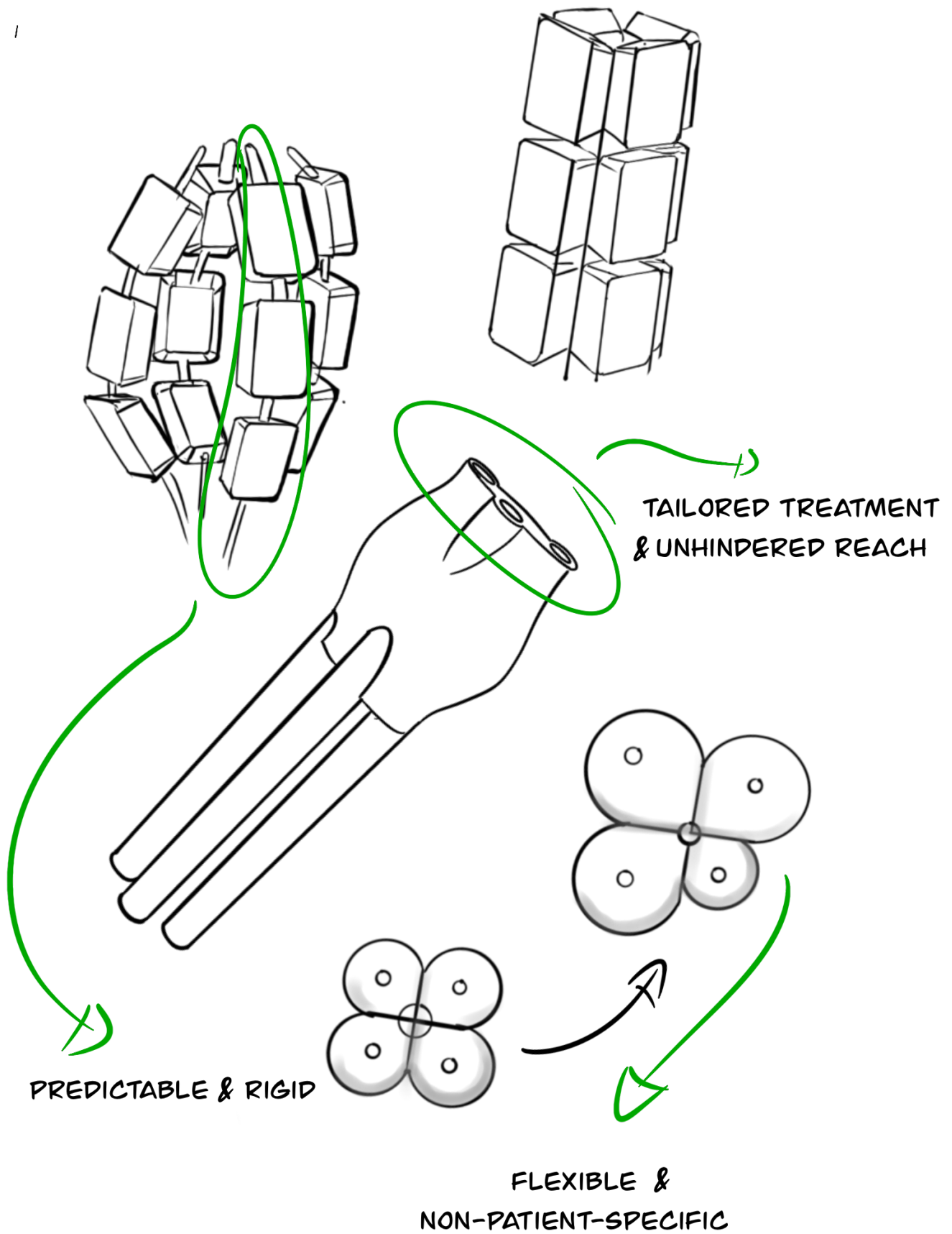


Concept synthesis

From the three concepts presented, multiple positive and negative aspects could be concluded. However, the solutions felt incomplete and not satisfactory for practical applications. Therefore, the positive aspects of the previous concepts on:

- Manufacturing feasibility
- Patient safety
- Radiation applicability
- Predictability of application

Were combined and applied to a newly presented applicator that would prove more feasible for iterations and prototypes to test.



Design concept synthesis:

A small piece of everything

After presenting the three concepts to the staff of the UMC Utrecht, we had a conversation on how realistic the concepts actually were and how we might be able to take all of the plus-points from each concept and convert them into an idea that might be a bit more realistically feasible in use and manufacturing.

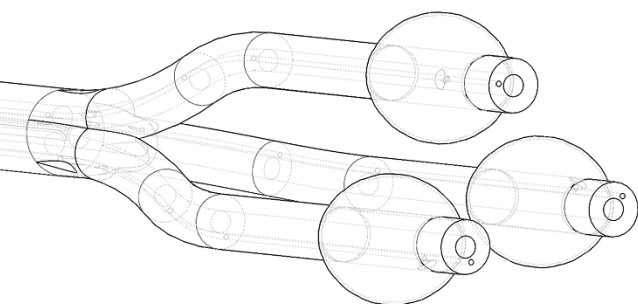


Figure 44: PORGES-14 applicator

For inspiration the PORGES-14 applicator which was previously mentioned was investigated more thoroughly. By taking one to the workshop and fully disassembling it to see all its inner workings and remodeling it on SolidWorks during the disassembly process created new insights. The manufacturing methods of these new insights however were not always fully clear, so the patents of: Di et al. (1973) and Daugherty et al., (1986) were consulted for explanation.

New Design direction

Out of this short research period a new design came forth. The central tube of the design is closely related to the PORGES applicator, of which the architecture can be identified in figures (46,47,48,49).

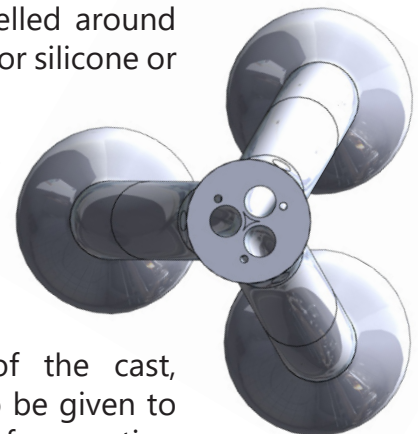


The design, inspired by the insights, splits into multiple directions as can be seen in figure (46) and makes use of the Di et al. (1973) method of applying balloons by melting/glueing thin silicone shrink sleeves around the inflatable area. These parts are inflated by a small hole connecting the airflow vents to the balloon cavity as per the patent description.

Manufacturing assumptions

The manufacturing method would consist mostly of that of the PORGES applicator. Firstly the inner channels are modelled in the configuration matching the amount of catheters needed. Then the outer lining of the overall applicator is modelled around it and combined in a cast for silicone or latex molding.

Figure 46: A cross-section of the stem of the redesigned integrated applicator



During the modelling of the cast, careful attention needs to be given to the angle and direction of separation between the cast and the final product. Fortunately the silicone/latex is rather flexible, allowing steeper release angles on the cast.

Casting principles

However, one of the more significant struggles with placement that remains is keeping the balloons at the same depth in the nasal cavity opposed to each other. As the segment of the applicator with the larger cross-section fills almost the entire diameter of the nostril entrance, placement with an endoscope is presumed difficult and maybe impossible.

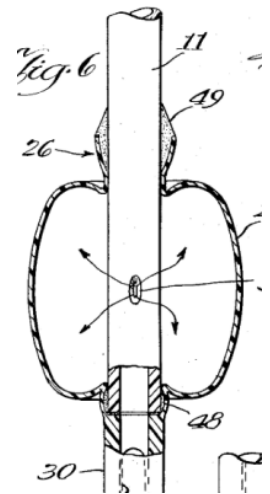


Figure 45: Di et al. (1973)

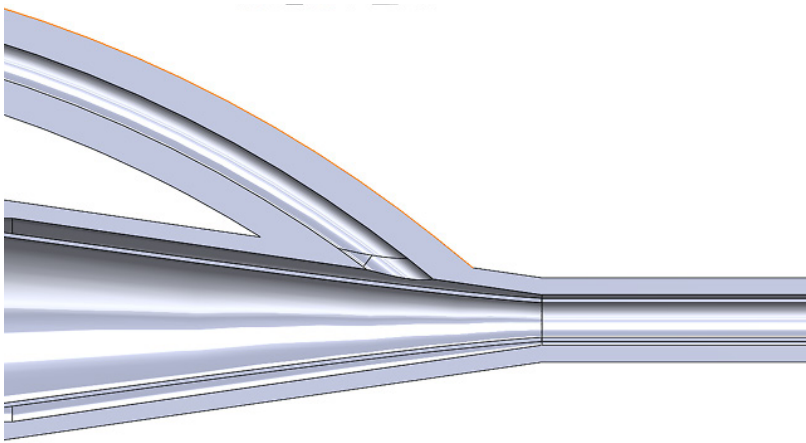


Figure 47: A re-created cross-section of the inflation-duct of the PORGES -14 applicator

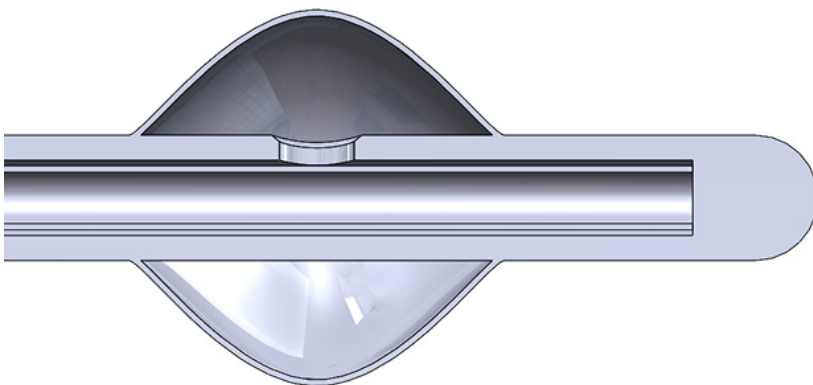


Figure 48: A re-created cross-section of the inflatable balloon of the PORGES -14 applicator



Figure 49: A re-created cross-section of the PORGES -14 applicator

Multiple solutions for this problem are proposed:

1. The same principle of concept 2 could be applied, where flanges are made on the individual separation branches of the design which are connected to a central 3D printed connector piece, keeping them in the same level of depth in the nasal cavity whilst also keeping them at a predictable distance from each other before inflation.
2. We could also take inspiration from the principles used in concept 1, where Nitinol wires can be used to both stabilise the orientation and depth of the individual branches and balloons.

A second application of this wire could be its shape morphing effect (SME) which could help navigate the catheter to their preferred location by being trained in a certain orientation. However, this would add another step to the manufacturing process of the UMC's in-house development.

A third application of the SME could be its shrinking properties. A stretched wire of Nitinol, when heated, compresses back to its pre-stressed length. Theoretically this stretch could be around 6 to 8% of the original length of the wire (however, this is highly dependent on the quality of the wire and its diameter). When allowing a wire to shrink inside of the applicator on an asymmetrical plane, we would be able to create curvatures in the catheter paths.

This second principle is tested in the lab at the TU Delft with a .5mm Nitinol wire with a Aft of around 50 degrees Celsius. By pre-stressing it and afterwards applying electricity to the wire (allowing it to heat up due to resistance inefficiencies), the wire shrinks.

Putting the wire through a silicone tube with three (non-centered) paths we can see that a curvature starts to appear in the tube. (figure 51)

For predictable numbers and applications more (official) testing needs to be done, but in it's premise this principle would mean the application of Nitinol in UMC's workflow without having to train the material for each patient specifically.



Figure 50: The pre-tensing setup for Nitinol testing

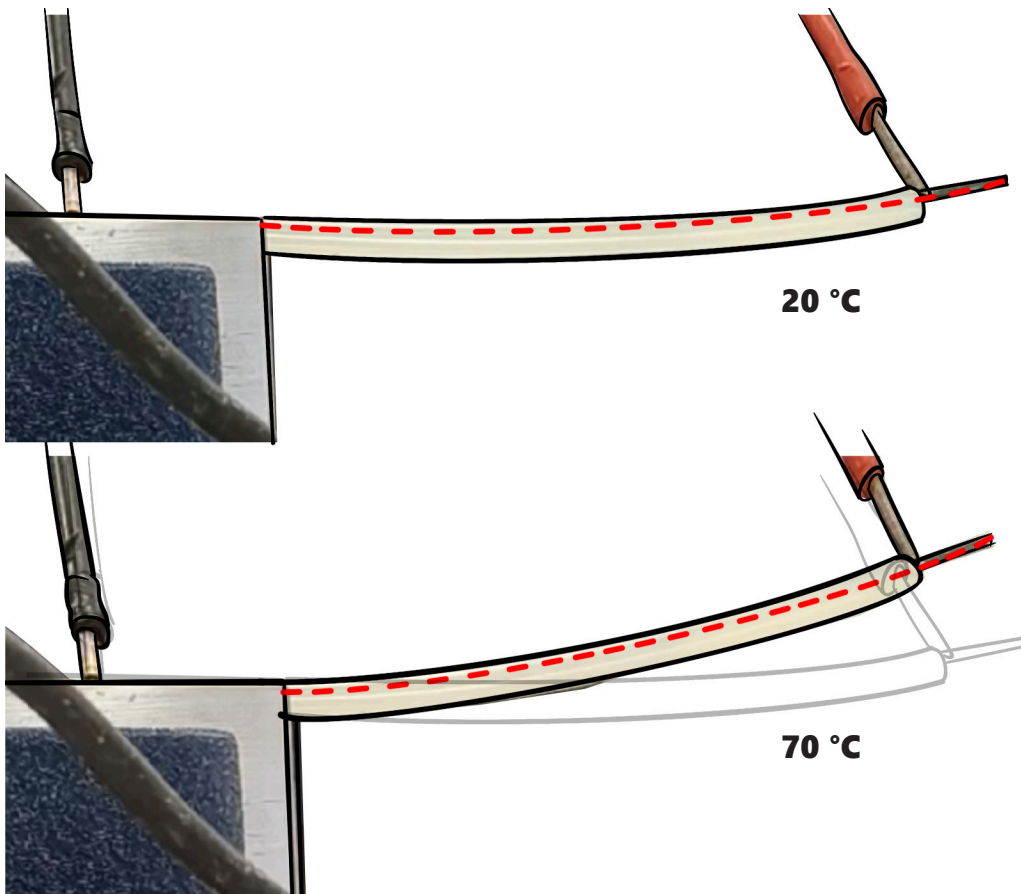
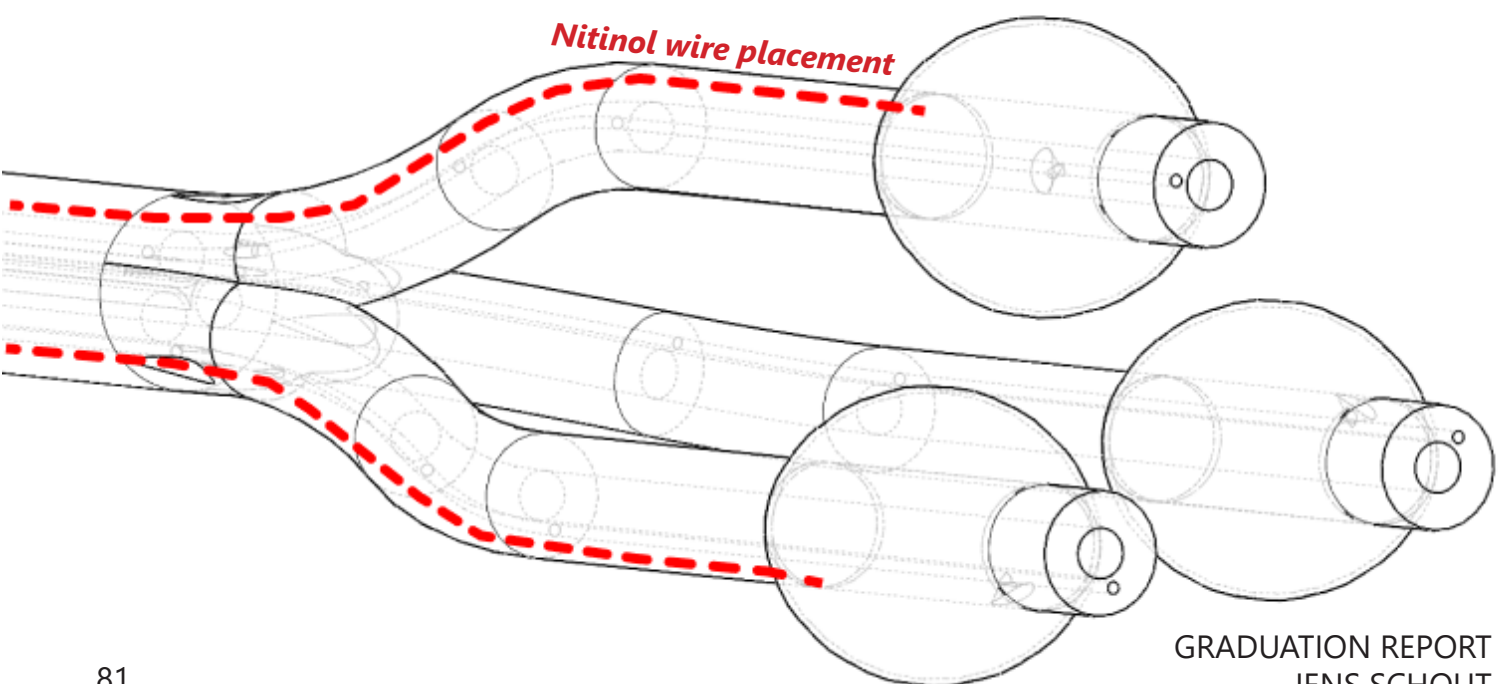


Figure 51: The first outcome of quick pre-tensing nitinol tests

By combining the most promising aspects of the previous concepts, this idea would:

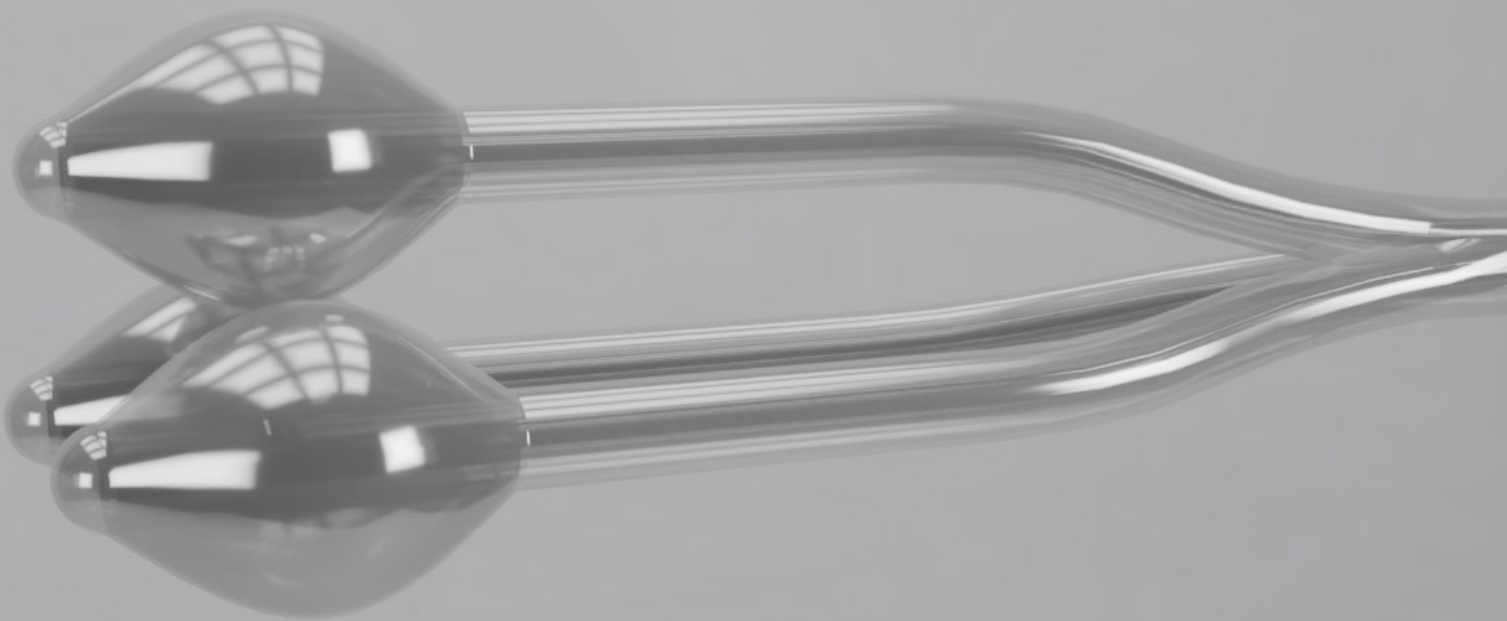
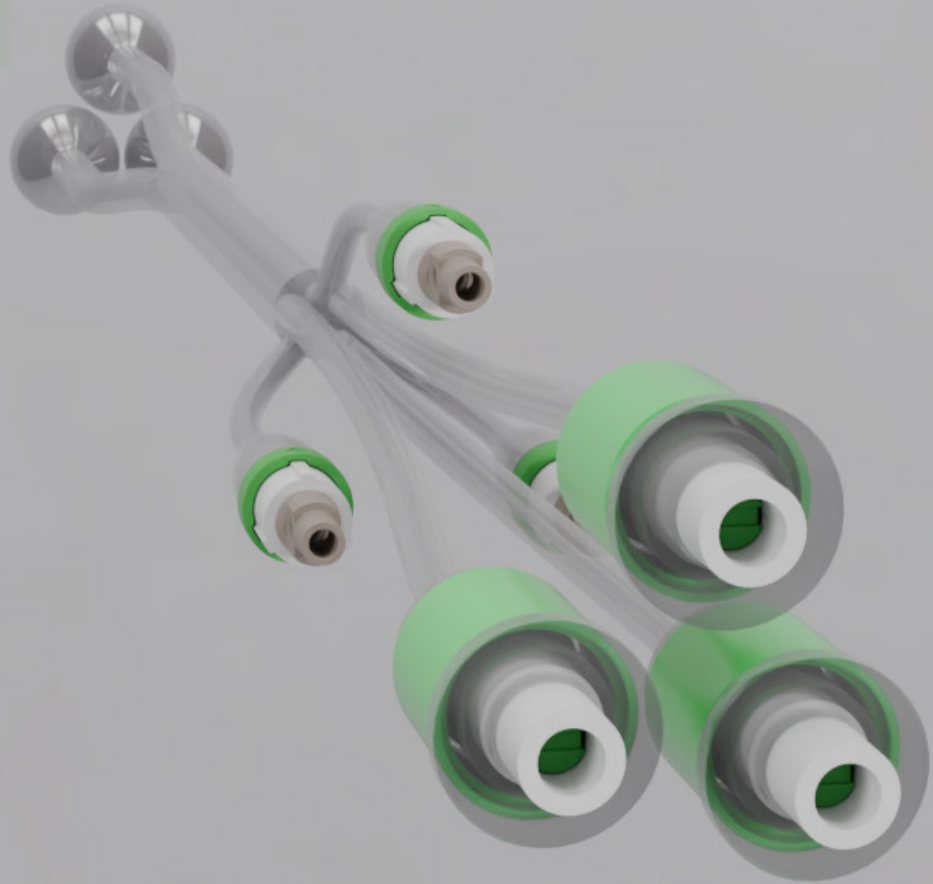
Meets	Partially meets	Does not meet
High deformation ratio	Radiation stability/predictability: Nitinol presence has unclear effects on radiation attenuation/absorption	Fully patient-specific geometry: Can only be adapted to a certain extent
Local structural stability	Manufacturability: Manufacturing process needs to be tested for feasibility within current facilities	Single-step insertion and deployment: Probably needs multiple cycles of imaging and position tweaking before optimal position is found (live imaging is an option at UMC-U)
A-traumatic insertion due to soft outer material (no exposed metals or catheters)	Sterilisation: Would likely function in the same fashion as the PORGES applicators, but should be tested	
Adaptable to various geometries		
Reversible removal		

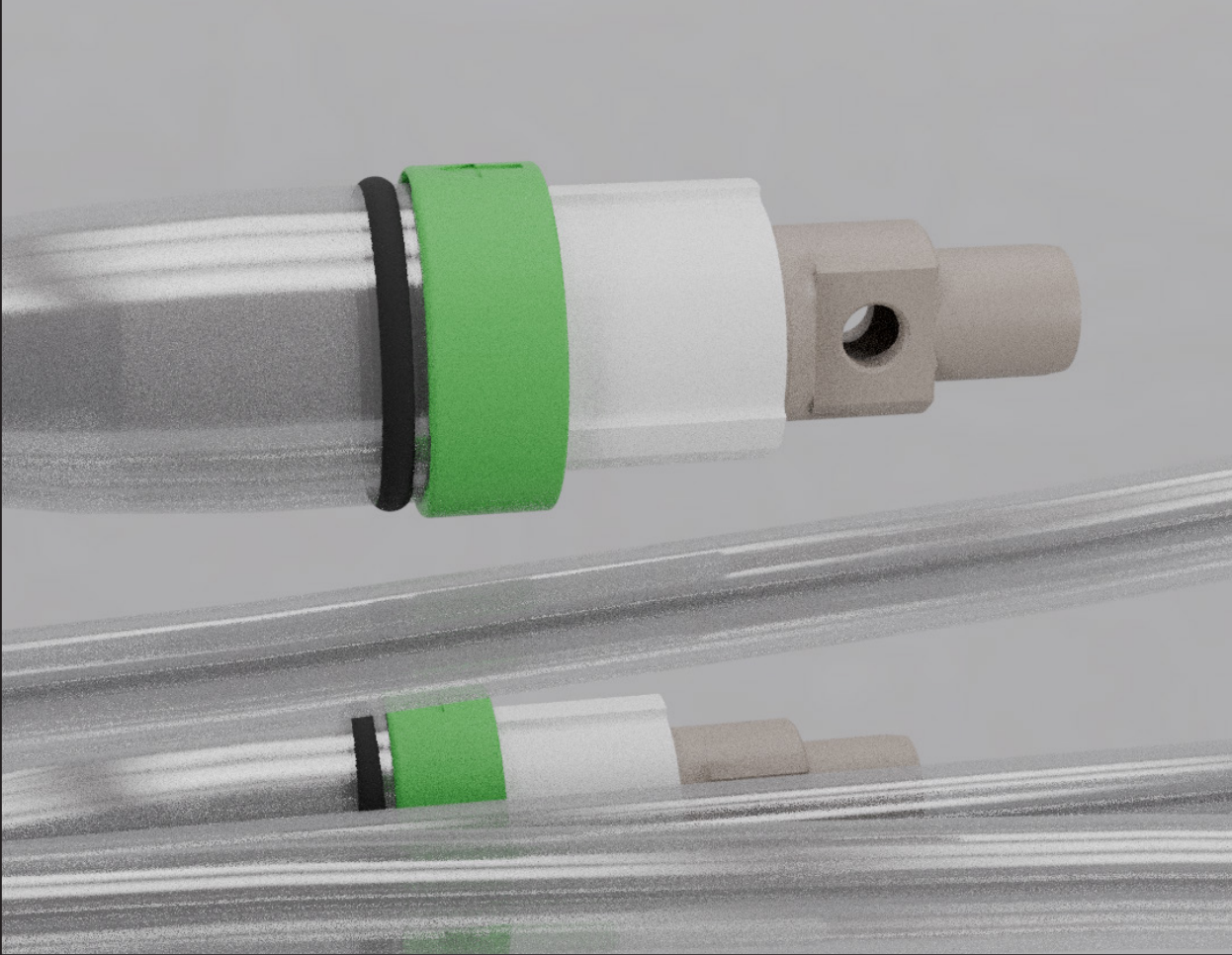
Figure 52: A quick sketch of Nitinol placement in the redesign



ADAPT

Version 1





Design features:

How does the design concept function?

In practice this design concept would function as follows:

1. The patient would enter the hospital and be scanned for tumor size, location and severity.
2. The hospital staff (radiation oncologists) plan treatment based on GTV and presence of OARs around the GTV. Out of this radiation plan, optimal amount of catheters and orientation of said catheters becomes clear.
3. Based on the amount of catheters needed, a configuration of the ADAPT applicator is chosen to match the oncologists plans.
4. The applicator can now be assembled. Out of the package, the applicator would have the inflation connectors already assembled. However, the lock-insert connectors need to be assembled manually if they are made in-house. The catheter guide tubes are cut to the appropriate length and the connectors are put into the tubes until the marked end. The connectors can be locked in place with the rubber ring and the slide lock over it.
5. The catheters can be fit inside the applicator. The catheters should be pushed up until they reach the closed end of the applicator. A lock-insert can be fit on the open end of the catheter and locked onto the connector piece, applied in step 4, to lock the catheter in place.

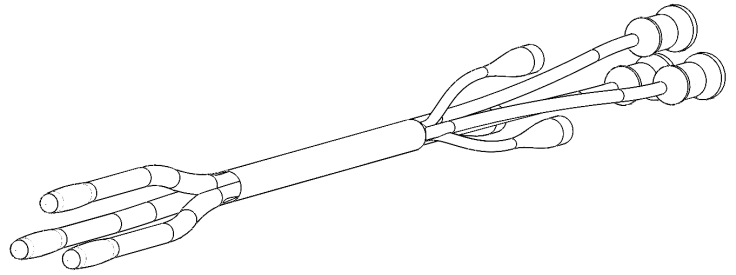


Figure 53: A sketch of the silicone body of the concept

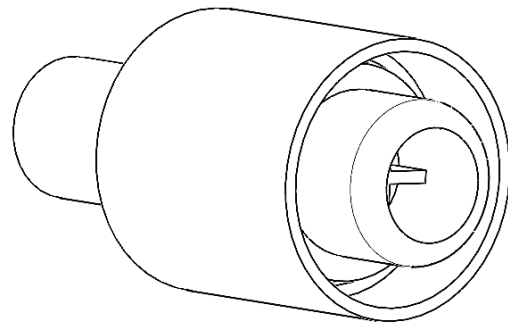


Figure 54: A sketch of the inflation valve

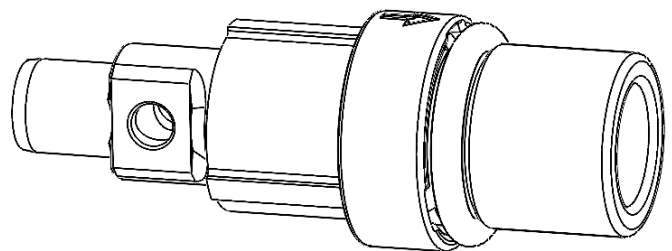


Figure 55a: A sketch of the connector piece (unlocked)

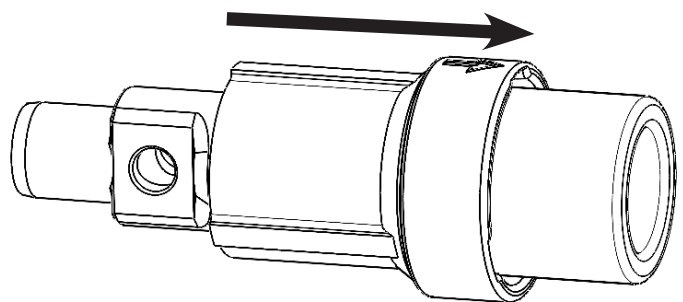


Figure 55b: A sketch of the connector piece (locked)

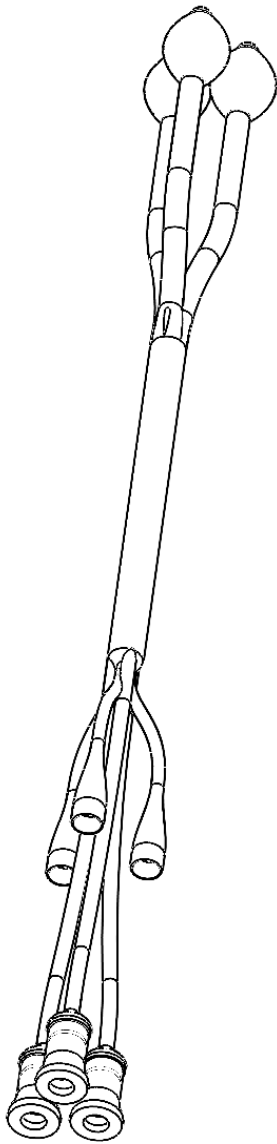


Figure 56: A sketch of the redesigned concept (inflated)

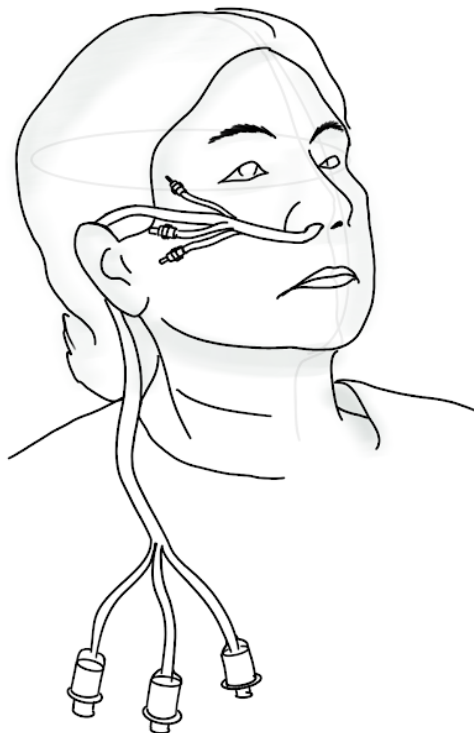


Figure 57: A sketch of the concept on a patient

6. Once the entire applicator has been assembled, it can be fit on the patient. With copper wiring through the catheters, the surgical staff is able to image the catheter orientation inside of the patient and match those images to the original plans. This imaging process can be done with MRI and CT, however, changing the orientation of the device can not be done. There are scanners with live-video feed which will need to be used for most efficient placement adjustments of the catheters.
7. The catheters are oriented by inflating the balloons to respective volumes, because the catheter is lined through the center of each balloon, inflating the balloon more would result in the catheter being placed farther away from the others.
8. After all balloons have been inflated to the orientation as it was planned (with an error margin of maximum 3%). The setup is ready for radiation cycles.
9. As the pressure in the balloons is presumed to release a bit, it is important to regularly check the inflated pressure or the catheter paths to ensure safe PTV coverage.
10. OPTIONAL, add pre-tensing of Nitinol and assembly of Nitinol



Prototyping

Creating (scaled) prototypes to test the design attributes and the design's manufacturing feasibility. By testing the different aspects of the concept, the design features can be changed according to the results before the entire manufacturing process of the product is determined. This way we won't run into issues with a pre-determined manufacturing plan that could interfere with optimizing design decisions.

Because the design almost solely relies on assumptions at this stage, the parts still relying on these assumptions are now tried in a lower fidelity to test their effectiveness and to hopefully prove or disprove the assumptions made in previous stages.

Vizcom generated image
for context placement of
the applicator



The aim of this prototyping phase is to challenge the following assumptions:

- We can replicate the manufacturing process of coloplast's PORGES applicators to create custom inflatable catheter applicators.
- We can create a (scaled) low fidelity prototype to test size constraints, placement and fixation constraints and treatment constraints
- We are able to predict the catheter paths, to optimise treatment plans for multiple (fictional) CTV's.

Prototyping:

How multiple aspects of the design would be made for future testing

Casting process

At the first attempt of prototyping the manufacturing plans, according to the previously mentioned patents (Di et al. (1973)) were followed to see if the product was already manufacturable with current means on a 1:1 scale.

The current manufacturing method, followed the same procedure as done with previous concept 3's manufacturing method. Appendix B

Results

The results of the first iteration, showed that the scale of the outer dimensions of the product is likely correct, however the internal details such as the inflation vents were not accurate enough.

This was mainly due to 3D-printing constraints and inaccuracies. Multiple printing orientations with and without support structures were tried. Next to that, the silicones used were likely too flexible and not sturdy enough for the delicate structures of a 1:1 scale.



Figure 58: Repeating the silicone casting procedure from concept 3, with the new design



Figure 59: A photo of the silicone bubbles in the vacuum chamber



Figure 60a: A photo of the first pieces of the redesign out of their moulds. With a 6-fr catheter running through

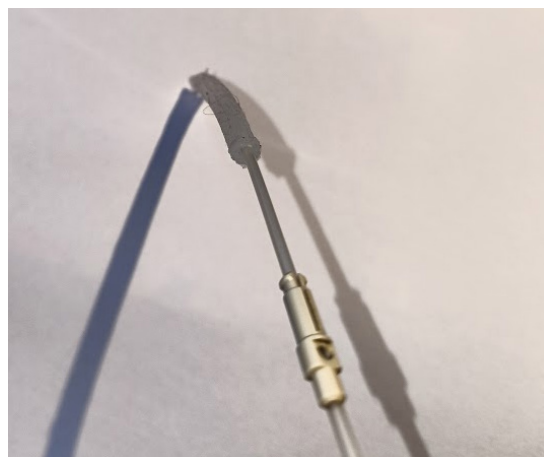


Figure 60b: A photo of the first pieces of the redesign out of their moulds. With a 6-fr catheter running through

Figures 62 and 63 show the difference in inflation shape and bonding seams of both manufacturing methods. Both examples are manufactured by Coloplast.



A diagram comparing two types of cables. On the left, a cable is shown with a prominent horizontal seam. An arrow points from the text 'LARGE SEAM' to this seam. On the right, a cable is shown without any visible seams. An arrow points from the text 'SEAMLESS' to this cable.

GRADUATION REPORT
JENS SCHOUT

Prototyping: Accuracy versus testing capabilities

A dilemma between recreating the concept visually versus the ability to test the functions of the designed concept as accurately as possible

Scaled iterations

Because a 1:1 prototype seemed infeasible with the current means of manufacturing, a second iteration was done at a 2:1 scale.

At this scale, the initial inner structure of the concept could be realised. However, after post processing (i.e. removing excess silicone and washing), the inner structure still seemed to fragile for effective testing.

For the sake of creating a prototype, giving the impression of what the final concept would entail. The 2:1 scale prototype was finished with a segment of a regular balloon over the end of the three-way split. A short test, trying to inflate the balloon-end however proved the silicone to be too flexible and the wall between the catheter path and the air duct being too thin.



Figure 64: A photo of the quality of the scaled redesign

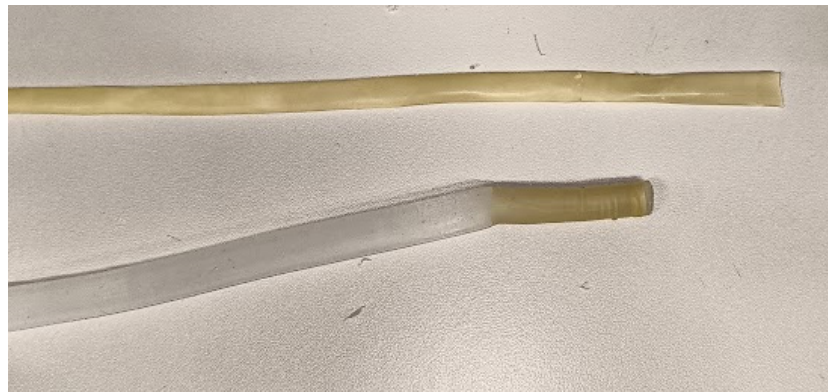
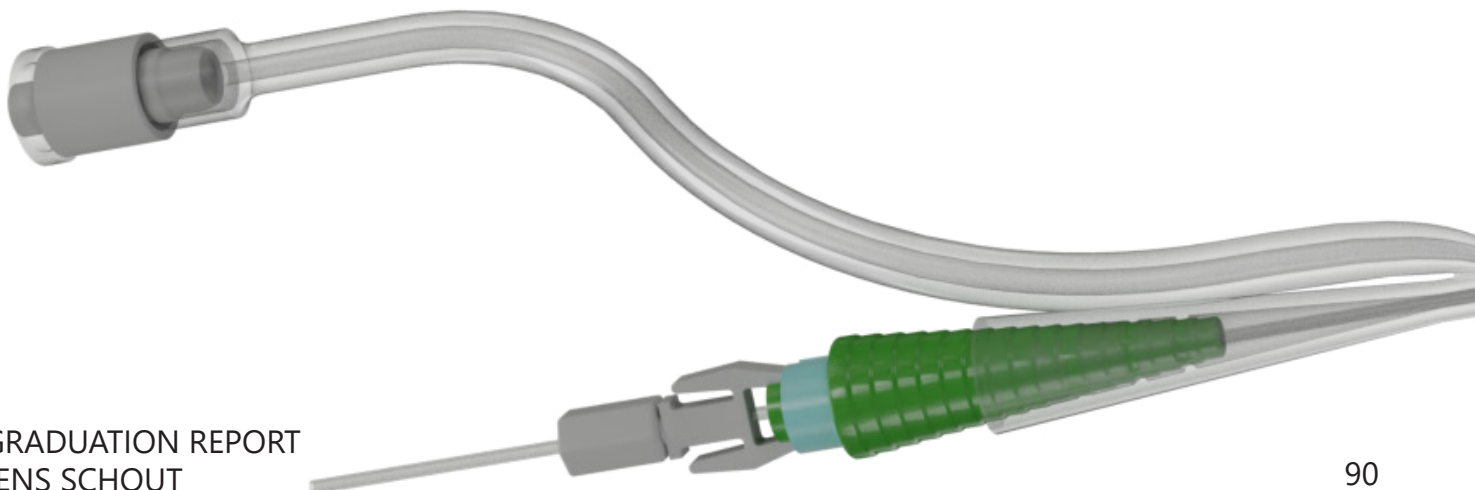


Figure 65: One of the branches of the redesign with a balloon fitted over the inflatable area





Resin printing

A second method was tried with resin-printing the prototype out of flexible material. This iteration was done with the use of (SLA 80A) a flexible resin in the FormLabs printers provided by the UMC-Utrecht.

The printing accuracy of the FormLabs printers should outclass the accuracy of Bambulab FDM printers by using UV-lasers to solidify a resin layer, by layer. Limiting the mechanical constraints to purely the material and the designs. Furthermore, we would remove the step of casting the material, likely reducing the inaccuracies of the prototype.

This material however also proved too brittle for proper fabrication of a working prototype (figure 66).

Adapting design direction

Finally, a decision was made to use the existing PORGES applicators in three-fold to test the technical usability of the concept and to (dis-)prove the assumption of being able to navigate the catheter paths by inflating the balloons at different volumes.



Figure 66: The FormLabs flexible 3D-printed segments of the redesign

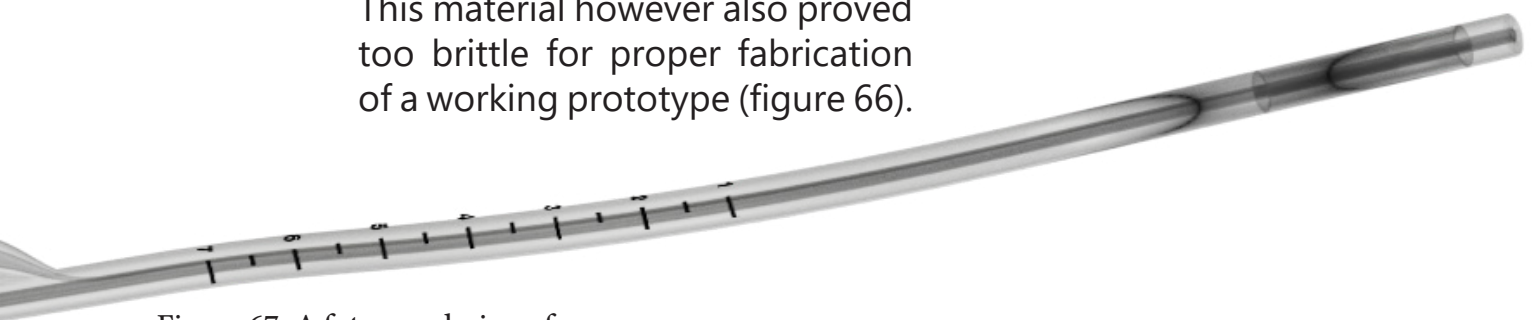


Figure 67: A future redesign of the PORGES applicator (4-fr)

Prototyping: 6-french vs 4-french, compromising size and functionality

How the different sizes of catheters would influence the functional and safety aspects of the designed concept

Redesigning existing products

At first glance, the PORGES-14 applicator with a diameter of 4.7mm seemed to large to for applying three or more applicators in the nostril. Measurements on various CT scans ranged from 8 to 10 mm, leading to the assumption the PORGES-14 would be to large.

One way to overcome this issue would be to use a smaller applicator, such as the PORGES-12 which would not be able to house a 6-french catheter, but could directly house a 4-french catheter.

The safety of not having a 6-french catheter to pull the 4-french out of, would have to be tested as the friction of a PORGES applicator is substantially larger. Next to that, the fixation mechanism needs to be changed conform the 4-french locks. (Figure 68)

Size compromises based on assumptions

A redesign is made, of the PORGES-12 applicator. The length of the applicator is shortened from 400mm to 200mm to be able to house the shorter catheters, and to allow the entrance of the catheters in the applicators to be relatively close to the nostrils of the patient.

Furthermore, the aforementioned inflation ducts are lengthened to a point where they can be easily reached by physicians if inflation or deflation needs to happen during the treatment period. The added length also allows the patient to hang the applicator around the ear, to improve comfort with eating and other daily activities.

One thing to note with the change to just a 4-french catheter is that extensive emergency testing needs to be done to construct safety clearance.

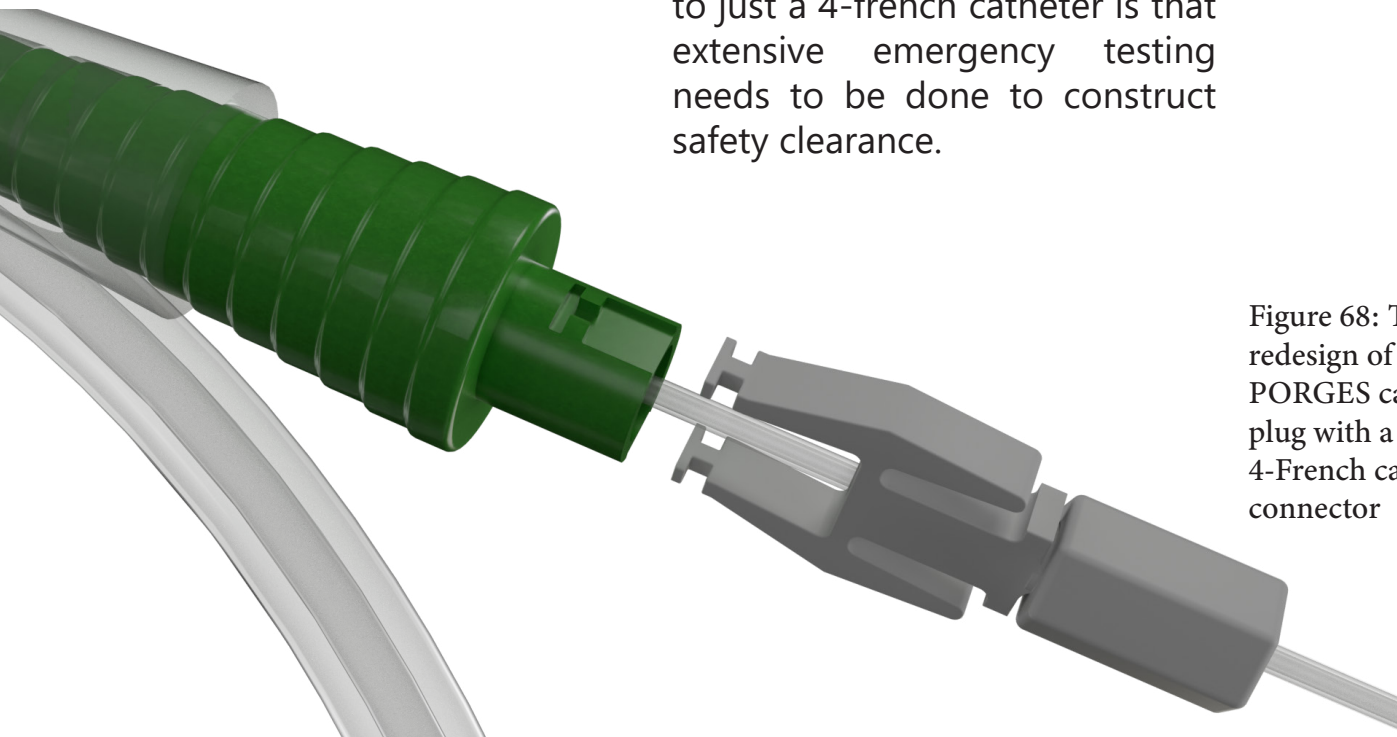


Figure 68: The redesign of a PORGES catheter plug with a 4-French catheter connector

When using 6-french with 4-french catheters, the existing MDR clearance can be used, speeding up the innovation process.

This was the original reasoning behind the 6-french catheter being a constraint in the list of requirements.

Challenging the assumptions

If during tests with phantom 3D prints (a replica of an anonymized patient in 3D-printed material) the conclusion follows the intuitive thought of 6-french being too large, the project will have to continue with just 4-french catheters. Otherwise 6-french (and thus PORGES-14 sizes) would still be the preferred size of applicator.

Figure 69: The redesign with a locking ring to keep the connector secure

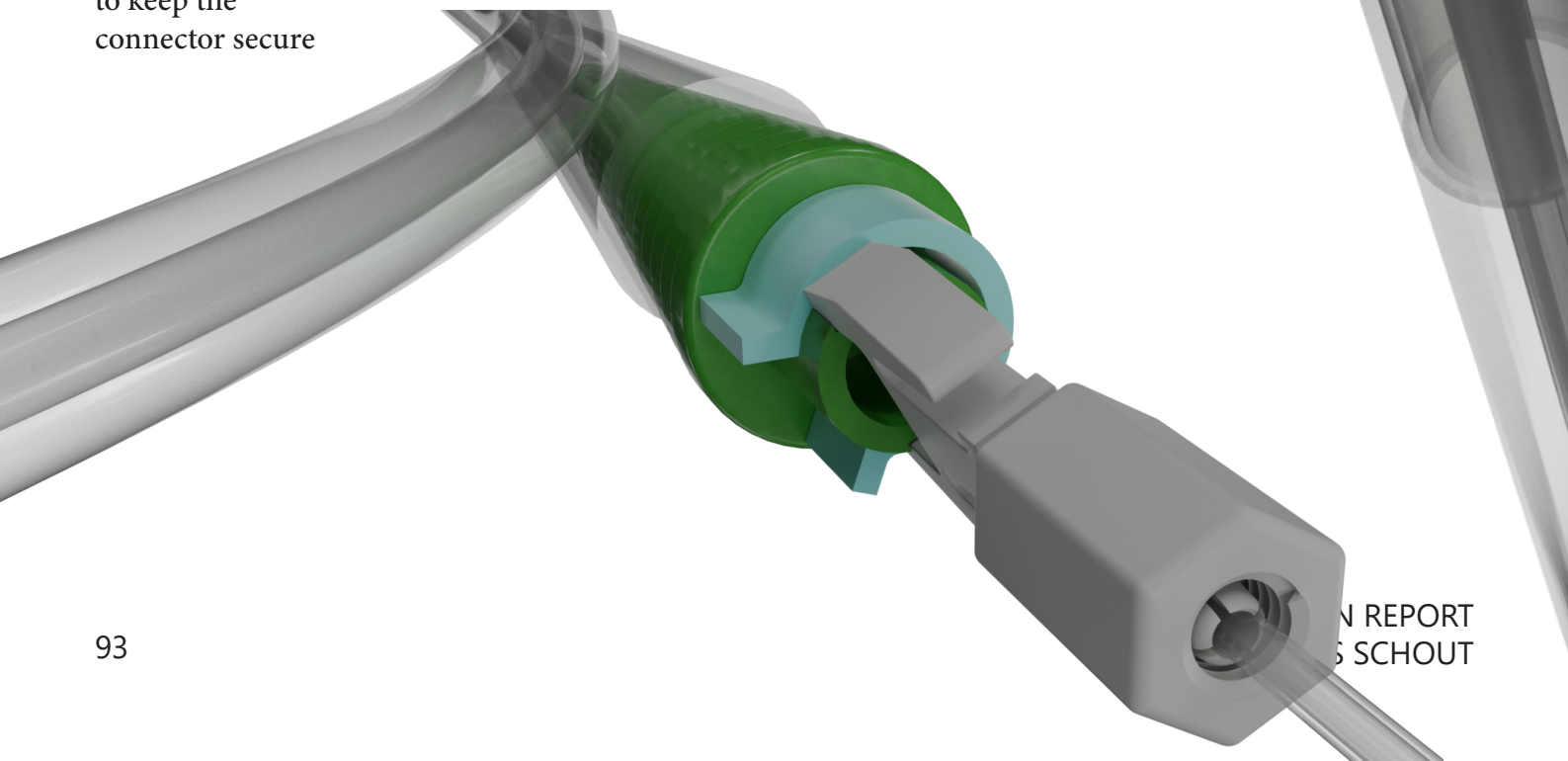
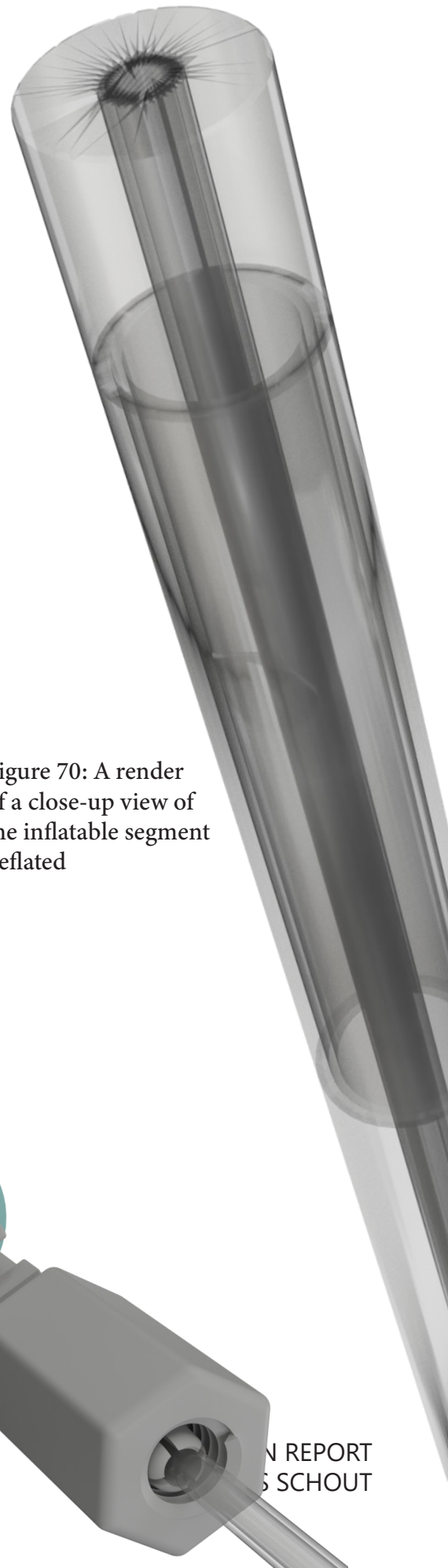


Figure 70: A render of a close-up view of the inflatable segment deflated



Prototyping: Integrated design vs individual redesigns

How the integrated concept would fair against the redesign of existing applicators for added functionality

Integrated catheter guiding device

The original concept relied on the principle of the entire applicator being a single integrated device. This was mainly done out of the belief that an integrated system would have a smaller relative diameter to three single applicators as redundant wall thicknesses could be avoided.

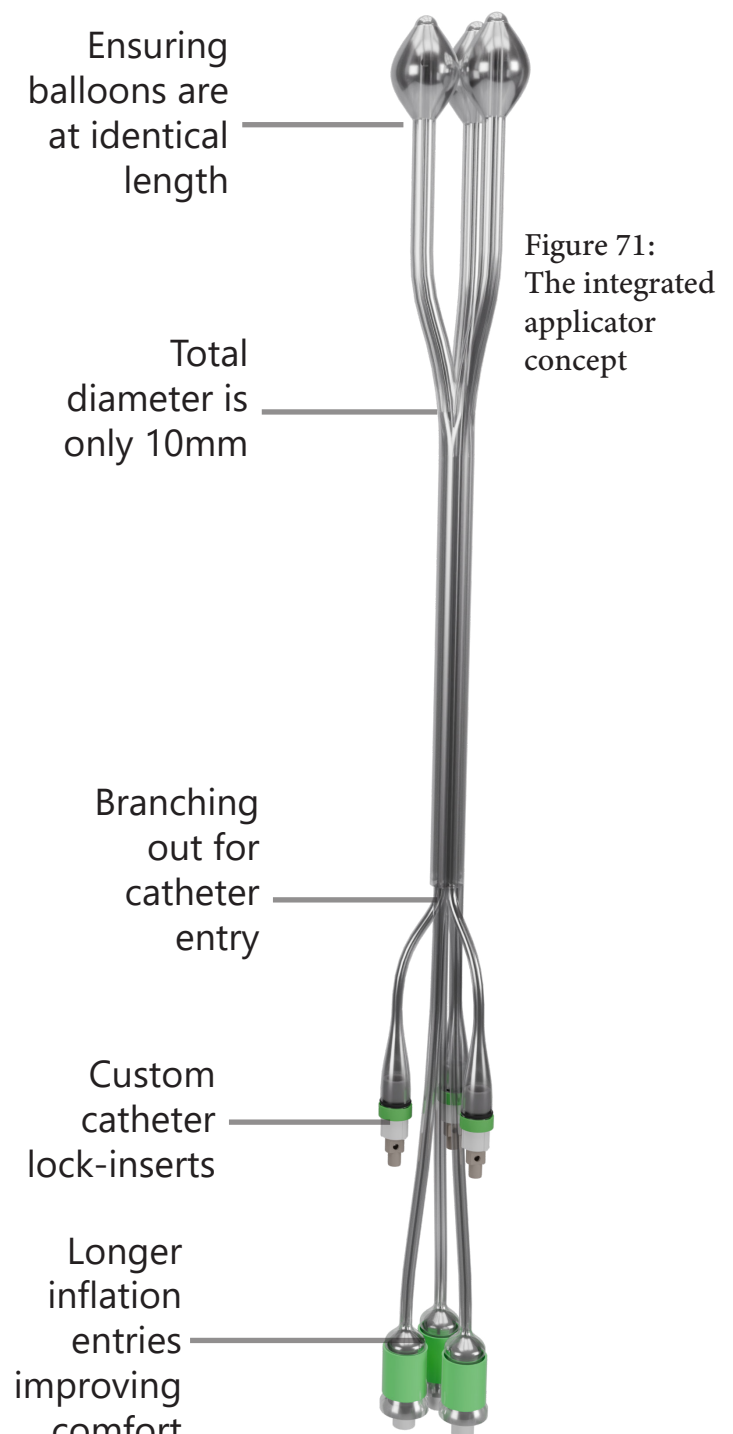
A smaller total diameter would increase the likelihood of successful deployment of an endoscope next to the applicator, probably allowing easier application.

A negative aspect of an integrated applicator would be the fact that the orientation of the three 'branches' would be harder to predict, as their insertion length is fixed from the y-split. This could result in weird bends and thus unpredictable angles of approach for the catheter paths.

Individual catheters

The insertion length of individual applicators could give an advantage in this matter, as the length could be determined per individual applicator. This would allow the physicians to be able to predict the shallowest curve / shortest path which would make predicting the catheter orientation easier. Furthermore, with individual applicators, measurement markings and indicators for inflators corresponding to balloons are easier to facilitate and navigate in reference to each other.

Mainly due to the non-patient specific nature of individual applicators. Due to these reasons, the integrated design concept will be let go of for the time being and the project will continue with an individual applicator design structure.



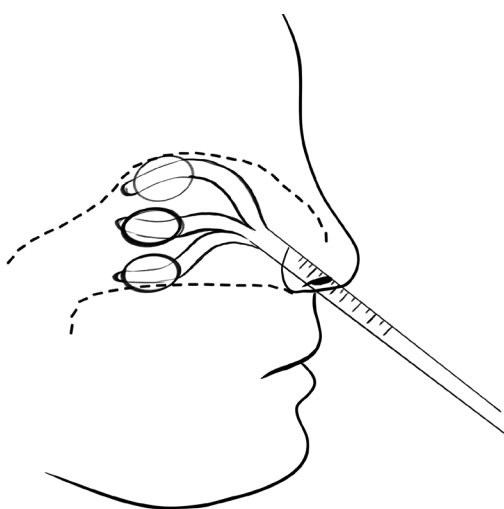
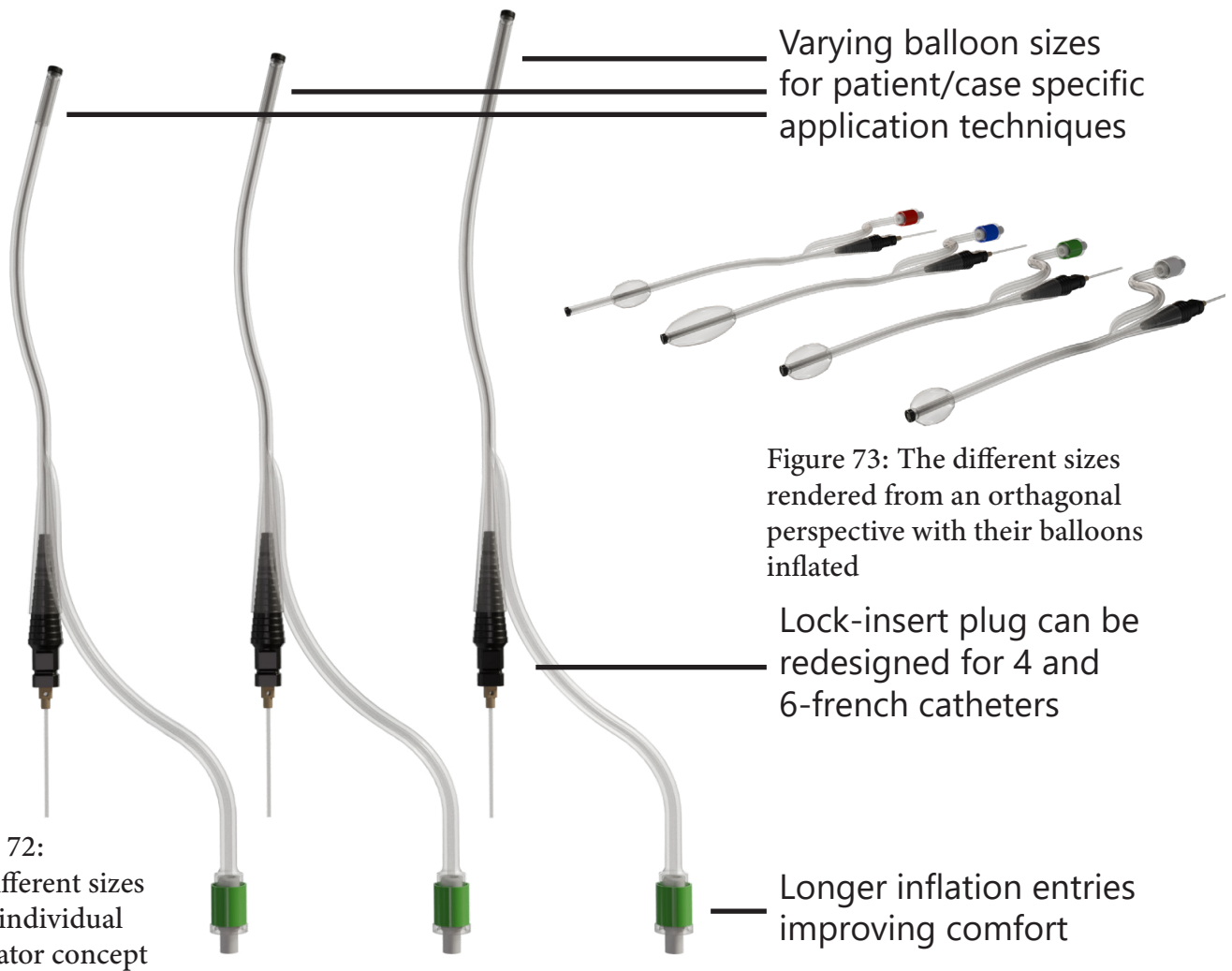


Figure 74a: A sketch of the integrated design, with presumably less predictable catheter paths

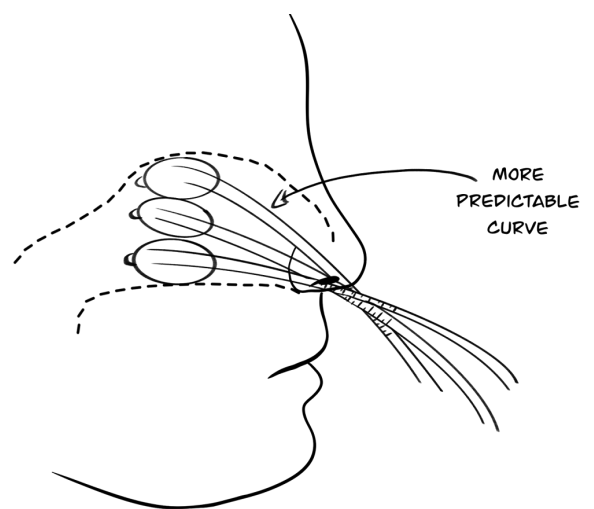


Figure 74b: A sketch of the individual design, with presumably more predictable catheter paths

Prototyping: Designing a new system

Everything that is theoretically needed for a 10 day treatment period

To overcome the issue of unpredictability with an integrated applicator design, a physical prototype would be needed to test with. This would also allow testing with Nitinol guiding wires. However, with the timeframe given for this project, this is unfeasible. Next to that the adoption of individual applicators is easier to test and will lead to earlier proof-of-concept results, leaving the option of an integrated design with guidewires for a possible recommendation of further development.

To fully adopt the new system of individual applicators, the PORGES applicator is redesigned according to the changes in the previous paragraph.

The applicators would also need to be fixed at the entryway of the nose (nostrils) to ensure their insertion length remains constant. At the first iteration a new nose mold conform the design requirements of the original nose-molds (Current brachytherapy specialism) is designed (figure 75). However, after printing the mold and conversing with the medical staff at UMC, we found that the application with an endoscope would be close to impossible if the nose-mould was applied before the applicators would be inserted.

Therefore a new mold was designed that would be placed onto the patient after the applicators were placed (figure 76)

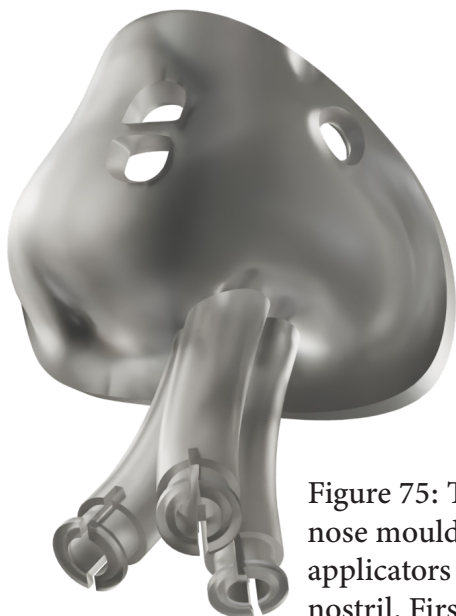


Figure 75: The redesigned nose moulds that keep the applicators fixed from the nostril. First iteration



Figure 76: The redesigned nose moulds that keep the applicators fixed from the nostril. Second iteration

Figure 78: The total setup of the system with: The redesigned mould, the redesigned applicators and lock-inserts on a phantom head

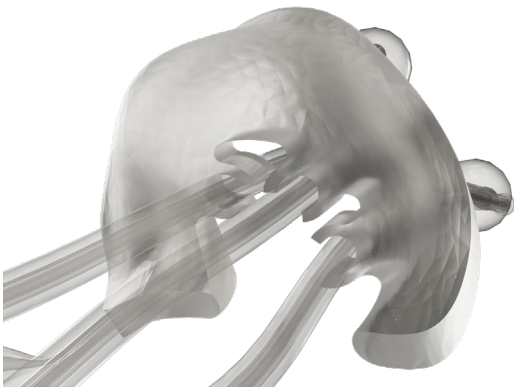
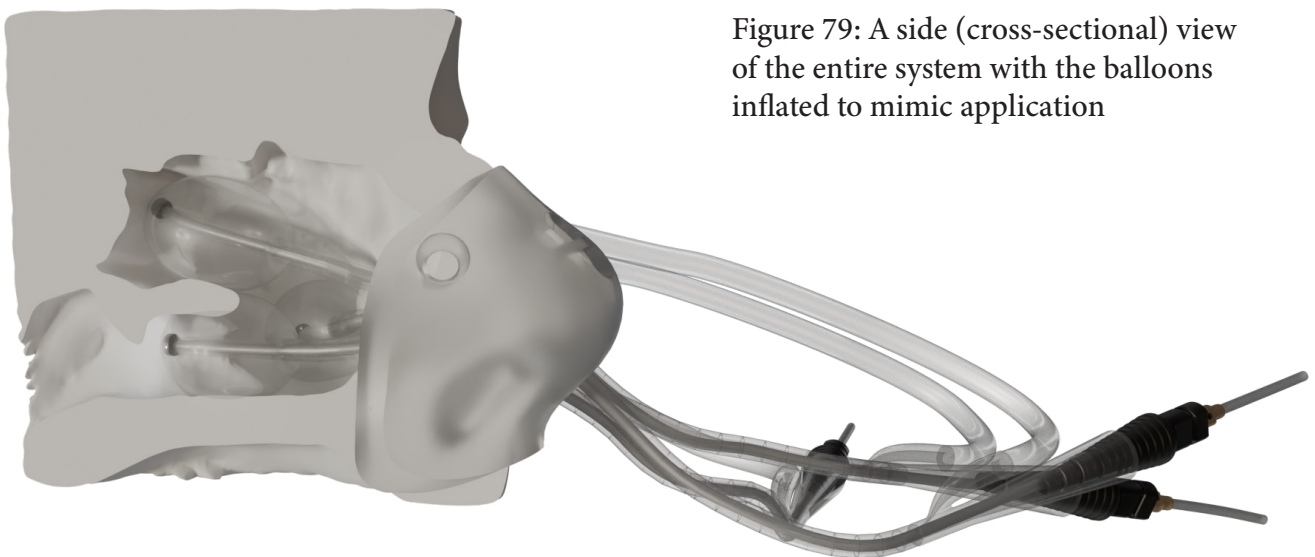


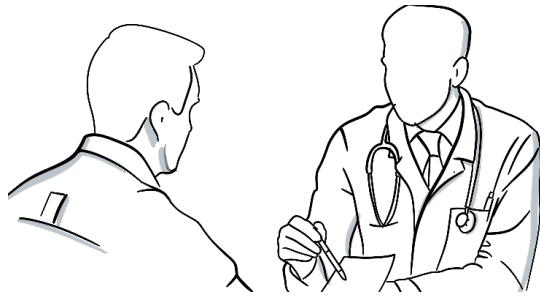
Figure 77: The new applicator with catheters

Figure 79: A side (cross-sectional) view of the entire system with the balloons inflated to mimic application

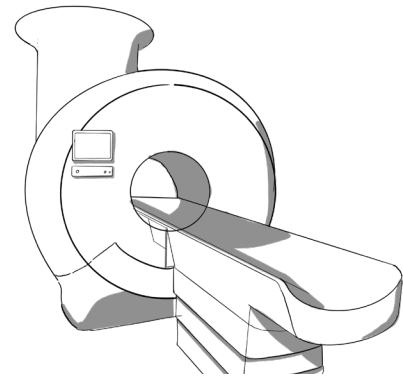


Prototyping: Journey mapping the new system

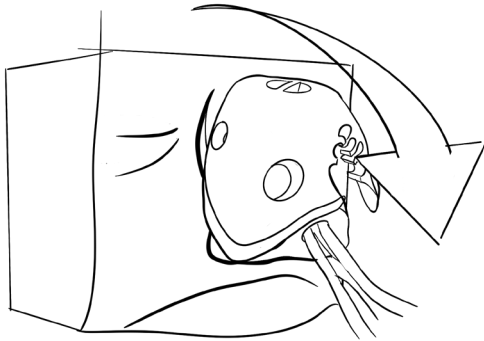
To give a brief overview of how the redesigned applicators and fixation mold would be applied in practise.



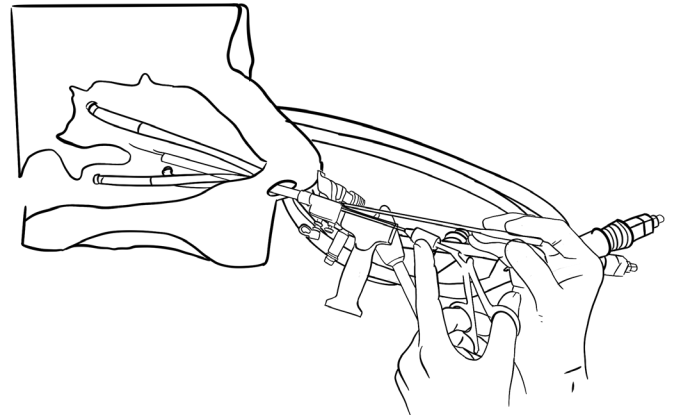
1. Consult



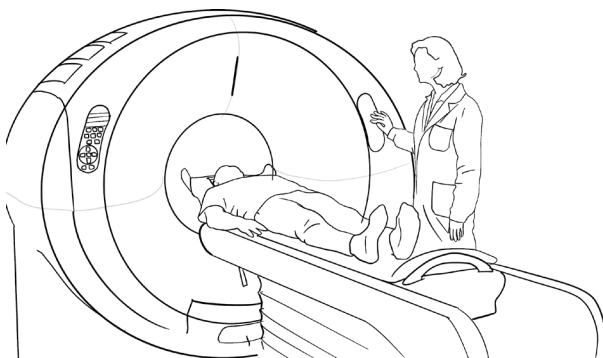
2. CT-scans



8. Fixating applicators with redesigned mold



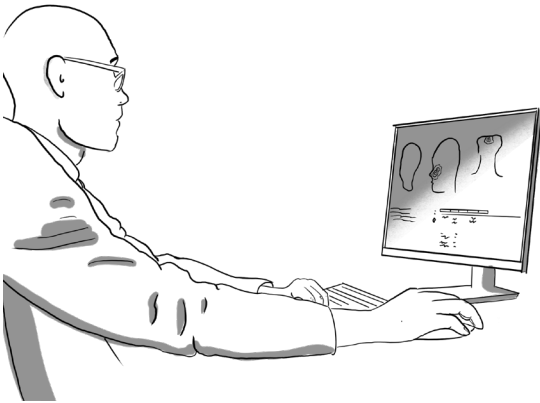
7. (Surgical) Placement of applicators



9. CT-scans & matching original planning to physical orientation



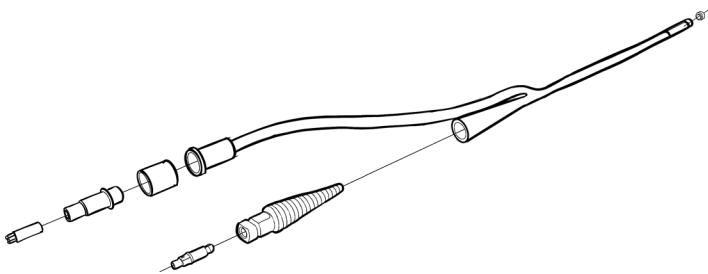
10. Re-planning based on physical catheter orientation



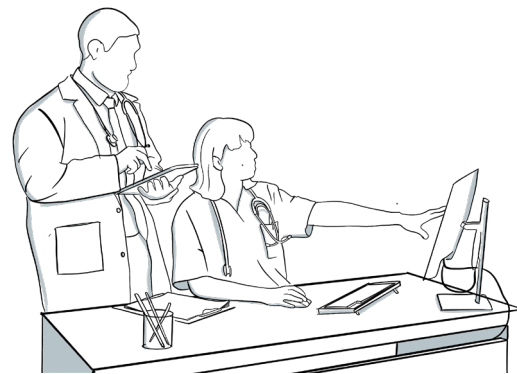
3. Pre-planning



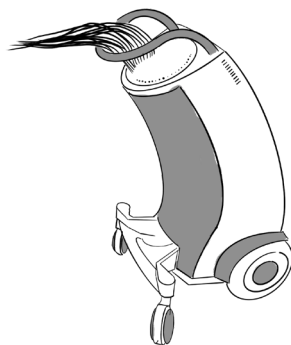
4. Removing GTV and opening accessways



6. Assembling & preparing applicators and printing mould



5. Re-planning



11. Pass-through test of source



12, Treatment period



Testing

Creating (scaled) prototypes to test the design attributes and the design's manufacturing feasibility. The aim of this phase is to create testing environments tailored to (dis-)proving the assumptions that are left over. The goal is closely related to that of the prototyping phase, but more focused on the practicality of the device.

In this phase we are mainly challenging the following assumptions:

- We are able to create effective treatment plans of physical scans of the applicators inside a replicated (fictional) patients nasal cavity.
- We are able to accurately predict and pre-plan the catheter configuration by inflating or deflating certain balloons
- We are able to fixate the applicators by inflating them in case-specific sequences.
- We are able to apply at least three applicators made for 6-french catheters to the nasal entrance of a patient with an 'average' anatomy.



Figure 80: Testing a segment in a water bath with the CT-scanner at the UMC Utrecht

Testing: Scaled Phantom

Creating a scaled environment for the first proof of concept

Regulation constraints

The concept can not be tested on real human samples (even if deceased). For this reason, an anonymized scan of a previous patient at the UMC-Utrecht is converted to a 3D-model by layering the slices on top of each other and importing them into modelling software (in this case Materialize and SolidWorks).

Digital surgery

For testing, one half of the (para-)nasal cavity is hollowed out almost completely, roughly simulating a post-operative situation. The other half remains intact to give both an easy overview of what the nasal cavity with all it's sinuses intact looks like, but also to give a better impression of what realistic cavity sizes would be.

It is also this 3D-printed model that would be used for checking the ease of application of the three PORGES applicators bundled together. At this stage the 3D-model is scaled to 150% of the real human to more accurately identify narrow passageways and in-situ orientation as there is more space to work with.

Next to that, it will be used to see if we would be able to replicate the treatment planning orientation in a real-life setting. The applicator will be put into place and inflated to the corresponding volumes. After that, the entire setup will be put into an imaging machine (CT or MRI) with copper wiring through the catheter paths. This copper wiring should be relatively easily visible in scans.

These scans will be overlayed on the planning software to check accuracy.

It is important to keep in mind that with the current prototype, no guiding mechanisms are implemented and that application would be merely endoscopic.

First results

By trying to fixate the combined three applicators in different parts of the (post-surgery) cavity, we can see that the applicator stays in place when inflated enough. However, the catheters do not stay centrally aligned with the inflated balloons and their orientation seems relatively inaccurate. To further investigate this, segmented tests are done.

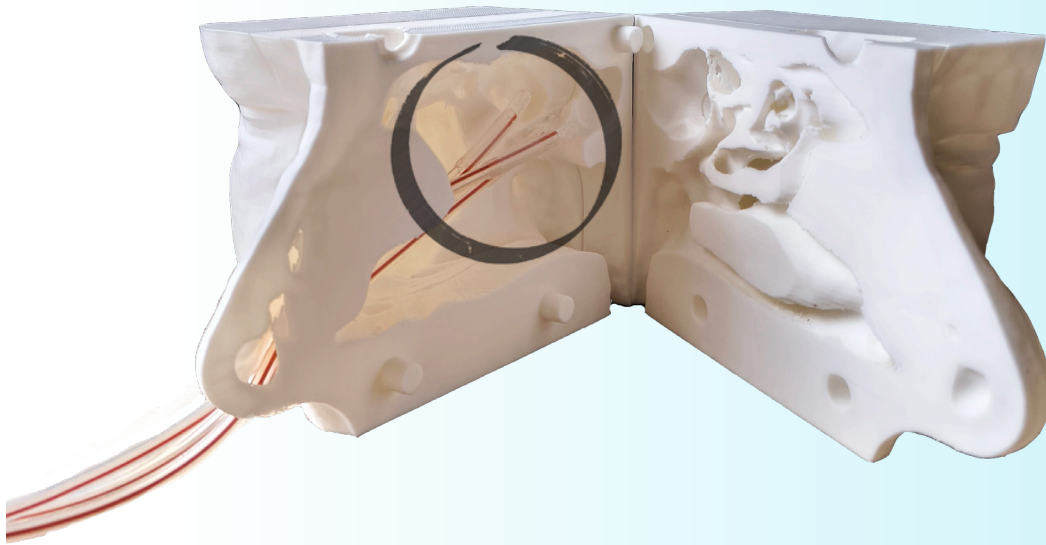


Figure 81: The first setup of the original PORGES-14 applicators on the ethmoid sinus in a 1.5x scaled phantom

Figure 82: The setup of the original PORGES-14 applicators in the nasopharynx of the 1.5x scaled phantom

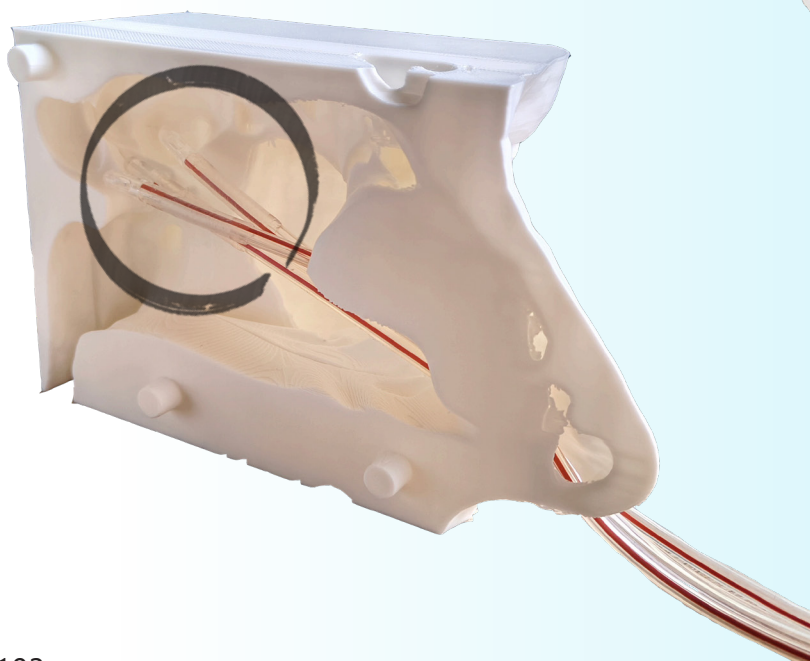


Figure 83: Testing the freedom of the original PORGES-14 applicators inside of the 1.5x scaled phantom

Testing: Segmented tests

Challenging the assumption of catheter and balloon alignment

One assumption that is left unattended up until this point is the fact that catheters inside of balloons would remain centrally aligned when fixated at the 'start' and 'end' of the balloons. Throughout the design process we presumed this to be the case and that this phenomenon would allow us to accurately define the catheter position in space by in- or deflating the balloons by certain volumes.

To validate this assumption a small test setup is designed based on a segment of the previously mentioned phantom print. In this test setup three balloons are aligned along a curve and inflated to the point of fixation.

This setup is put in a so called 'water bath' and scanned with a CT-scanner with slices of 1mm to easily identify if the catheter paths remain central (or at least predictable) to the center balloon.

Even before the CT-scan we were already inclined to a conclusion: The catheter paths do not necessarily stay aligned to the central balloon path (figure 84).

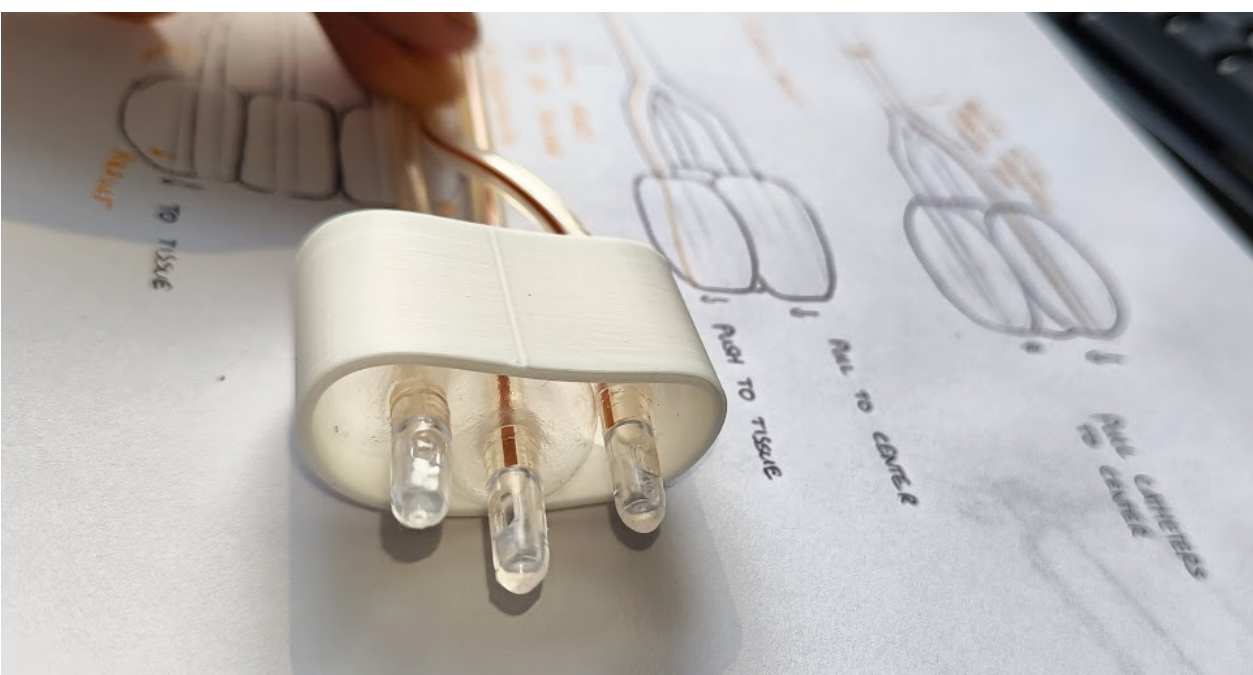


Figure 84:
3D-printing
a segment of
a potential
CTV, to test the
alignment of
catheter paths
in the inflated
balloons

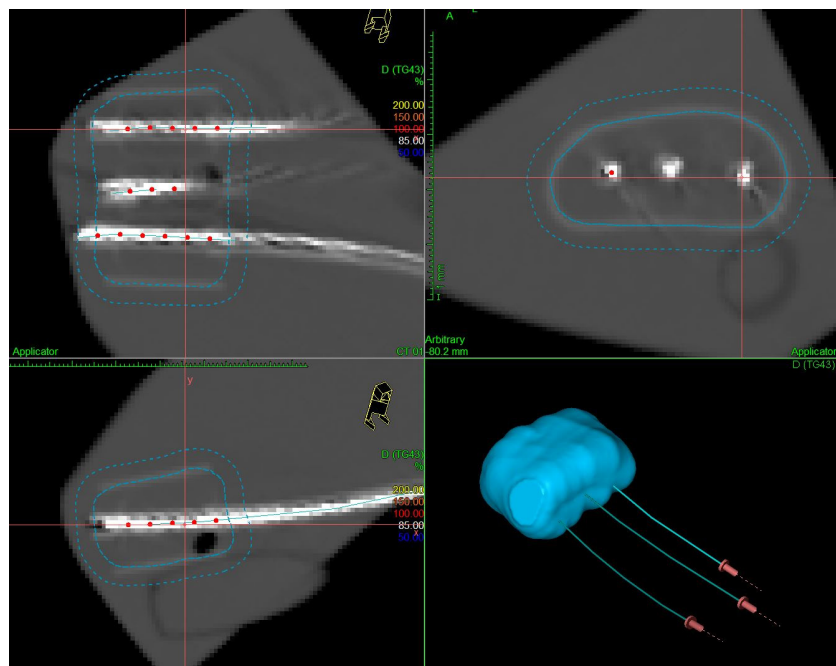
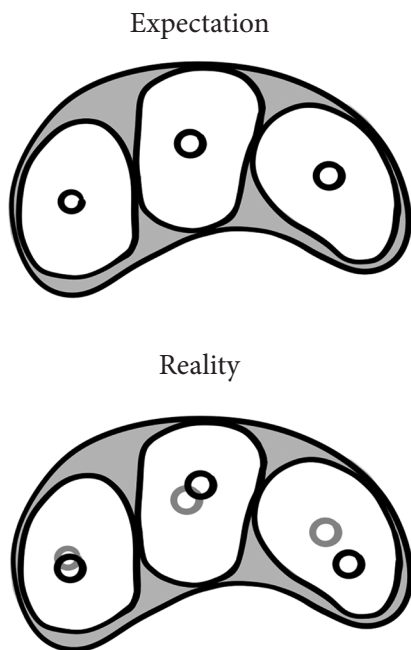


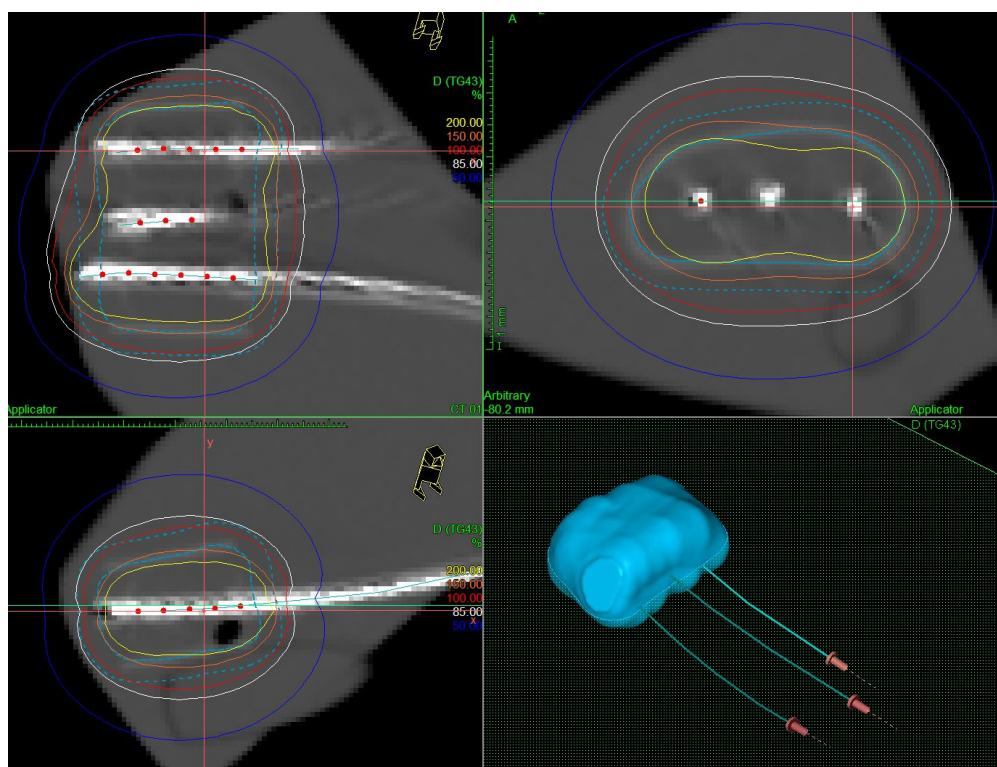
Figure 85: A sketch of the expected results vs the real results in the worst slice

Figure 86: The original scan of the segment in a water bath with the CTV drawn in light blue.

The CT-scan confirmed that the catheter paths were not central to the inflated balloon. At first this seemed to form a problem, as we would now not be able to accurately mimic the original brachytherapy planning.

However, when trying to implement dwell points and actual radiation values on the scans. We can see that even if the catheter paths were not perfect, the combination of catheters would still be able to accumulate somewhat accurate dose-lines on the CTV (light blue dotted area). What we are looking for is the 100% (red) line to cover the CTV as close to 100% as possible without the 200% (yellow) line exceeding the 3D-printed area too much.

Figure 87:
The view of the segment in OCB after adding dwell-points to the physical orientation of the catheters to check whether the isodose lines can be matched to the CTV



Testing: Segmented tests

Challenging the assumption of catheter and balloon alignment

To quantify the results from the segmented tests, OCB gives a brief overview of the radiation coverage of the CTV, so called Dose Volume Histogram (DVH) parameters.

This histogram shows how much of the radiation dose in percentage reaches how much volume of the CTV.

For example, the first row of the table gives a dose of 99.57% with an accompanied volume percentage of 90%.

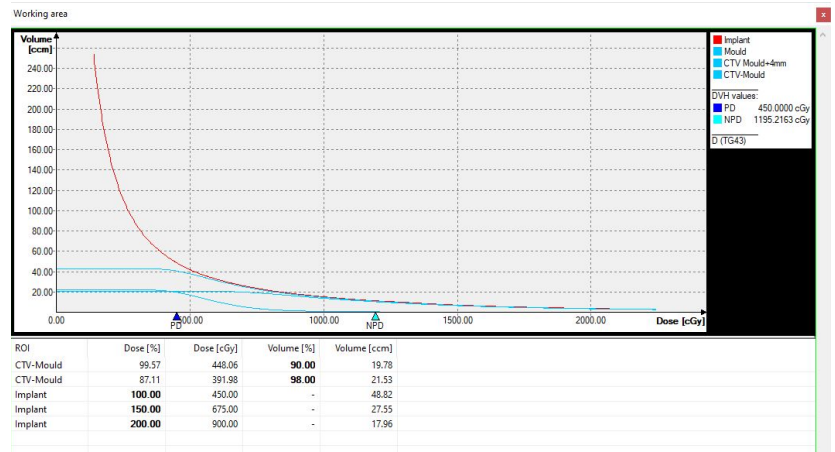
This means that 90% of the drawn CTV receives a dose of 99.57% of the planned radiation energy.

As a point of reference Baltas et al. (1998) introduce the conformal index COIN to assess HDR brachytherapy implant quality and dose specification (appendix H).

$$c_1 = \frac{PTV_{ref}}{PTV} \quad c_2 = \frac{PTV_{ref}}{V_{ref}}$$

$$COIN = c_1 \times c_2$$

Where a COIN value of 1 would stand for an ideal implant.



For the case of the segmented test a 90% coverage of the $\approx 100\%$ isodose-line is quite accurate for how fast the test was executed. Using the Conformal Index and a Coverage Index (CI), this segment has a CI of 0.90 and a COIN value of approximately 0.4. For further testing, a more anatomically accurate environment needs to be recreated and OAR's could be added to the equation to grasp the clinical benefits of brachytherapy versus external beam radiation.

$$c_3 = \prod_{i=1}^{N_{CS}} \left[1 - \frac{V_{CSref,i}}{V_{CS,i}} \right]$$

N_{CS} is the total number of critical structures for which a V_{CSref} exists such that:

$$COIN = c_1 \times c_2 \times c_3 \quad (5)$$

Testing: Button-end design sprint

Redesigning button-ends for predictable catheter lengths

The original PORGES applicators used, had a so called 'cystodrain' tip at the end of roughly 5 to 10 mm, which stuck out beyond the balloons (figure 88). This poses a problem when dealing with situations where the end of the balloon is pushed into the back of the CTV (this will be further identified in one of the CTV analyses).

This cystodrain tip is redundant in the application we are designing for, which is why a design sprint is done on a button-end catheter application that also ensures the future physicians that the catheter actually runs all the way to the end of the applicator.



Figure 88: A close-up picture of the inflated PORGES-14 applicator and its cystodrain tip

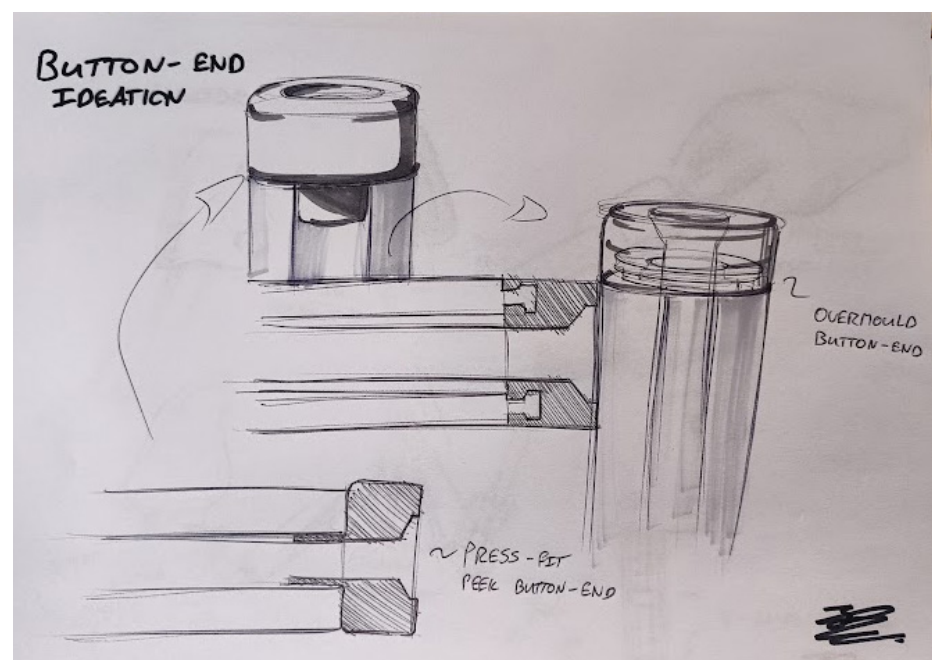
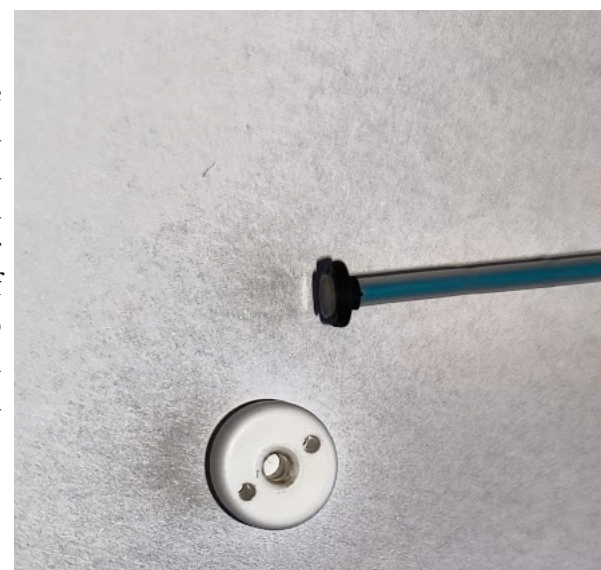


Figure 89: Sketches on the design of a button-end to ensure catheter coverage at the end of the applicator

Figure 90: A close-up render of the designed button-end on an applicator



Figure 91: The redesigned button-end 3D-printed with a catheter inside of it next to an original button-end



Testing: Target CTV's

Setting up volumes to target with the applicators

From the results of the initial scaled phantom tests, together with the UMC staff, we concluded 5 target CTV's that would be realistic target volumes for our applicator. Out of these potential CTV's, two are chosen for further testing in a more realistic setting.

The two CTV's are visualized in OCB (imaging and planning software) in light blue ■ and orange ■

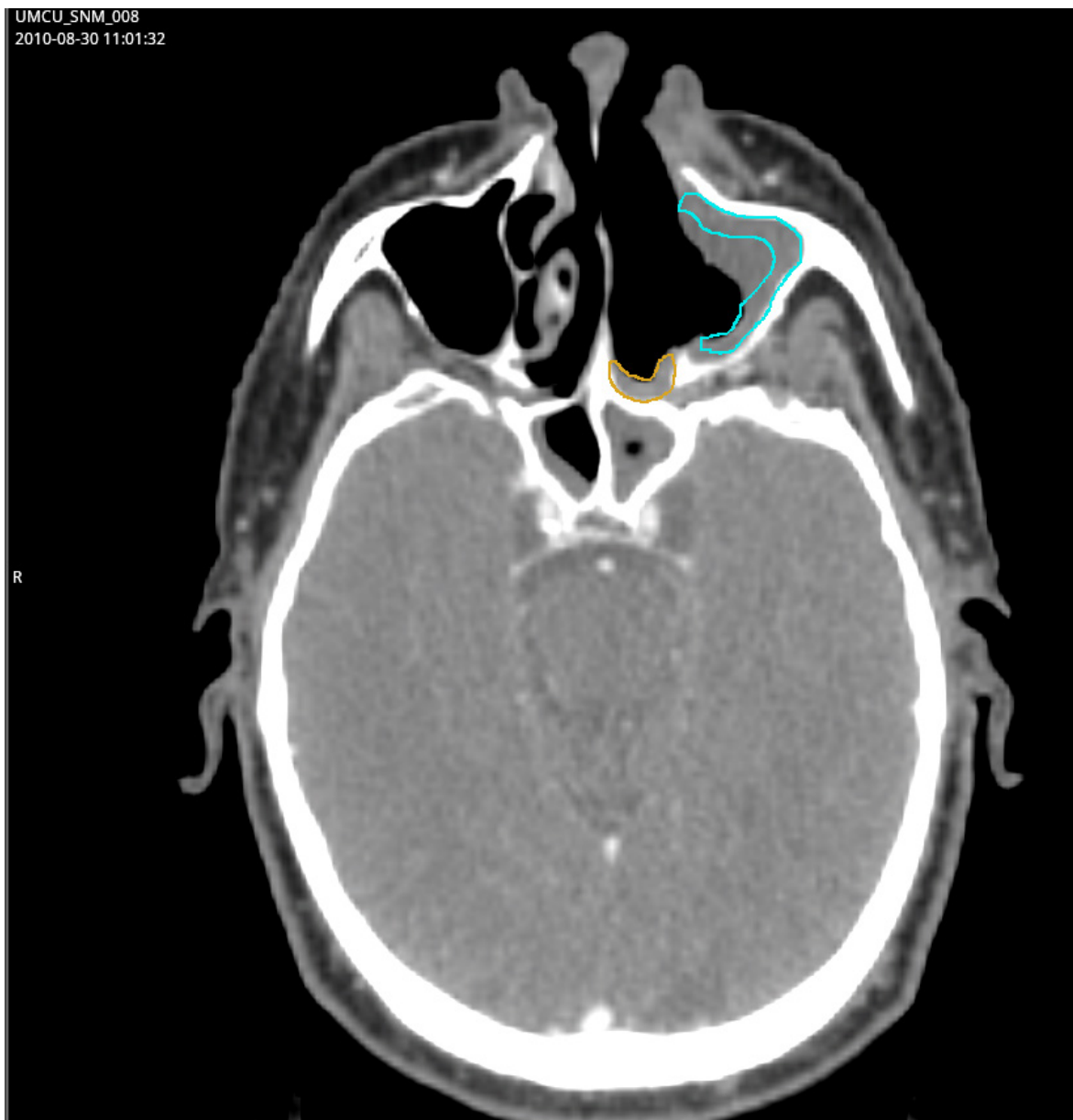


Figure 92: A screenshot of a CT-slice of the chosen CTV's for testing (axial view)

The 5 CTV's are identified on the probability of tumor locations based on previous cases from the UMC repository and expertise from UMC medical experts and surgeons.

The two chosen CTV's for further testing are mainly chosen on intuitive probability of success with the current applicator techniques, factors weighing in on this decision are:

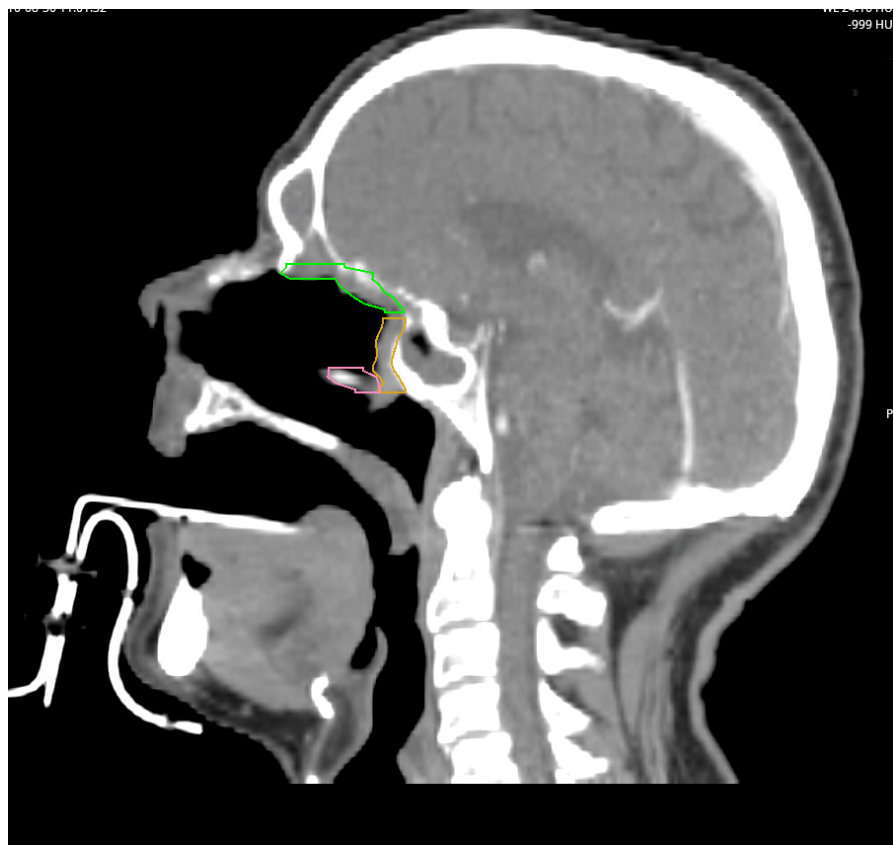


Figure 93: A screenshot of a side-view (sagittal) CT slice of the chosen CTV's for testing

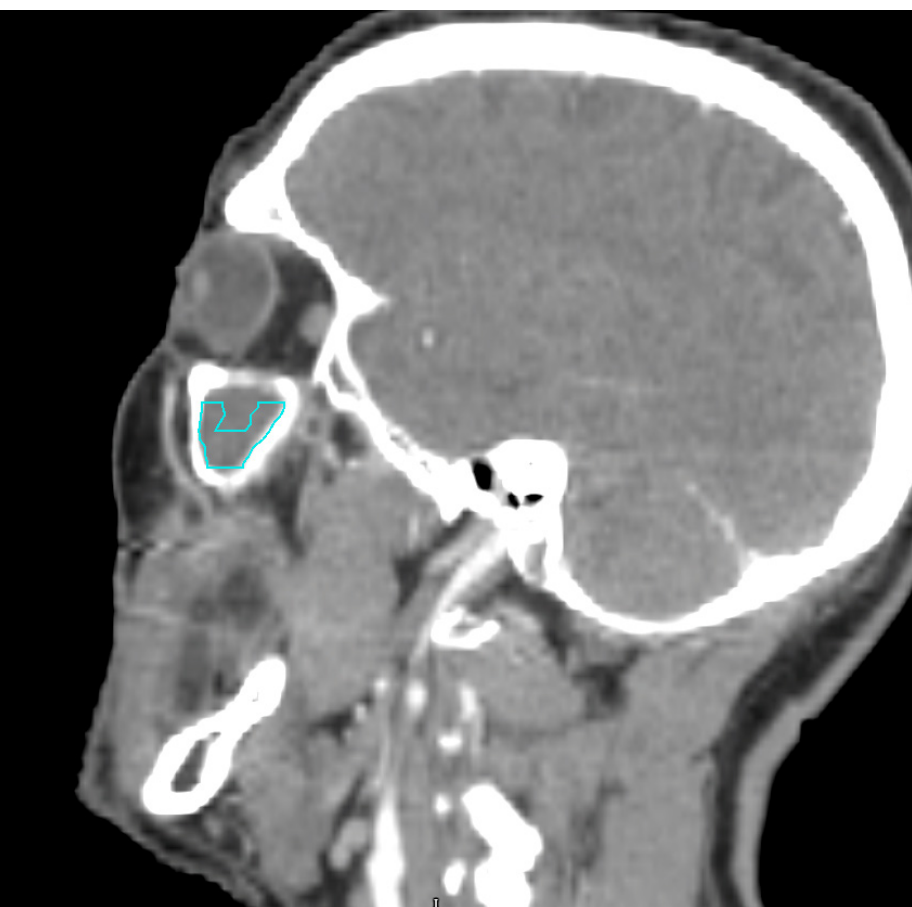


Figure 94: A screenshot of a side-view (sagittal) CT slice of the CTV in the maxillary sinus

- The presence or absence of structures around the CTV for the balloons to 'latch' on
- The overall shape of the CTV, rounder would suit the application technique better, as the balloons naturally conform to these spaces
- The amount of catheters needed to properly treat the CTV. No more than three and ideally more than 1. This is mainly due to the non-exact nature of the catheters inside of a balloon (Segmented tests). More balloons would mean a more evened out spread of catheters and therefore a more effective application.

Testing: 3D printing the ideal environment

Converting the patient from the target CTV's into a physical phantom

Based on this new digital environment around the chosen CTV's a new 3D print could be made. More accurately defined to a real life situation and this time in 100% scale. Because the applicators fit so easily in the 150% phantom print, the confidence grew that testing at 100% would be possible.

Dealing with 3D-printing limitations

The scans were made post-surgery. Which at first glance would indicate that the phantom could be printed directly based on the scans. However, some aspects when 3D printing this phantom would need to be taken into account first:

1. A real human head would consist of soft tissue and (hard) bone tissue. In a 3D-print all tissue would result in hard plastic, which could lead to unrealistic results.
2. The scans were made 2 weeks post-surgery, meaning new scar tissue would already have been formed and other soft tissue might be swollen. Combining this with the fact that all this soft tissue will become solid 3D-printed material, will further deteriorate the realism of our test-phantom

3. The nostril (or entryway of the nasal cavity) is also a mostly flexible part of the human head. For a realistic implementation of 3 to 4 applicators this flexibility is needed.

Therefore, some alterations are made to the digital model to adapt to this lack of flexibility.

Firstly, the soft (scar-) tissue is removed digitally, by 'erasing' the green area (figure 95) layer by layer in a program called Materialize (Materialise | 3D Printing Innovators, n.d.).

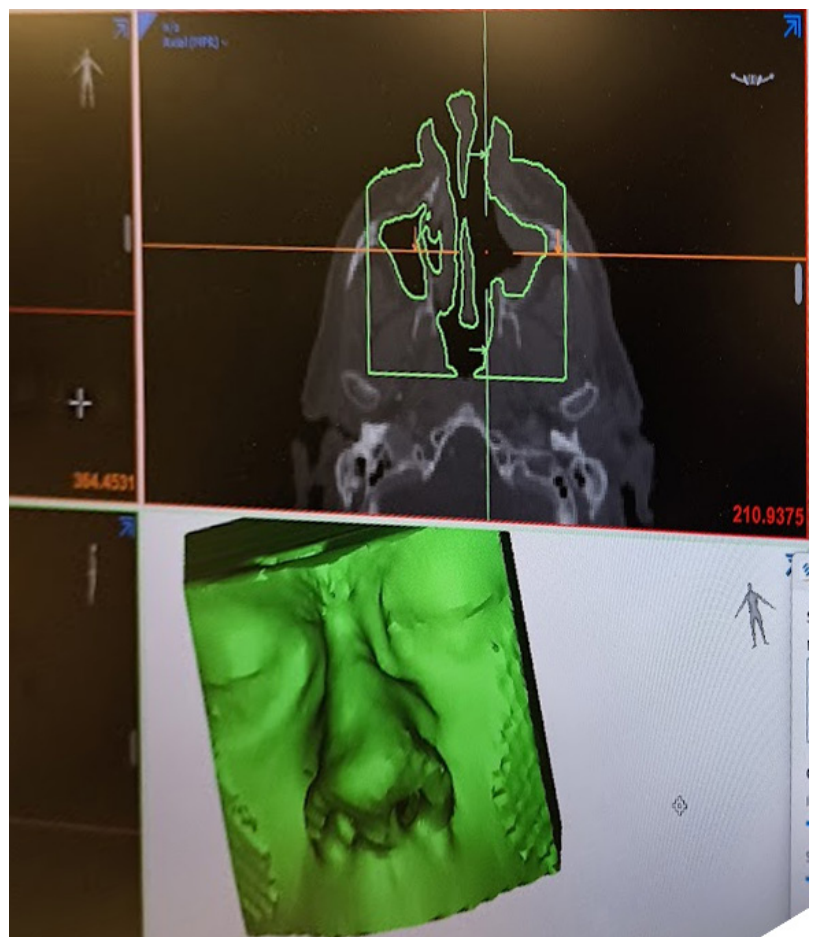


Figure 95: A screenshot of the Materialize modelling process

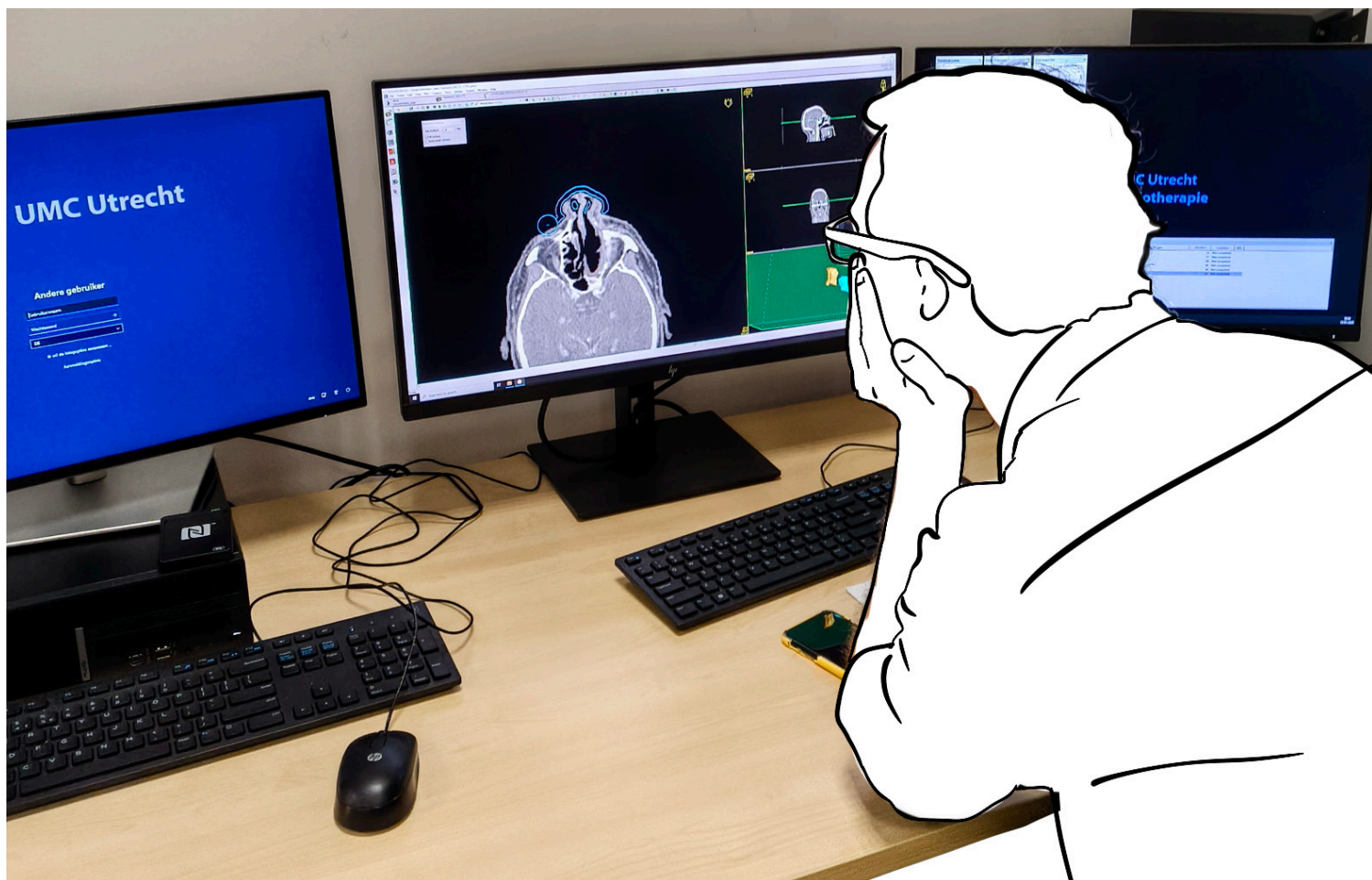


Figure 96: Modelling the phantom and accompanying nose mould

Secondly, the nostril that would be used as an access point for the applicators was broadened slightly to mimic the flexibility of a real nose. It should be noted that this broadening was done under expert supervision, but is still estimated and could definitely have caused more or less space than realistic tissue would facilitate.

Still, the notion of the UMC staff that at least 3 applicators would be feasible and that 4 would have to be tested on real tissue remains.

Phantom objectives

With these alterations in mind, the phantom head was 3D printed on FormLabs resin printers out of BioMed white resin.

Now that the phantom 3D-print is made the hypothesis of a PORGES-12 or -14 applicator and 3 or 4 applicators actually fitting the nostril could be tested.

Next to that (if the applicators fit) the CTV's can be targeted and copper wires can be scanned through the CT-scanner which can be matched with the original planning to see if the applicators can be steered enough for feasible treatment.

Testing: Phantom scans

How the applicators were applied and scanned in the phantom print

Preliminary results

Testing with the new phantom 3D print gave the following results:

- 3 Applicators for 6-french catheters fitted with relative ease (PORGES-14), 4 applicators was more difficult, but did fit.
- The application of 6-french catheters is preferred as 4-french catheters could now be put inside the 6-french for emergency removal procedures.
- The placement of the balloons was relatively easy and inflating them in situation specific sequences proved effective
- Both CTV's could be mimicked with the balloon orientation with a few alterations which will be discussed in their respective analyses (Phantom scans CTV_1 & Phantom scans CTV_2)
- The radioactive source passed through the curves of the most complex CTV (CTV_2) (figure 98)

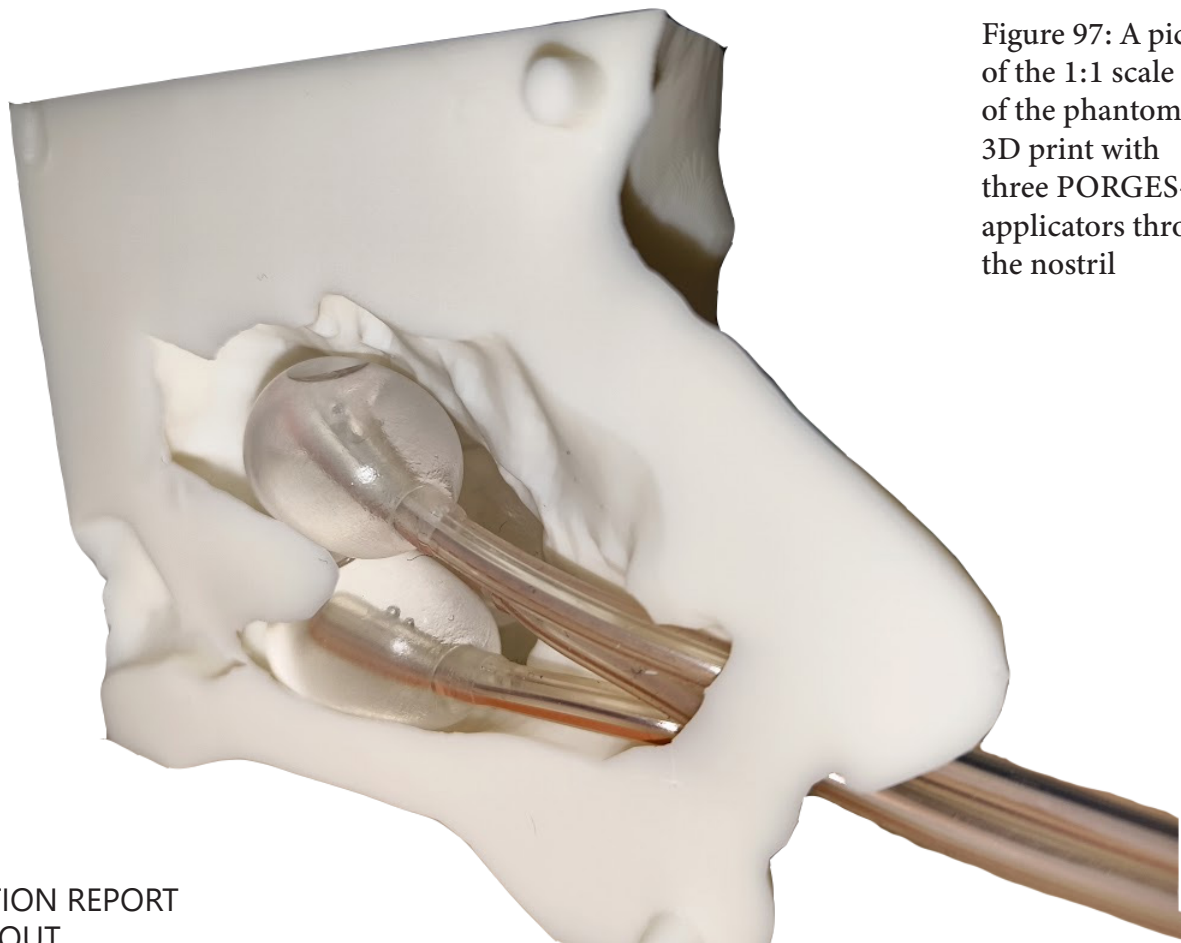


Figure 97: A picture of the 1:1 scale of the phantom 3D print with three PORGES-14 applicators through the nostril

Application assumptions

Some complications also arose with these tests:

- The current application method on the phantom seemed relatively easy (as the head was literally cut in half, allowing access to the most critical areas). In a real world scenario however, the endoscopic placement of the applicators would be more difficult with such little room for an endoscope and its movement.

When working with 3 applicators and when opening the septum in between the nostrils, enough space is presumed to exist for proper endoscope navigation through both nostril openings. However, this would need to be tested on a more real-life (flexible) situation as well.



Figure 98: Testing the possibility of the radioactive source passing through the curves of the catheters with the flexitron afterloader.

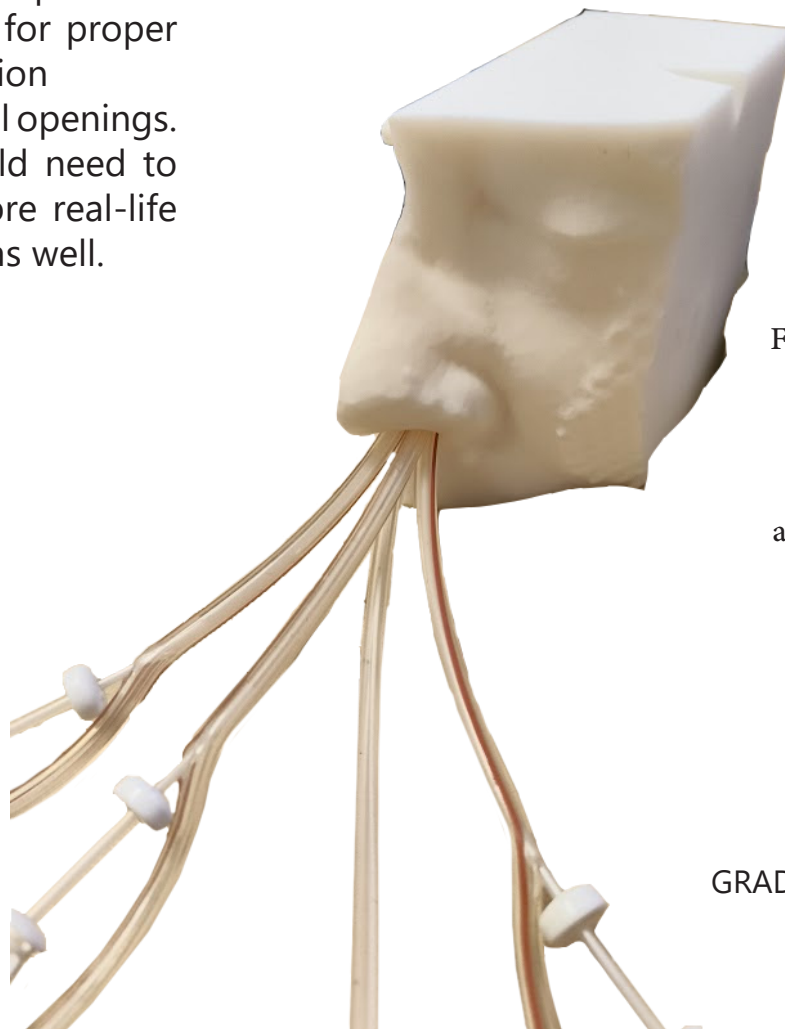


Figure 99: A picture of the 1:1 scale of the phantom 3D print with four PORGES-14 applicators through the nostril

Testing: Phantom scans

How the phantom was tested in the first CTV situation

The 3D-printed phantom was prepared for both CTV cases in a manner that resembled a real-life situation as closely as possible. That means:

- The cystodrain-ends of the PORGES-14 applicators are cut off as much as possible without penetrating the balloon seal
- The redesigned button ends are placed on the flanged 6-fr catheters and pulled through the applicator
- The PORGES applicator gets a small incision (without penetrating the inflation-duct) through which the 6-fr catheter can escape as it is not long enough for the normal PORGES applicator.
- The 4-fr catheter is placed inside the 6-fr catheter and fixated through a standard-procedure method that fixates the clips allowing the 4-fr catheter to be easily removed at any point in time.
- Through the 4-fr catheters a copper wire is placed to make the catheters more visually present on CT.

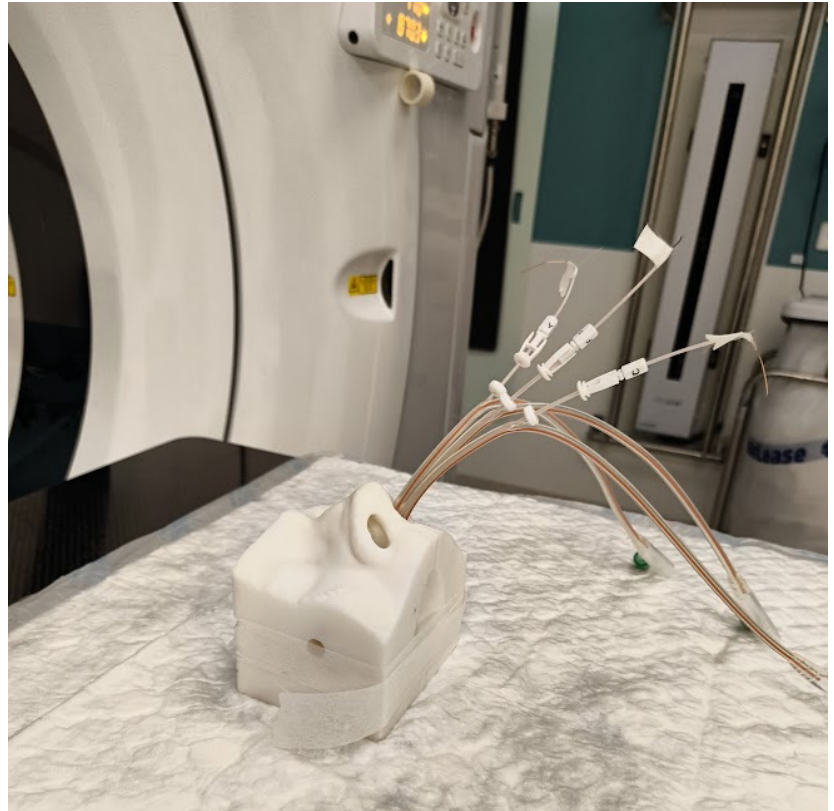


Figure 100: A photo of the phantom 3D print with the applicators applied to treat CTV 2 (the maxillary sinus) with three applicators and copper wiring through the 6- and 4-french catheters

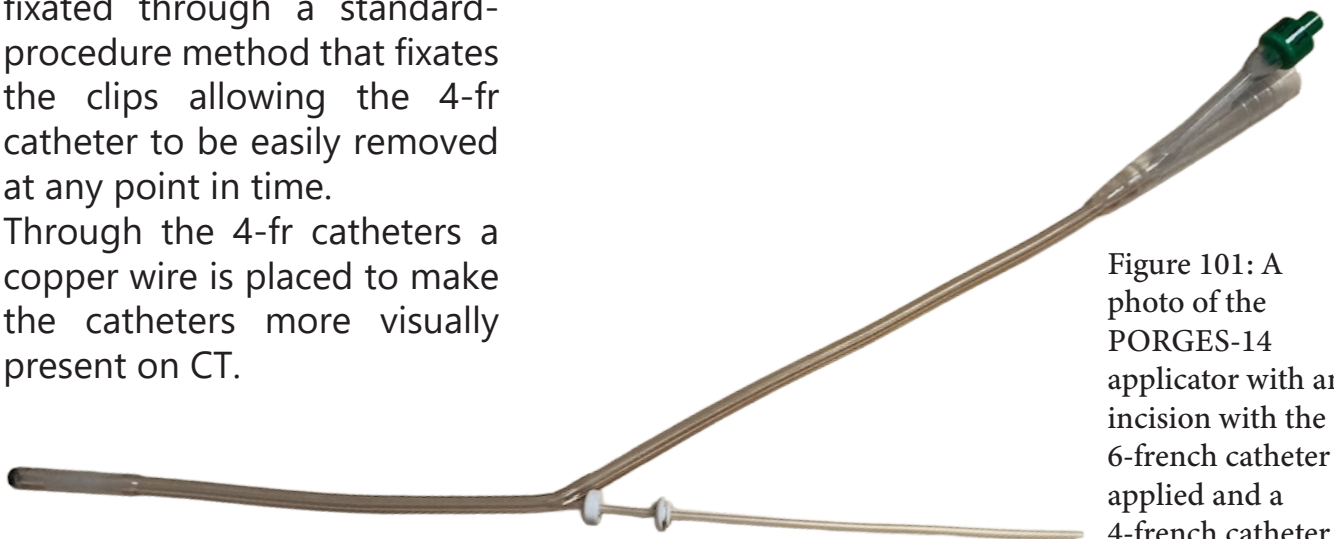


Figure 101: A photo of the PORGES-14 applicator with an incision with the 6-french catheter applied and a 4-french catheter through it with copper wiring for imaging

After placing the phantom with the placed catheters and fixated balloons on the CT table, they are scanned. In contrast with MRI scans (which are highlighted in Appendix G) the phantom material will be fully visible on the CT, giving us a clear view slice per slice of the situation.

As the model almost perfectly resembles the original scans on which it was based. The assumption is made that the scans made now could be digitally matched with the original plans, giving an immediate overview on the placement accuracy of the catheters.

One sidenote needs to be made before we continue to the results :

- Because of the availability of the CT-rooms or lack thereof, the catheter placement needed to be done spontaneously and without the original planning in sight, which could lead to inaccuracies. Additional placements are tried after CT-scans and will be presented later in the report, but additional scans were infeasible within the timeframe of this project.

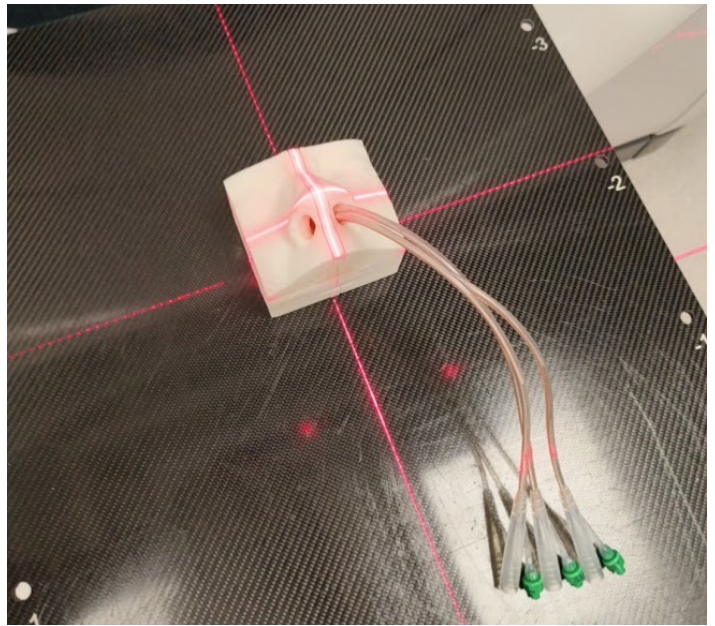


Figure 102: A photo of the phantom with three PORGES-14 applicators applied on the CT-table

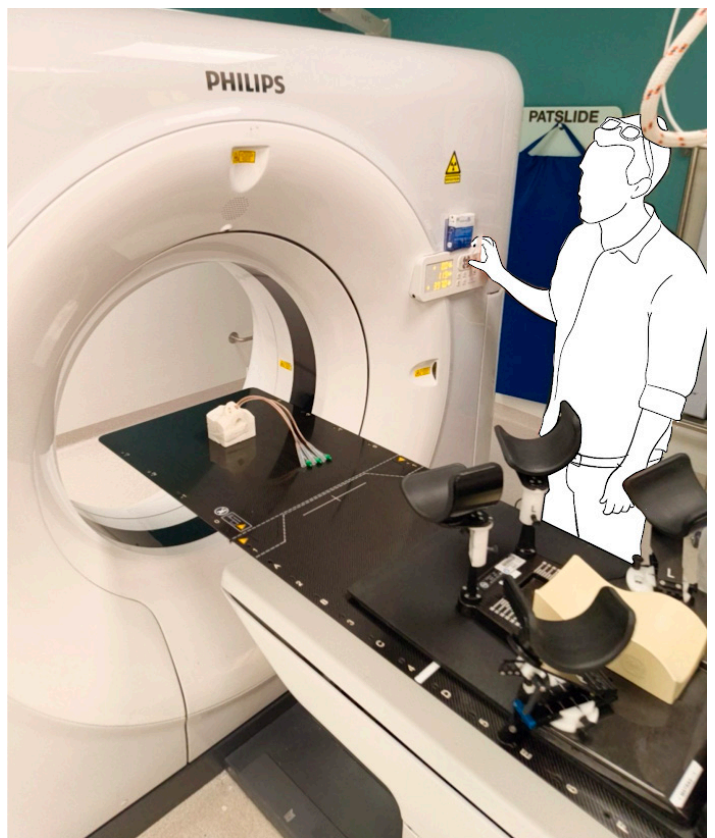


Figure 103: The CT-scanner being aligned and prepared for imaging

10

Results

The applicators we scanned through CT and MRI and the images were overlaid and matched with the original planning for both CTV's. The results are analysed in a fashion comparable to the segmented tests. The results will be visually investigated for realistic treatment, and through the DVH-parameters, to get a numerical insight into the effect of the applicator.

These results will reveal whether this applicator has any technical or clinical benefit. Furthermore, the recommendations for further development will be discussed to overcome the shortcomings the system might not have covered during this 5-month development period.



Results: Phantom scans CTV_1:

Investigating the CT-scans

When looking at the CT-scans from the application on CTV_1, there are a few aspects we can already identify:

1. The original plan (blue paths in figure 104a) was not designed for the application with balloons, as the bottom catheter path would be floating in space, without being supported by the nasal cavity floor.
2. The catheter paths do not fully enter the CTV as they do not completely reach up until the tissue at the 'end' of their paths.

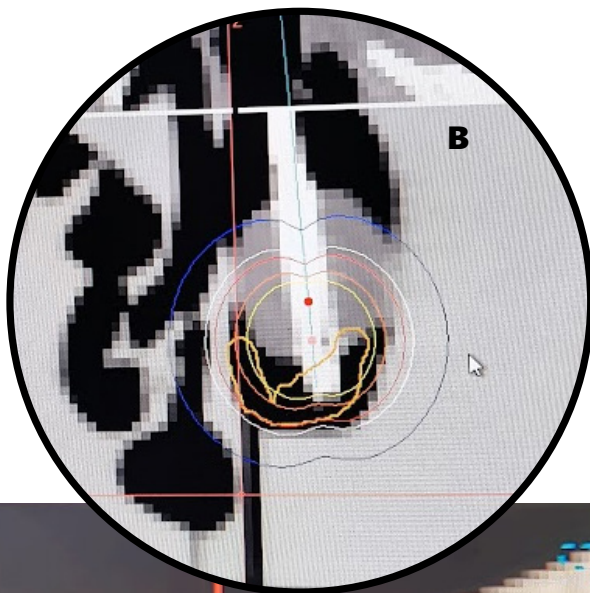


Figure 104b: An axial view of the upper applicator and catheter piercing the CTV

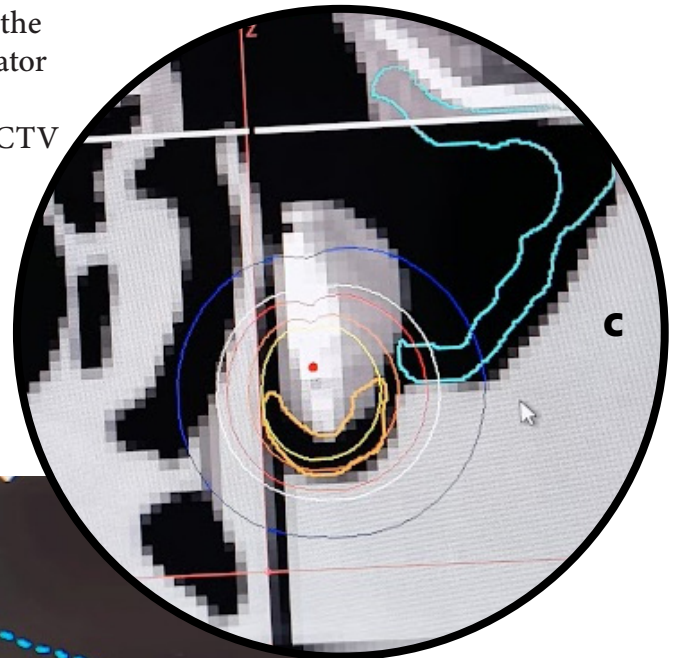


Figure 104c: An axial view of the middle applicator and catheter barely piercing the CTV

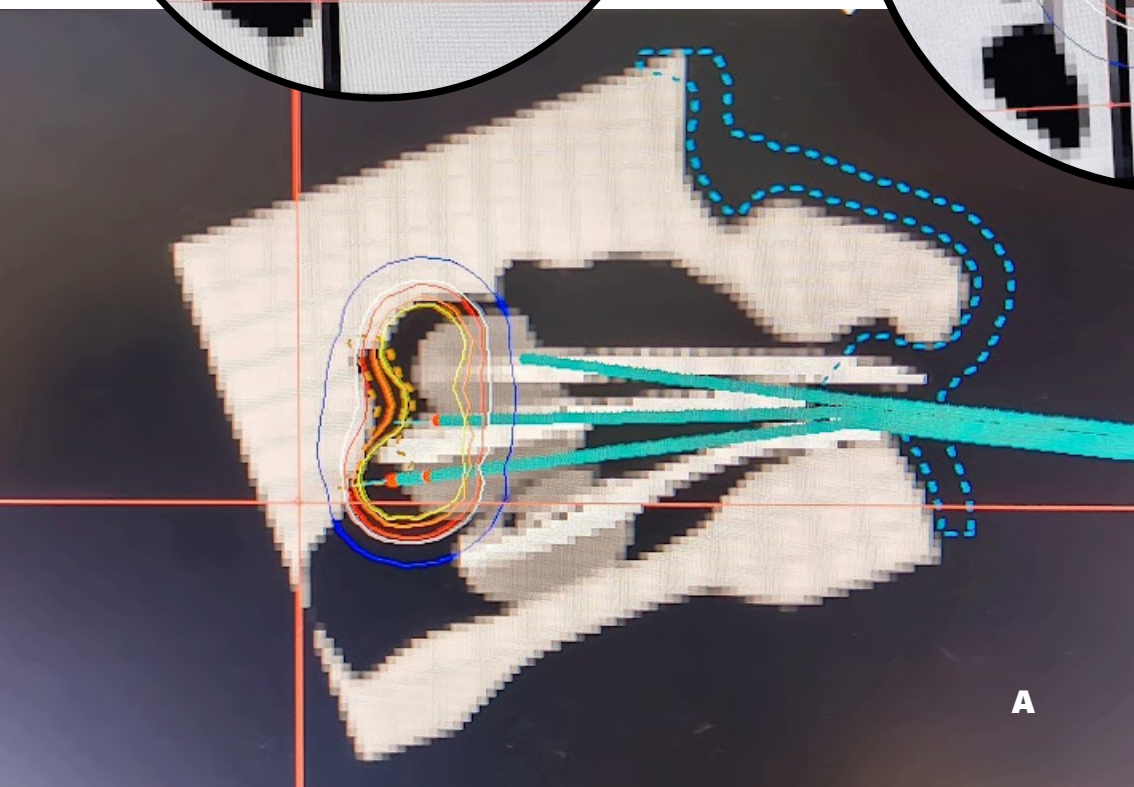


Figure 104a: A sagittal view of the old planning (blue lines) and the physical applicators (white)

Remark 1

The real-life catheters not fully overlapping with the original planning should not form an immediate problem. As long as the CTV is properly radiated with the 2 catheters that do actually reach the CTV. The third one would be needed for supporting the two radiating catheters (figure 104a).

What we can quickly extract from the side and top view of the CT is the fact that the 100% isodose-lines can almost fully cover the CTV (90% coverage at 100% dosage, with 98% coverage at 74% dosage (figure 105)) and the balloons almost fully capturing the 200% zone. A redesigned plan aimed toward the application limitations of the balloons, could achieve more efficient results.

Remark 2

Exposes more of a design issue. Even though the idea of the custom button-end ensures that the catheter follows all the way to the end of the applicator, there still remains an air-cavity at the end of the balloon.

As mentioned before, air-cavities can cause dose inaccuracies through the Compton (back-) scatter effect. In addition, the dwell points at the end of the balloon are covered less with balloon or NaCl material, meaning the 200% zone at the end of the applicator reaches air-cavities causing calculation inaccuracies. This could lead to overradiation of otherwise 'healthy' tissue or OARs, or underirradiation of the CTV.

A solution to this issue could be to further optimize the size of the button-end of the applicator. With manufacturing techniques, such as injection molding, smaller dimensions could possibly be achieved. Furthermore, the catheters used in the test were manufactured with a shrink sleeve balloon instead of the (more expensive) soluble coated dip balloon. This second manufacturing method could further decrease the distance between the end of the balloon and the custom button-end.

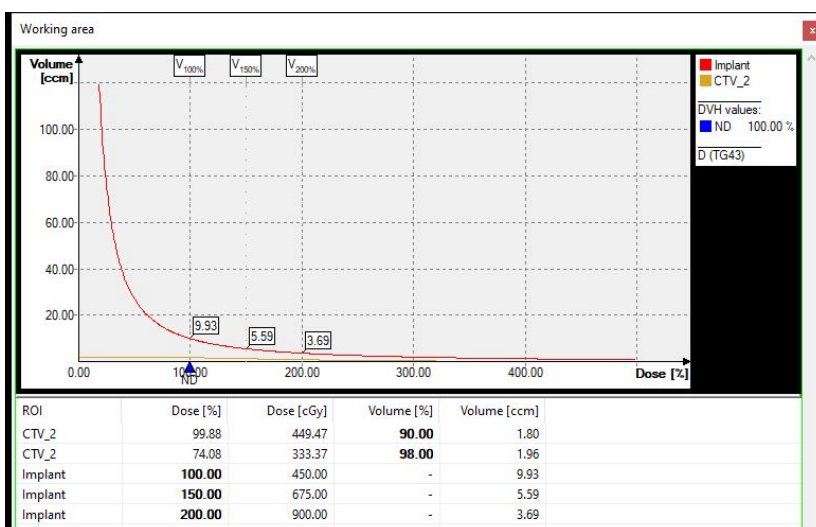


Figure 105: A graph and table showing the coverage of the CTV by the dwell points based on the physical catheter orientation.

Results: Phantom scans CTV_2:

How the phantom was tested in the second CTV situation

When looking at the CT scans of the situation in CTV_2 we can conclude the following:

- The three catheter configuration could be mimicked with more accuracy than CTV_1. However, a bend such as the middle catheter (figure 107a) could not be realized. Not necessarily because of the balloon configuration, but because of the bending radii of the catheters limiting the applicators movement.
- The general cavity could be almost completely filled with the applicators, allowing the radiation oncologists to plan relatively large radiation doses as they will be effectively covered by the NaCl in the balloons. Large doses are beneficial as they generally level the spikes of the isodose lines to a more predictable round shape.

Figure 106b: A sagittal view of the two left (105a) catheters in the nasal cavity

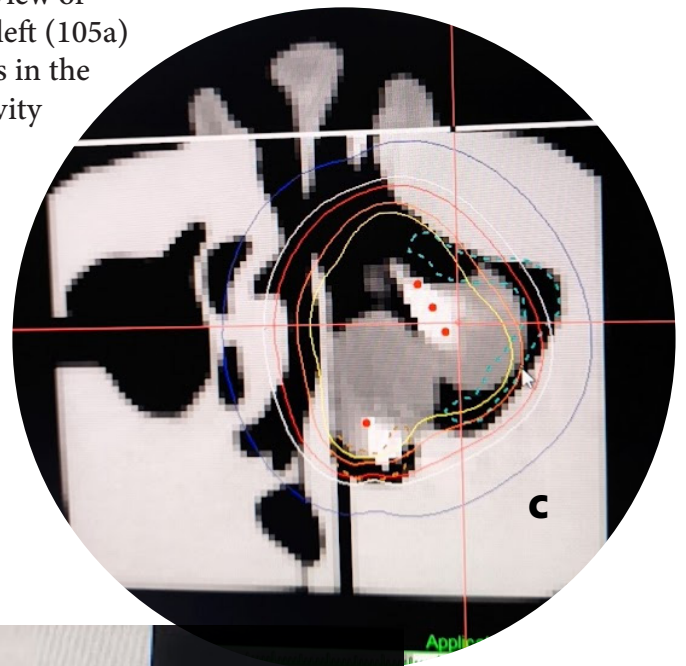
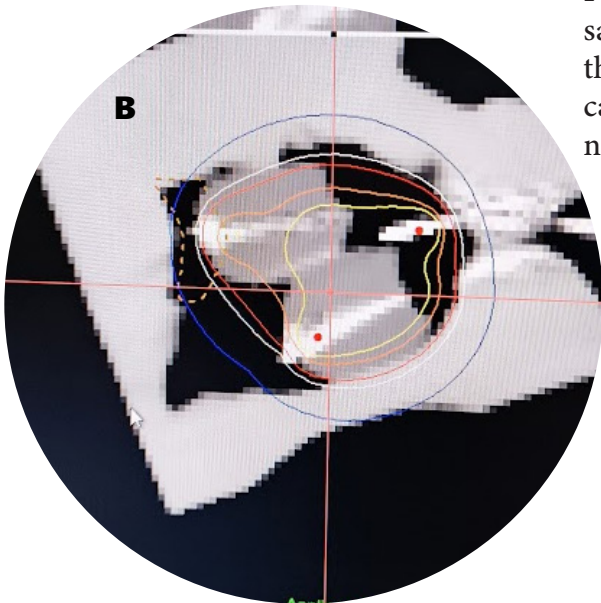


Figure 106c: An axial view of the upper two catheters (106a)

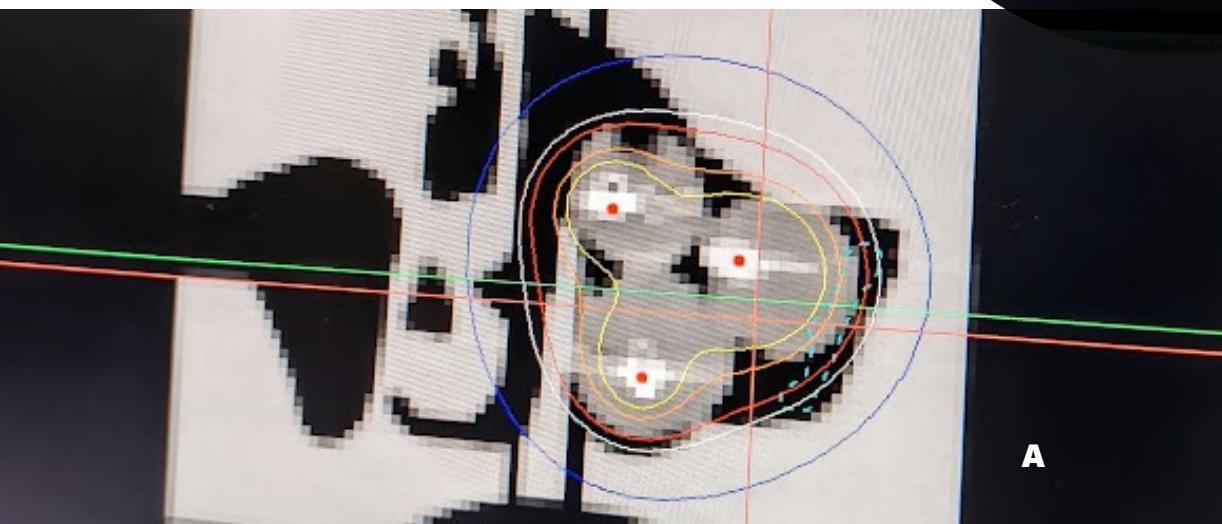


Figure 106a: A coronal view of the three applicators and catheters filling the maxillary sinus

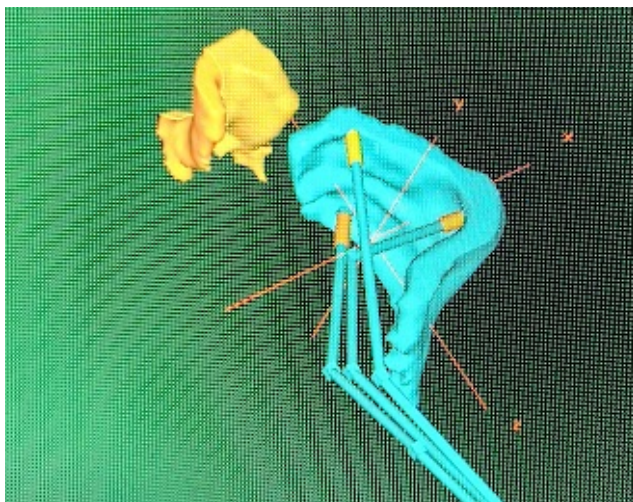


Figure 107a: A visualisation of the original planned catheter orientation (with the CTV visualised as a 3D volume)

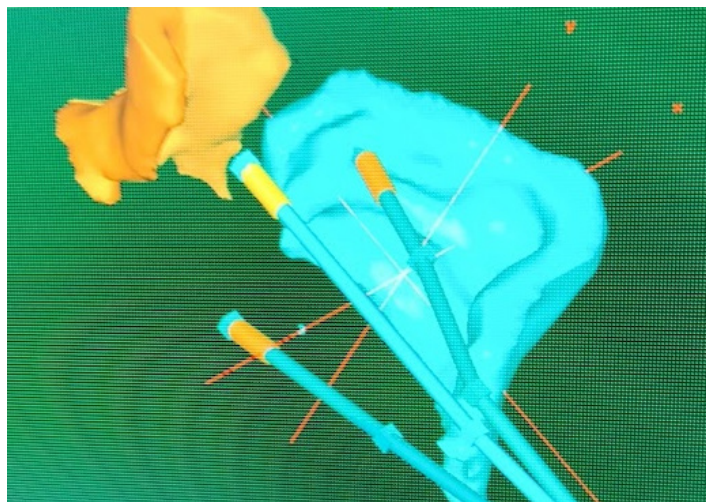


Figure 107b: A visualisation of the actual catheter orientation with the applicators (with the CTV visualised as a 3D volume)

Looking at figures 106 to 108: the following indications can be perceived. The CTV gets a 90% coverage with a dosage of around 83% and a 98% coverage at dosage rates of 72.5%. This means CTV_2 is less efficiently treated than CTV_1 as can be deduced from figure 106. However, both CTV's could be radiated with the applicators to a considerable degree. Especially with CTV_2 however, the amount of 100% dosage outside of the CTV (figure 106a) should be taken into careful account.

This excess dosage overradiates a substantial amount of healthy tissue. With OARs such as the brain, eyes and jaw so close to the CTV, this radiation can have consequences for the patients overall health.

To assess whether this amount of overradiation is an improvement from external beam radiation should be further investigated.

UMC-Utrecht's PhD candidate Renske van Noortwijk is performing a study on the application of the perfect amore (our applicator, with a theoretically perfect volume) versus external beam radiation. For her study similar considerations apply.

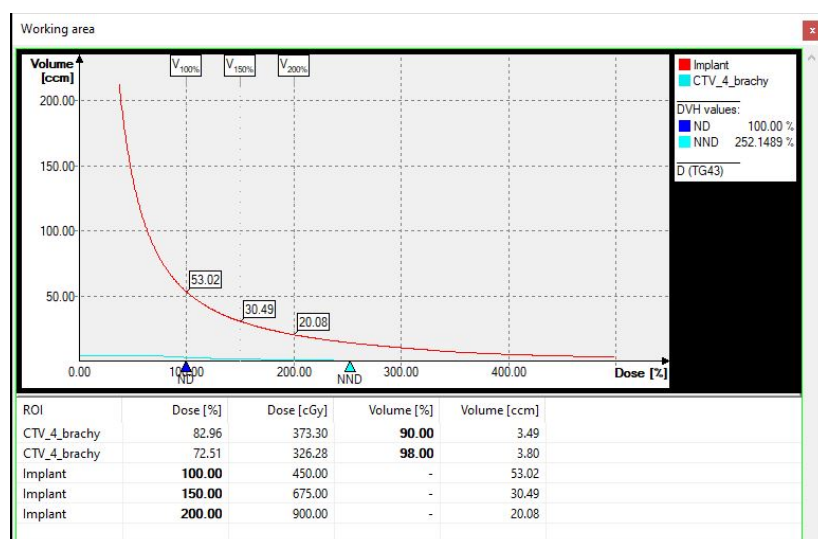


Figure 108: A graph and table showing the coverage of the CTV by the dwell points based on the physical catheter orientation.

Result conclusions

What conclusions can we draw from the testing results on the phantom scans of two CTV-case studies.

From the scans and DVH-parameters a few early-stage conclusions can be drawn.

Visually

The scans of the phantom setup and dwell points with their corresponding isodose-lines, show that the low dose bath on the temporal lobes of the brain is no longer present. Additionally, the higher dose baths (200% isodose lines) seem to be shielded by the NaCl balloons.

The dose baths on the eyes, amygdala and jaw, however, do seem to remain present, raising the question whether avoiding radiation on those OARs is possible and if these higher OAR doses are worth the avoidance of lower dose baths on other OARs.

Mathematically

Two forms of analyses can be employed. One, already mentioned in the segmented paragraph, is the COIN method of calculation (appendix H):

$$c_1 = \frac{PTV_{ref}}{PTV} \quad c_2 = \frac{PTV_{ref}}{V_{ref}} \quad c_3 = \prod_{i=1}^{N_{cs}} \left[1 - \frac{V_{CSref,i}}{V_{CS,i}} \right]$$

$$COIN = c_1 \times c_2 \times c_3$$

The DVH-parameters from the previous scans, can be linearly extrapolated to depict the volume of the 100% dose and its corresponding coefficients.

Keep in mind that extrapolation of the current DVH parameters, is nothing more than an estimation. The dose falloff is not linear as can be seen in the provided graphs of the results page, meaning inaccuracies occur when using this method. However, with the data available at this timeframe, these calculations are the most accurate. Furthermore, the OARs (c3) are not taken into account due to limited time and expertise in drawing the OAR volumes in OCB.

For CTV_1 the calculation results in a conformity index of 0.16

For CTV_2 the calculation results in a conformity index of 0.059

Initially, these indices appear relatively low. This is mainly due to the large volume of radiation that is not covered by the PTV. In other words, the COIN method assumes the volumes of the balloons are healthy tissue, while in practice these volumes should receive the radiation dose to shield the healthy tissue. The shielding capabilities of the applicator should be included in the calculation method, how this could be done will be discussed in the recommendations chapter.

$$CI = TV_{PIV} / TV$$

$$HTCI = TV_{PIV} / PIV$$

Another method is the Coverage Index CI (Appendix H), which calculates the amount of target volume covered by the 100% isodose line.

For CTV_1, this is estimated around: 0.85 to 0.9 when we extrapolate the DVH-parameters to 100% isodose (99.8% dosage gives 90% coverage)

For CTV_2, this is estimated around: 0.6 to 0.8 when we extrapolate the DVH-parameters to 100% isodose (82.9% dosage gives 90% coverage)

A coverage index of 0.85 to 0.9 for CTV_1, provides a range that proves the likelihood of suitable treatment. CTV_2 would, however, need improvement in placement for more optimised treatment plans, as visible in the scans as well. The catheter placement could be improved with simple changes in additional placement iterations.

Quantifying success

Studies like Kannan et al. (2015) show that coverages of 87.75% and 82.37% are accurate enough for effective treatment, but most studies focus on older applications of brachytherapy targeting for example the cervix or prostate.

The exact quantitative threshold for treatment application is highly situational (especially in the H&N region) and needs to be further investigated by medical professionals. The conclusions for this study will therefore be mostly drawn on the visual evidence the scans provide.

Result conclusions

What conclusions can we draw from the testing results on the phantom scans of two CTV-case studies.

This project was aimed to investigate the adoption of emerging materials in a brachytherapy context focused on the (para-)nasal cavity. The project shifted toward the investigation whether multi-catheter shape-adaptive bio-compatible stabilisation solutions could be realised.

Based on clinical analysis, literature review, material experimentation, and experimental validation techniques, this project concludes that such an approach is technically feasible and clinically relevant, and therefore suitable for development continuation.

Clinical problem definition

The clinical problem underlying this project relates to current treatment predominantly relying on external beam radiation, despite brachytherapy offering dosimetric benefits. These advantages are mainly in terms of reduced low-dose exposure of radiation to surrounding critical organs.

The absence of a reliable non-invasive method to stabilize catheters within the irregular anatomy of the paranasal sinuses forms the primary barrier to adoption.

Technical constraints

The main technical constraint of this project: The paradoxal size difference between the nostril entrance and the (para-)nasal cavity behind it, calls for the use of shape-adaptive design features. Through iterative prototyping the use of inflatable devices has been investigated and validated by phantom-based testing.

With these tests, the first signs of stable and predictable deployment are established. The results demonstrate technical feasibility and justify further iterative development aimed at improving repeatability, deployment control and positional predictability.

Results

Although the test results show technical feasibility, the clinical benefits are to be further investigated. The tests showed multiple CTVs can be targeted and radiated with the applicators, however, a decrease in the radiation of healthy tissue or OARs is yet to be numerically identified. Therefore a clinical benefit remains theoretical and should be validated in follow-up research phases.

Based on the results of phantom testing and the medical expert insights from the staff at the UMC Utrecht, the following requirements and assumptions can be (dis-)proven, challenged, or accepted. A complete overview can be found in Appendix J.

Requirement / assumption	Check	(dis-)proving data / notions
The applicator can be placed without invasive surgical intervention	No	Beyond the aspect of surgically removing the Gross Tumor Volume there are some internal structures such as the septum which will likely have to be (partly) opened for accessibility and fixation.
The applicator needs to be removable without additional surgical intervention	Yes	By deflating the inflatables, removal should be as simple as pulling them out of the nostril. With phantom testing this posed no issue, but with real-life testing the requirement could be tested more thoroughly
The applicator leaves enough room for deployment with an endoscope	Yes, but	When working with three applicators, the room for an endoscope in the same nostril would need to be tested (four applicators will not leave enough room). When opening the nasal septum, the endoscope can be used to place the applicators through the second nostril
The device is biocompatible	Yes	Based on the bio-compatibility of the original PORGES catheters (medical silicone) and the application of PEEK in-house 3D-printing the applicator can be made bio-compatible for a 10-day treatment period
Application must not take longer than 60 minutes	Yes, but	The application of the applicators in a phantom took no more than 5 to 10 minutes, to place the applicators with an endoscope in a real-life situation will be more difficult and time-estimations would need further testing.
The applicator needs to be able to facilitate complex patient-specific dosimetry plans (more than 1 dwell point or 1 single catheter)	Yes	As shown in both CTV's the use of multiple applicators proved to be possible where each applicator served a crucial function in the dosimetry plans.
The applicator can replicate a pre-planned orientation (given that the pre-planning is made with the limitations of the applicator in mind)	Yes, but	The CTV case studies showed that catheter orientation can be predicted before placement, more practise and case-studies are however needed to improve the skill placement and of pre-planning within applicator constraints.
The device can be fixated without displacement over at least a 10-day period	Undetermined	With previous uses of the PORGES-14 catheters the balloons remained accurately inflated during a 2-week period, however, displacement of the catheters has not yet been tested.

Recommendations

Based on the results and the conclusions, what recommendations remain for the future of this project?

While this project demonstrates technical feasibility of a shape adaptive-stabilisation approach designed for brachytherapy applications in the (para-)nasal cavity, multiple critical aspects of development of a medical device remain insufficiently explored and would require further research before this innovation could continue to clinical applications.

The following recommendations identify knowledge gaps that should be addressed before claims on the clinical benefit or patient impact can be responsibly made.

Tissue response

All of the experimental validation was done using 3D printed phantom-based models, which do not fully resemble the mechanical compliance features of all the different tissues present in *in vivo* situation. Further research using cadaveric models or more advanced tissue-mimicking phantoms would be necessary to assess the applicators' behaviour, stability, and potential tissue trauma it might cause. A more realistic research environment might also expose or debunk the aforementioned endoscopic placement constraints.

Patient comfort

Mainly due to time constraints and the inability to test on human subjects, this project performed no quantitative or qualitative research on patient comfort, pain perception, or tolerability during insertion, deployment and treatment of the device. Future research should include patient-centred evaluation methods. This could be done through (dis) comfort scales, pressure mapping, or comparative studies with existing nasal devices. Tackling this aspect could significantly influence clinical acceptance.

Quantitative dosimetric values

Although the dosimetry in the case studies was briefly planned and discussed, the sample size and the quality of this study is not strong enough for empirical evidence of the device being dosimetrically sound. Future work should include detailed treatment planning studies to assess whether the designed applicators lead to measurable clinical benefits such as reduced dose in OAR's compared to current clinical practice.

Long-term stability and patient behavior

This project solely covered the short-term deployment and positional stability of the applicators. The effects of prolonged inflation with NaCl and other fluids in combination with patient tissue and patient movement throughout the 10-day treatment period are yet unknown. Furthermore, the natural processes of swelling and mucosal secretion and their impacts on the devices behavior have not yet been addressed. Further research should investigate whether the stabilization performance can be maintained in a real-life situation and for how long.

Sterilization pathways and sustainable responsibility

The selected materials were based on biocompatibility considerations from existing products. However, sterilization compatibility, degradation, and fatigue effects were left out of scope for this project. These factors are essential for clinical medical device design and should therefore be further evaluated.

Clinical workflow integration and procedural burden

As briefly mentioned, the proposed design influences the overall clinical workflow, procedural timeline, staff burden and application knowledge needed. These influences are not yet fully explored, mapped and optimized. A future study should evaluate whether the benefits of the designed applicators outweigh the potential increases in procedural complexity.

Sustainability and life-cycle analyses

For efficiency purposes this project was directed at development of a single-use device. Primarily, because the requirements around sterility and risk mitigation could complicate the project to an infeasible extent within the given timeframe. As a result, the aspects of ecological impact, recyclability, or even reusability are left out of scope. New studies could explore the feasibility of these aspects through alternative material decisions, modular design choices, or sterilisation compatibility. Which possibly enable recycling or reuse without compromising patient safety.

Recommendations

Based on the results and the conclusions, what recommendations remain for the future of this project?

Calculation recommendations

Furthermore, to get more irrefutable proof of the concept's potential to outperform the external beam radiation, the calculation method needs to be improved and more variables would need to be extracted from the OCB software.

Firstly, the volumes of the OARs need to be plotted in the OCB software to calculate their volumes and location. Letting the software calculate the BVH-parameters of a situation with OARs plotted would allow the calculation of the third coefficient.

$$c_3 = \prod_{i=1}^{N_{cs}} \left[1 - \frac{V_{CSref,i}}{V_{CS,i}} \right]$$

With this method the low dose bath of the applicator on OARs does not have to be estimated to give a comparison to external beam radiation.

Furthermore, a shielding coefficient should be formulated. Firstly, the balloon (water-equivalent) volumes would need to be plotted in OCB to calculate their volumes and the overlap of the 200% and 100% isodose with the balloons. These values can be subtracted from the radiation volume that does not cover the target volume, to give a more realistic insight into the efficiency of the applicators and the concept of application itself.

Future medical device design roadmap

Next steps for medical device production readiness.

Phase 0: Clinical Commitment Validation

For starters, the clinical need should be reconfirmed with UMC stakeholders (a study on this matter is already in progress).

Secondly, a manufacturer (like Coloplast) would need to be convinced of the relevance and would need to see commercial value in further development.

Phase 1: Formal Development setup

Matters such as IP-ownership and regulatory responsibility would need to be re-stated, especially when collaboration with a manufacturer comes into play. Patent-possibility would also need to be discussed.

Furthermore, the regulatory classification needs to be confirmed Under European Commission MDR. The applicable rules provided by the MDR need to be consulted, likely rule 7 (Surgically invasive- Short term use Intended to supply energy / ionizing radiation) would suggest classification of a class IIb medical device.

Phase 2: Design Controls & QMS Integration

Under EU MDR and ISO 12485 the design in- and outputs need to be documented, along with a verification plan, validation plan, Risk management file (ISO 14971), Engineering files and a Clinical evaluation plan.

Mainly in the aspect of risk management, the biological safety of materials, mechanical failure modes, sterility assurance, and use errors need to be identified and documented.

Phase 3: Formal preclinical validation

The mechanical durability of the device would need to be tested to the limits by a certified facility (think of cyclic behaviour, yield stress, pressure sensitivity and piercing resistance). The biocompatibility of the material (even though it is already certified) would likely need to be tested for cytotoxicity, sensitization and irritation. And lastly, the sterilization process would need to be validated (including packaging).

Phase 4: Clinical evaluation

Aside from the aforementioned tests on more realistic models and in the far future even testing on humans, ethical approval would need to be granted and the clinical protocol would need to be formalized and audited. All tests and their accompanied risks need to be predetermined and carefully analyzed by multiple parties before they are executed to prevent harm. Lastly, a notified body should be engaged to iteratively cycle the process before a CE mark can be granted.

All in all, this process is long and complex. Therefore it is of utmost importance that the clinical benefit is carefully analyzed before such a journey is set in motion. It is also important to note that manufacturing validation and market strategies are assumed feasible within this roadmap. However, if clinical benefit is unanimously recognized this roadmap could be followed with the first step: finding a supplier.

Personal Reflection

How I experienced this project, what it has taught me

Over the past five months I have had the opportunity to work on this thesis, a project that I think accurately resembles my learnings throughout my masters education at IDE over the past few years.

The first time reading the project brief of this graduation project, I remember it feeling as the ultimate combination of challenges I have wanted to tackle during my time as a student at the TU Delft.

From the interdisciplinary design aspects to the social weight of the challenge itself, it felt like the optimal case to work with as a graduation project.

Designing for healthcare

Working closely with medical specialists at the UMC Utrecht definitely changed my understanding of what "designing for healthcare" truly means.

Being constrained by the intricacies of patient safety, regulatory frameworks, and the practical time constraints of medical professionals was something that I was told multiple times during my studies, but had never experienced in a way like during this project.

I feel lucky for the opportunities

the UMC Utrecht has provided me, from making use of their CT and MRI scanners, the time investment from the staff and the honesty of their ambitions and opinions during meetings has not gone unnoticed.

This has also taught me a lot about my professionalism as a design engineer: preparing our meetings for optimizing the limited time available, managing the workflow around the schedules of others, and keeping an overview of the vast expertise that was provided. I became more aware of how easily I could misunderstand terminology, oversimplify clinical workflows, or assume that a technically or visually elegant solution would not automatically result in clinical value.

Managing ambition

For me, the most challenging aspect of this project was probably the fact that proof of medical benefit was very likely unreachable within the time-frame of the project.

Reaching technical feasibility of a new concept in the medical device field is something I am incredibly proud to have achieved to the reported extent.

However, not yet being able to prove the medical benefits is relatively dissatisfying, but maybe also a good personal learning point.

Achieving proof of medical benefit was assumed to be out of reach from the beginning of the project. Even providing a 100% scaled technical proof of concept was doubted at the beginning.

However, the closer I got to reaching this proof of medical benefit, the more I reached for it. I think a good learning point is to look back more often on the original planning and objectives

of the project and to see what I actually achieved. This graduation project might not have resulted in a finalized clinical product, but it did result in a validated concept direction, a clarified pathway for future development and a increased personal awareness of the complexity behind medical innovation.

Personal takeaway

It strengthened my motivation to pursue work that contributes to societal value and increased my ambition to let design shape society's (medical) future in unexpected and innovative ways.

AI Declaration / Statement

How and why AI was used in this study.

I acknowledge the use of Large Language Models (LLM) such as ChatGPT, NotebookLLM, Perplexity.ai and Gemini to help brainstorm topics, ideas, and research directions. Furthermore, they helped digest and summarize research papers to identify relevant topics. These topics were always consulted from the paper itself and just like the written text in this report are never directly copied from LLM outputs. Outputs were only used as a starting point before narrowing down the topics for assessment.

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Apa-7

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Appendix A:

How 3D-models are extracted from DICOM files in OCB

At the radiotherapy section of UMC-U, many different softwares are combined to develop easy to understand images and models to work with efficiently.

One of the examples of this is the method of extracting 3D-models in the form of STL files from slices and images from CT -scans in the form of DICOM files.

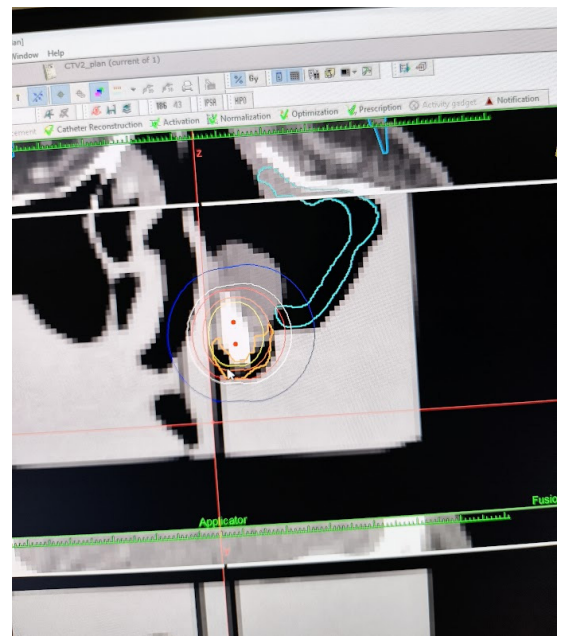
The DICOM files are first imported in OCB, a professional imaging and planning software. In this software the staff can manually 'draw' cross sectional areas in each individual slice.

Figuratively glueing these 2D drawings to eachother would create a 3D-model which can directly be exported from OCB in STL files.

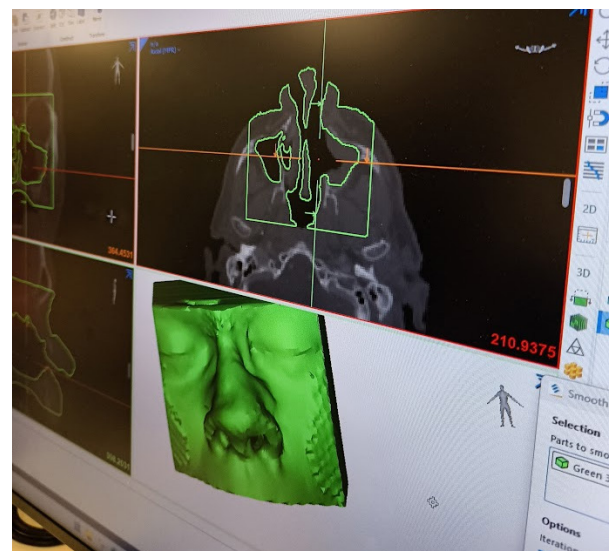
However, these models can be quite rough, of lower quality and are sometimes difficult to change once they are made.

Which is why sometimes the software Materialize is used, which has more features around quality improvement and alterations of 3D models.

These STL's can be used as a main body to add or subtract components on/from in traditional CAD software such as Fusion.



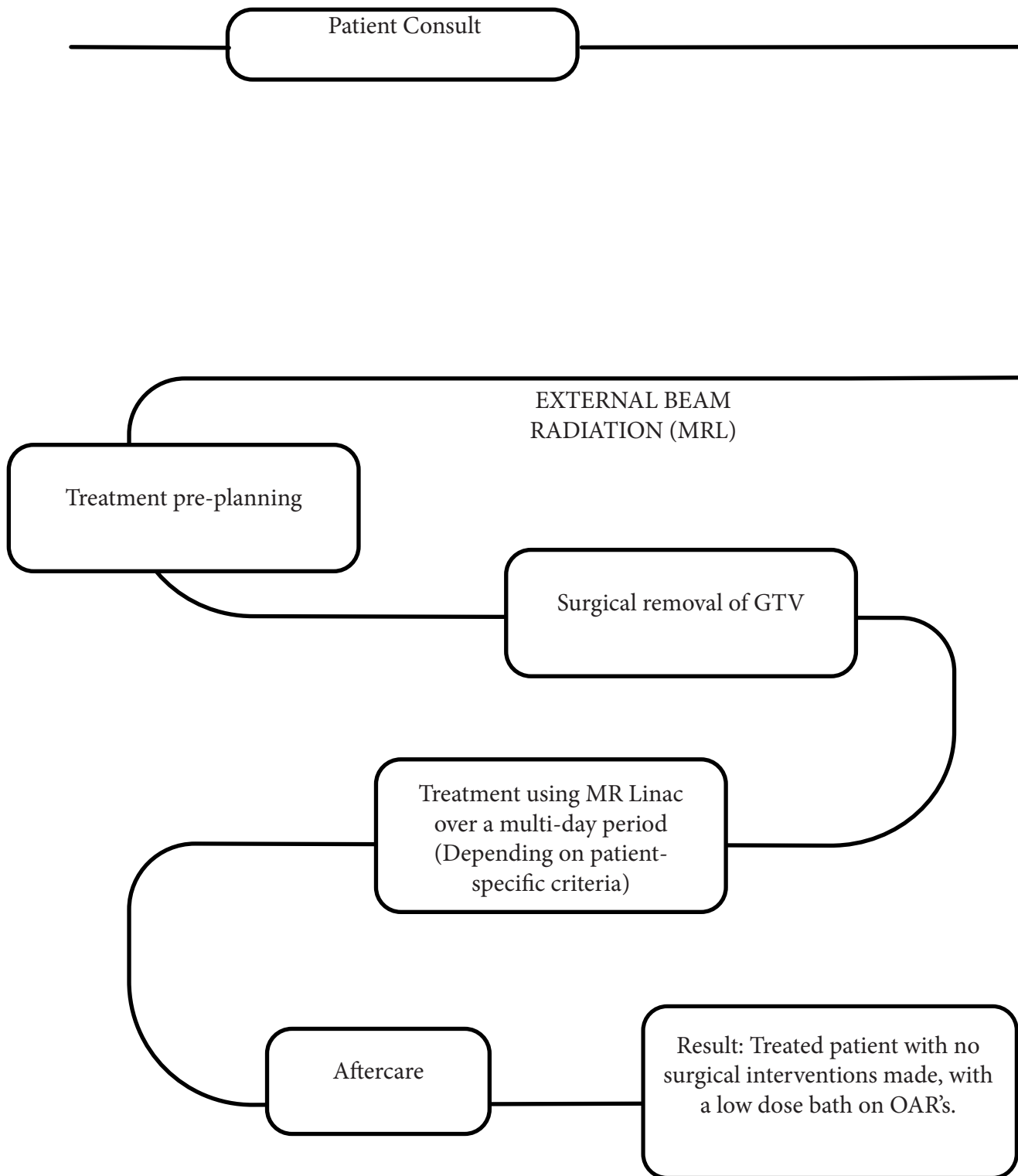
OCB

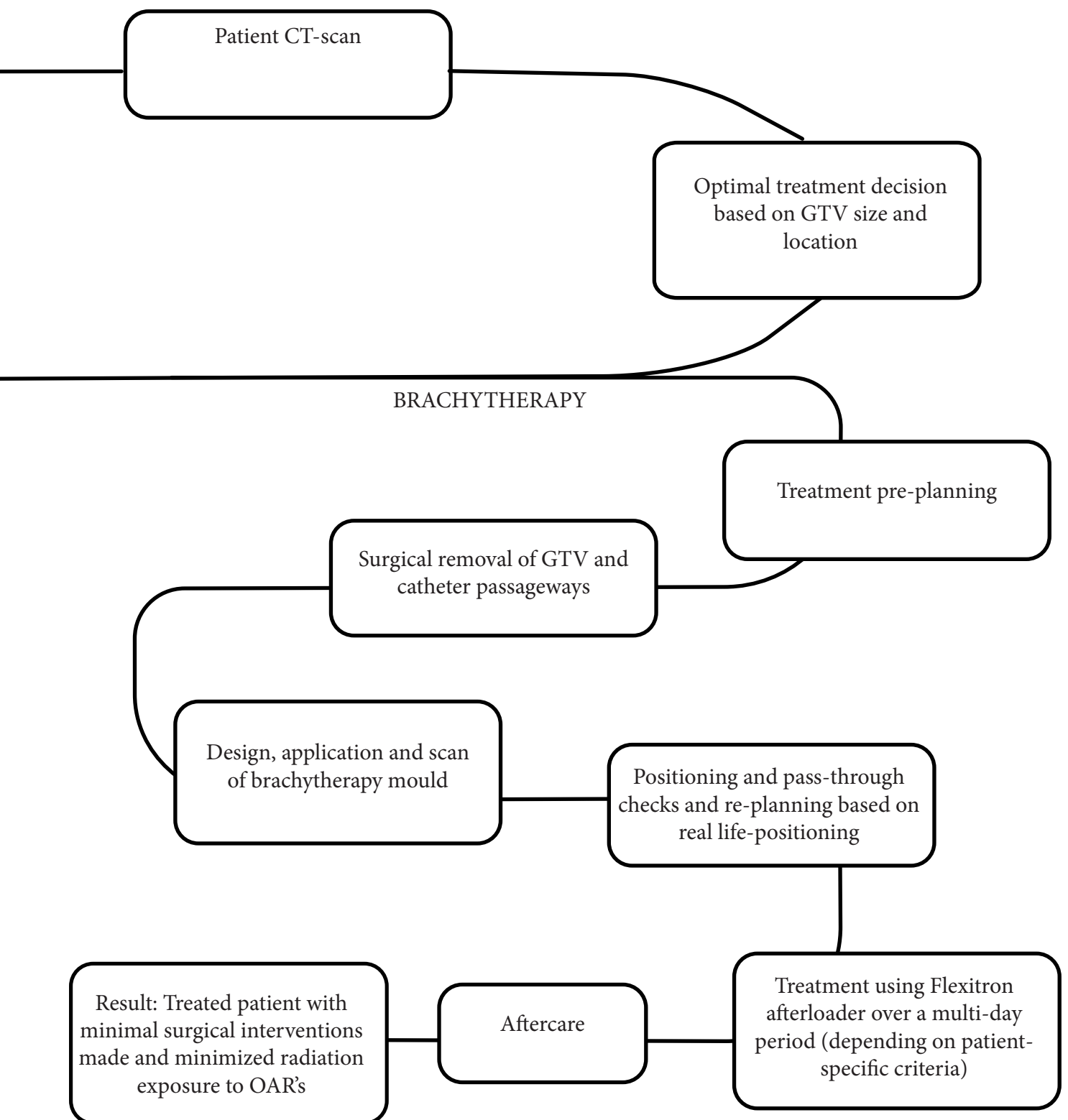


Materialize

Appendix B:

Current UMC Utrecht procedure journey





Appendix C:

Expanded risk analysis

Category	Risk	Potential Impact	Potential mitigation strategy
Clinical	Misalignment with real clinical workflow	Low adoption, overcomplication of workflow, over-increase of treatment steps	Early and repeated clinical validation, workflow simulations
Clinical	Insufficient treatment performance	Suboptimal dose distribution -> clinical rejection	Quantitative dosimetric validation (through scans and comparison with current treatment)
Patient safety	Tissue damage, perforation, misplacement, improper radiation results	Patient harm, regulatory halt, reputation damage for the UMC Utrecht	Anatomical tolerance analysis, cadaver testing, human testing before clinical use
Patient safety	Sterility failure	Infection risk, patient harm, regulatory halt	Early sterilization consult from professional companies or experts, using compatible materials from the start
Regulatory	Insufficient or incorrect technical documentation	Approval delay, increased compliance burden	Maintain design history file (version history management)
Technical	Material incompatibility (biocompatibility, degradation)	Iteratively testing and redesigning	Early material screening, through literature studies and small-scale material testing
Technical	Integration with existing system fails	Clinical impracticality, incorrect source location behavior, breaking components, catheter resistance	Early identification of existing component limitations, safe small-scale tests to prove compatibility
Dosimetric	Inaccurate source positioning	Underdose/overdose of target or OARs	Tolerance analysis, imaging verification, fixation mechanism optimization through iterative testing
Sustainability	Single-use waste burden	Environmental and cost concerns	Explore recyclable polymers, modular/reusable components where safe

Financial	Underestimated development costs	Project discontinuation, spending time on financial sponsors	Early cost-modeling, exploration of cheaper options for development in graduation timeline
Stakeholders	Limited clinician availability	Limited feedback, incorrect assumptions,	Identify availability, co-creation sessions and prepare meetings for efficiency
Ethical	Premature clinical testing	Patient harm, reputational damage	Strict adherence to ethical review procedures, phased validation strategy, early incorporation of notified bodies
Timeline	Overambitious scope for graduation timeframe	Incomplete validation for continuation beyond graduation timeline	Clear scope boundaries, focus on proof of concept
IP	Freedom-to-operate conflicts, continuation discussions, financial disputes	Legal barriers, discontinuation	Preliminary IP discussion and legal documentation
Data	Overreliance on limited case data	Poor generalizability	Use representative case sets, document assumptions transparently

Appendix D:

A short design sprint on creating a connector piece between a balloon and the elekta lock-insert

As previously stated, the UMC staff mentioned concerns with the complexity a connection between their tried and tested lock-inserts and a leak-proof balloon would bring.

The connector piece is created on the idea of squeezing the balloon sleeve as tight as possible, creating a watertight fit without the use of any glue or heat.

The design has an embedded slot for a rubber ring which can be bought from third party suppliers, this rubber ring creates the first seal around the already tight balloon sleeve. To fully ensure the balloon and rubber ring stay in their designated place, a slide-lock is designed with a triangular lock.

The assembly process would be as follows:

1. Pull the balloon sleeve over the end of the connector to which the arrow points.
2. Put the rubber ring over the balloon sleeve, on the beveled slot where it should fall in naturally.
3. Once all components are in place and the balloon length is controlled . Push the slide-lock over the rubber ring until it clicks
4. Go to the next steps of assembly

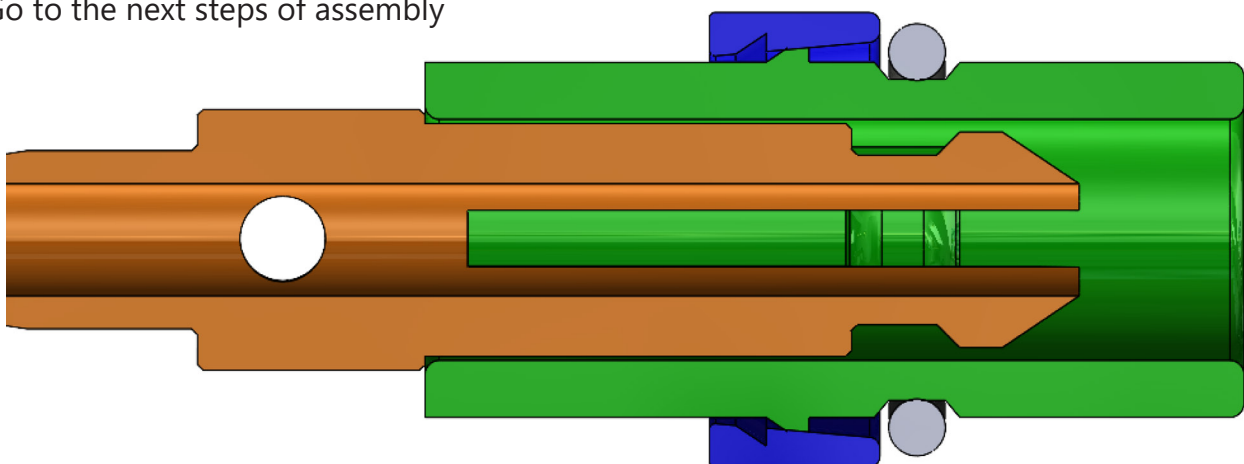
After connecting the lock-inserts to the individual balloons, the subassemblies can be combined to create the final custom balloon structure.

Out of the radiation plans an ideal number of catheters should be identified. The amount of catheters could directly be linked to the amount of balloons in the final assembly.

By inflating each balloon with a pre-determined amount, theoretically a vast variety of orientations can be reached.

The balloons are connected by a designed flange in the balloon mold, which can be inserted in a 3D printed central hub. Depending on the amount of balloons and maybe even the curvature of the balloon paths, for cases where a bend needs to be made. The design of this central piece is very case-dependent as depth, curve and amount of balloons varies greatly.

Looking at the aforementioned list of requirements and design implications from the research chapters, the second concept:



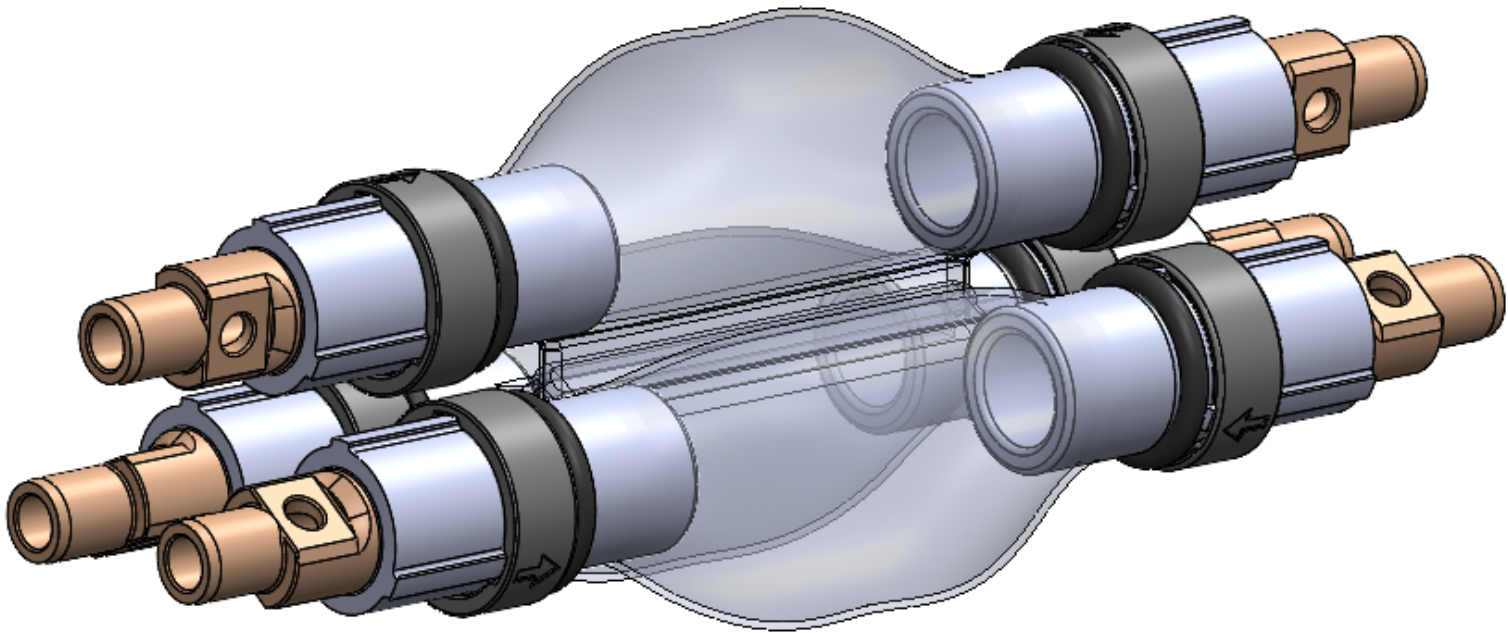


Figure 36: Concept 2 assembled in SolidWorks

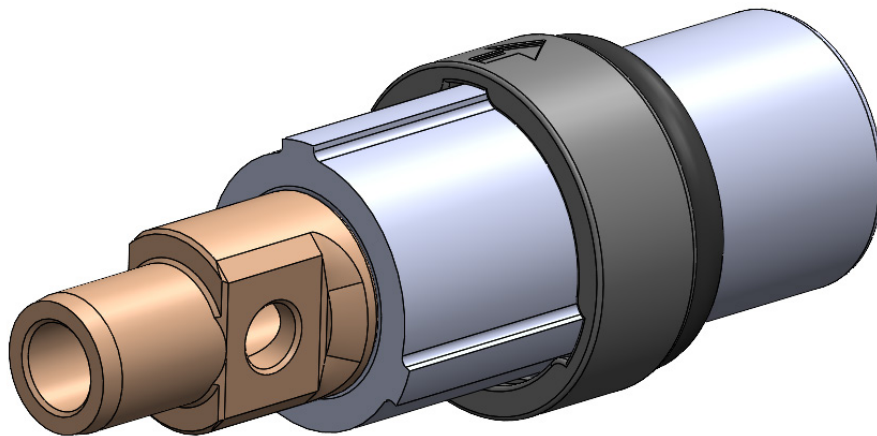


Figure 37: lock-insert connector

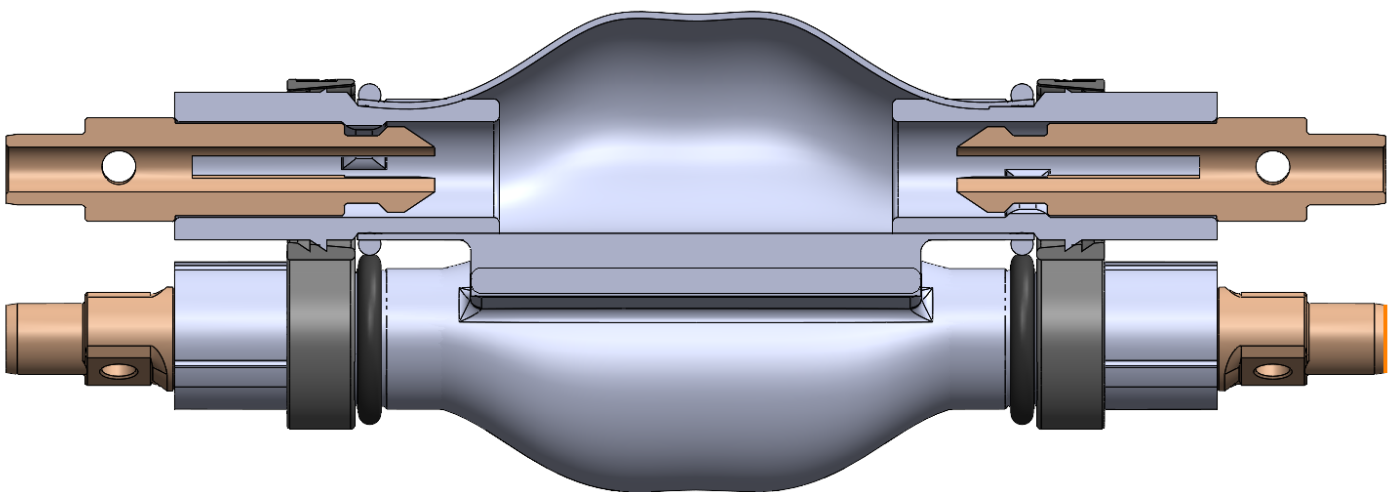


Figure 38: A cross-sectional view of the assembly of concept 2

Appendix E:

How AMORE's are made and used

The UMC 3D-specialists extract 3D files from their scans and imaging software for creating the molds and amores they use to treat their patients with.

They do this by drawing the volume with a digital brush tool layer by layer. The software meshes these layers together to form a 3D-model that can be edited in CAD or mesh modelling softwares.

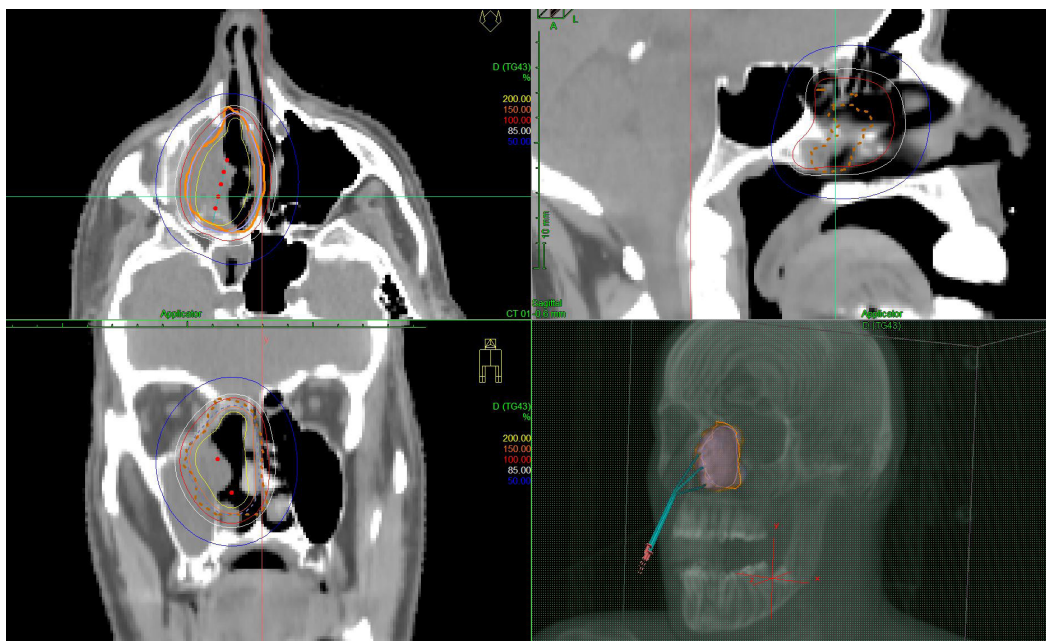
Treatment with amore's at the UMC Utrecht is something that is very briefly explored in this report, but might need some additional explanation.

To explain this principle a bit more, a theoretical case used earlier in this report will be used.

In the screenshot provided below a digital amore can be seen. It is basically visualized as the ideal water-equivalent shape that (if it can be physically placed) would create an optimal treatment situation. This volume could be 3D-printed out of PEEK, to guide the catheters and keep them in place for the 10-day treatment period.

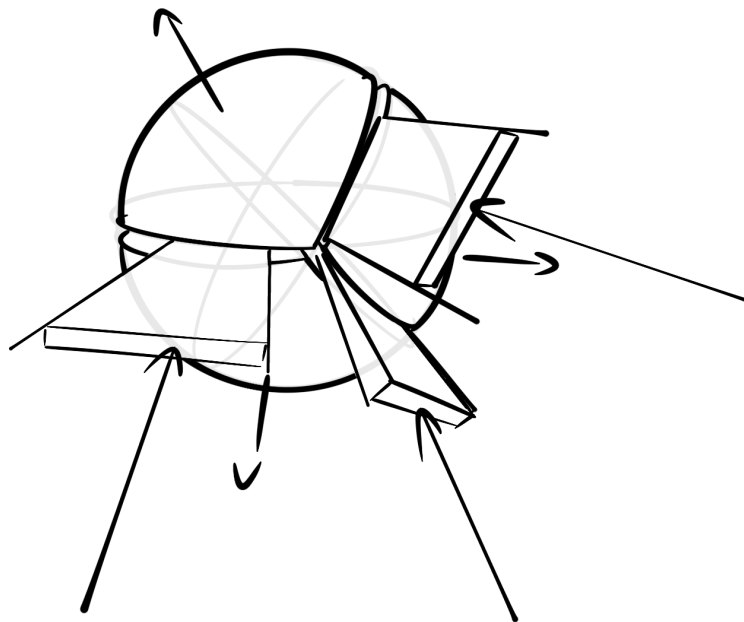
However, a volume this large can not physically be placed inside the patient without surgical intervention.

One of the early ideas of this project was to design a mechanism that could split this amore in multiple parts that could be re-assembled in the nose. However, the solution was assumed impractical with the

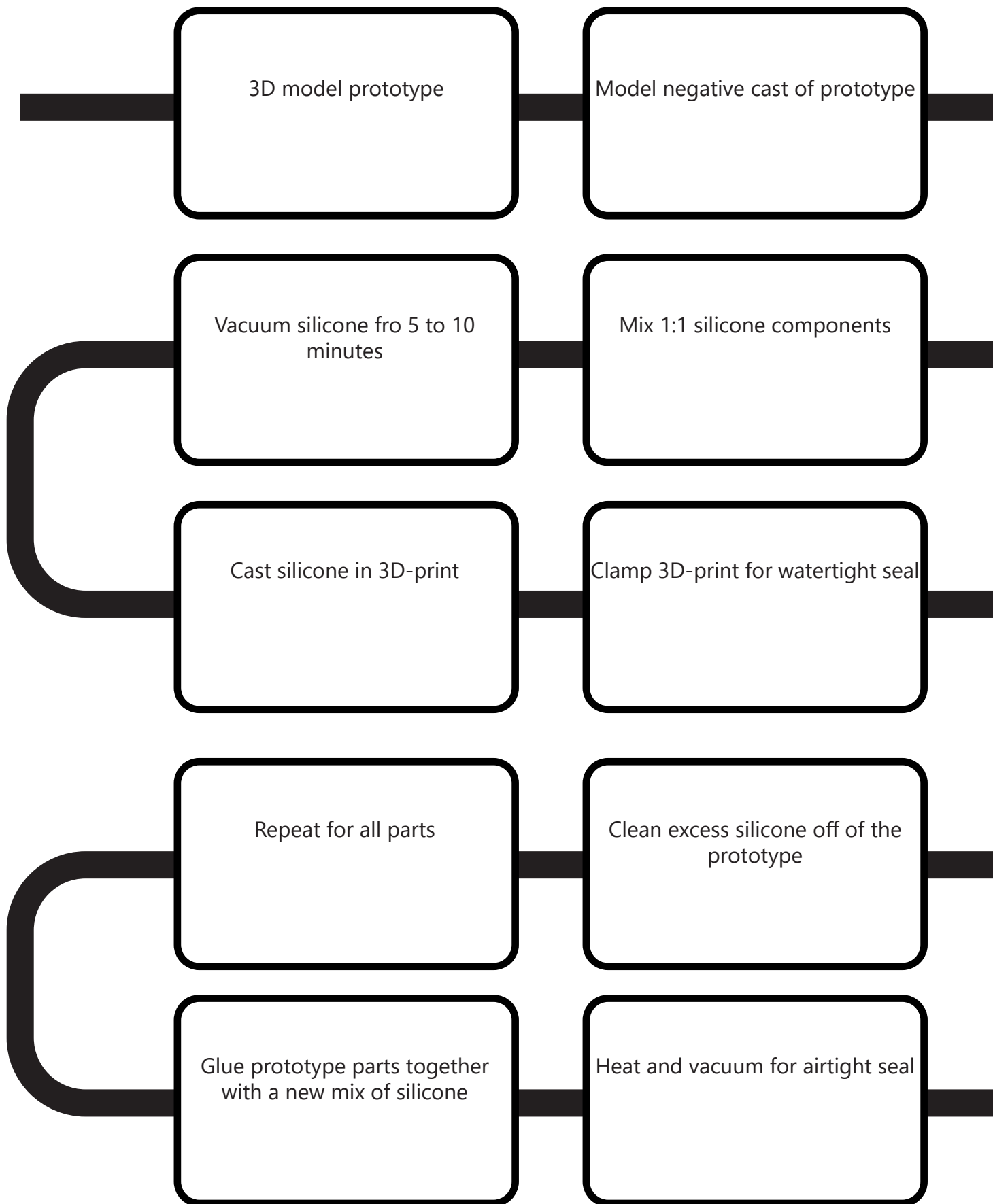


bending radii of the catheters when moving the individual parts through the nostril entrance.

Another way of using this amore technique which is actually applied by the UMC radiotherapy section, is the application of amore's in the eye sockets of patients with tumours around the eye. In these cases the amore is drawn digitally conform the dimensions of the eye socket, the 3D-model is split up into multiple segments, and the segments are kept in place by wedges that fixate them in situ.



Appendix F: Prototyping manufacturing roadmap



Define and implement release angles and -directions

Design connections in between the cast pieces

Spray release solvent on contact surface with prototype

3D print cast

Wait until air escapes and top off cast for a homogenous prototype

Wait approximately 4 hours until the silicone has hardened

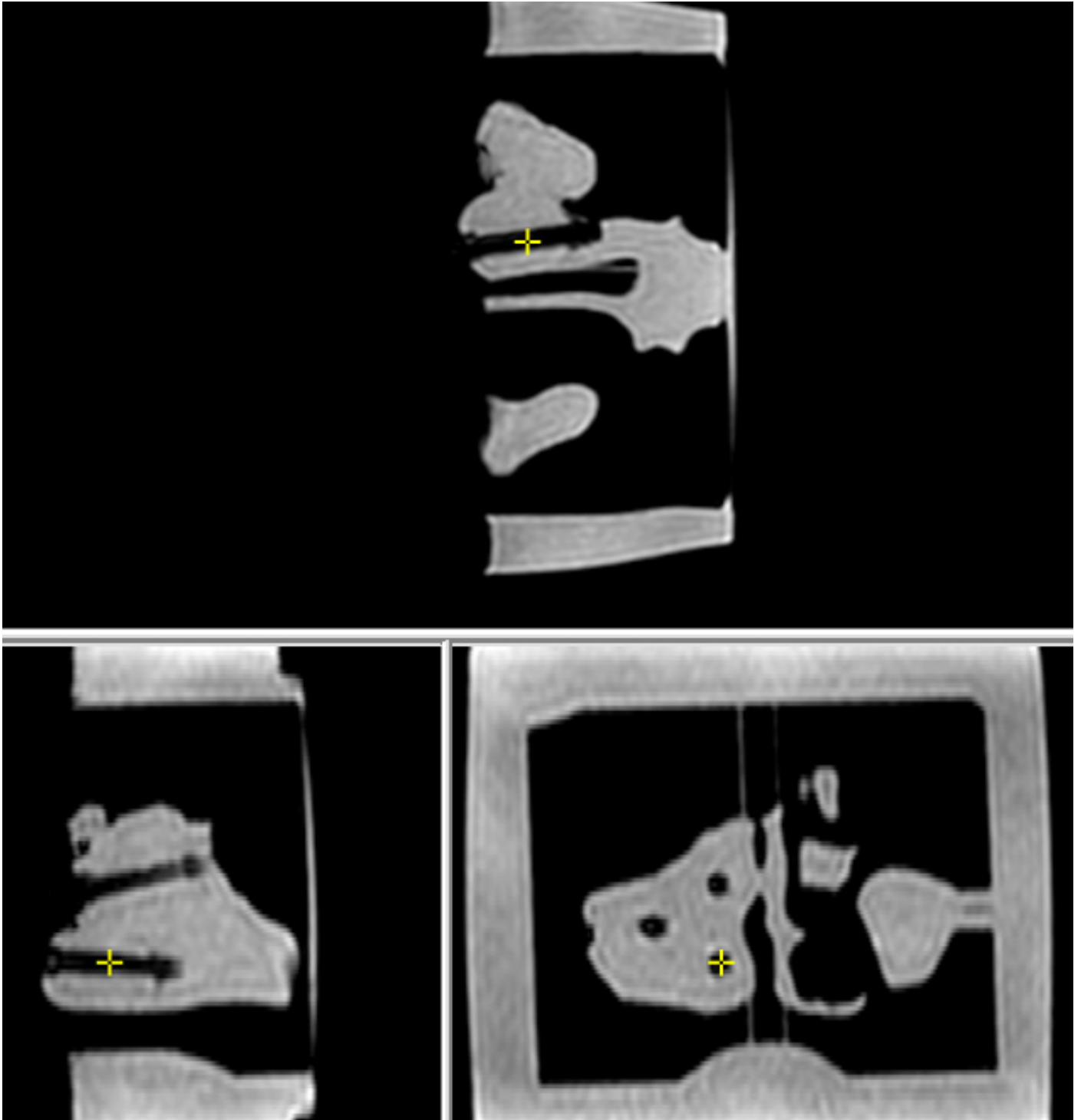
Take 3D-printed cast apart carefully

Remove clamps and clean off excess silicone

Clean off excess silicone

Appendix G:

MRI scans



The MRI-scans of the applicator are significantly more difficult to read than the CT's. This is mainly due to the applicators material behaving identically to the material of the phantom head. Next to that the water, used to inflate the applicators balloons, has an almost identical profile to the air-pockets in the phantom. This complicates identification of the applicators volume and the air pockets around them.

Mainly due to these reasons, the CT-scans are preferred over the MRI scans, when attempting to identify the applicators behavior in a phantom situation.

In a real human head however, the different tissues could possibly be more easily identified with an MRI.

Appendix H:

Calculating applicator effectiveness and efficiency through conformity analyses

$$c_1 = \frac{PTV_{ref}}{PTV} \quad c_2 = \frac{PTV_{ref}}{V_{ref}}$$

C1: Calculating the fraction of the PTV (in our case CTV) that is enclosed by our applicators 100% line

C2: Calculating the fraction of the applicators isodose lines that is covered by the PTV (in our case CTV)

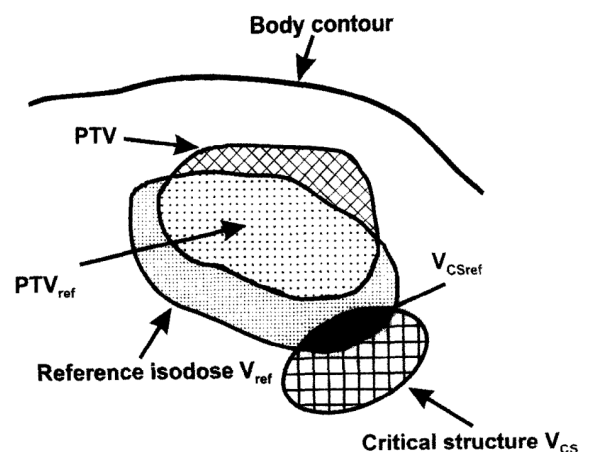
C = 1 is ideal for both coefficients

$$COIN = c_1 \times c_2 \times c_3$$

The conformal index COIN is the product of both coefficients.

The closer to 1, the better the applicator performs

$$c_3 = \prod_{i=1}^{N_{cs}} \left[1 - \frac{V_{CSref,i}}{V_{CS,i}} \right]$$



A third coefficient can be calculated for $i = 1, 2, 3, \dots$ amount of OAR's where V_{cs} is the volume of the OAR and V_{csref} is the overlap between the 100% line of the applicator and the OAR volume ()

$$CI = TV_{PIV} / TV$$

$$HTCI = TV_{PIV} / PIV$$

A second conformity analysis employed by the UMC Utrecht researchers in Van Noortwijk et al. (2025) works as follows:

TV represents: Target volume

TV_{PIV} represents: volume of TV receiving the prescription dose (PIV)

CI (Conformity Index) indicates the coverage of the target by the prescription dose

HTCI (Healthy tissues conformity index) indicates the amount of prescription dose outside the target

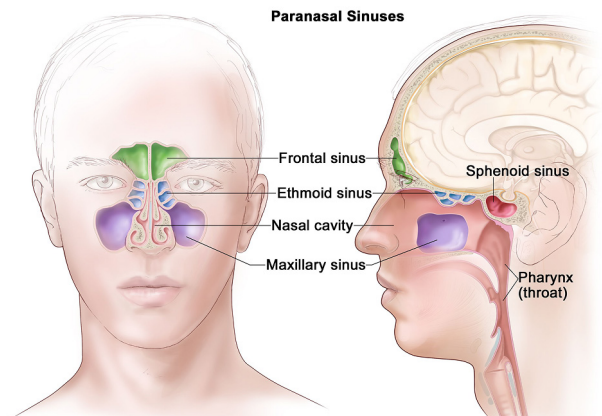
With an applicator like the one designed in this study the CI is the most prominent value for indication of effectivity as the PIV mostly exceeds the TV, but not into healthy tissue as the balloons cover most of the excess PIV.

Appendix I:

3D printed biocompatible shape morphing device for innovative cancer treatment

Background

Paranasal sinus cancer is a rare type of cancer originating in one of the paranasal sinuses (see figure). Optimal treatment consists of endoscopic debulking via the nostrils followed by radiation. Since the paranasal sinuses are located in an anatomical challenging area between the eyes, skull base, upper jaw and vertebral column, cancer treatment in that area can be accompanied with a high risk of (serious) complications. The radiation is delivered via external beam radiation, consisting of a photon beam generated by a linear accelerator. With that photon beam we are capable of delivering high doses of radiation accurately



at small areas. The downside is the inevitable “bath” of low dose in the trajectory of the beams, causing unwanted side effects like cataract, dry eyes, dry mouth/throat, visual decline, cognitive decline and more. Brachytherapy is another method of delivering radiation dose, whereas this method uses I-192 sources to deliver radiation. This source can be guided through wires, meaning that everywhere in the body where it is possible to stabilize a wire it is possible to deliver radiation via brachytherapy. The intensity of radiation decreases inversely with the square of the distance from the I-192 source. With that, brachytherapy for paranasal sinus cancer would be the most optimal way of delivering postoperative radiation since the “low dose bath” is very limited with this technique. Currently, there is no device or material that is capable of stabilizing wires within the paranasal sinuses after surgery.

Given that it should be possible to introduce the device or material via the nostrils (shape morphing), leave it in the nasal cavity or paranasal sinuses for a certain time (shape memory) and remove it again via the nostrils (shape morphing again) would change the field of this cancer treatment tremendously. Patients would suffer from less side-effects and the radiation doses would be delivered more precise.

At the Industrial Design Engineering (IDE) faculty, the [Emerging Materials Lab](#) focuses on designing shape morphing objects using shape memory materials. These materials belong to the smart materials group, known for their ability to change properties in response to external stimuli like heat or a magnetic field. They exhibit kinetic effects, allowing them to move or change shape. Designers leverage these materials and their creative freedom to develop interactive objects that establish dynamic relationships with users.

The aim of this graduation project is to develop printable biocompatible (smart) material that can be modified in shape and hold its shape after the shape modification.

In this project

You will design a prototype using smart materials capable of shape morphing and shape retention. The key objectives are: developing a biocompatible smart material system, ensuring the prototype that can be customized for patient-specific or post-surgical cavity applications, demonstrating shape morphing capabilities and shape memory properties.

This project offers a unique collaboration between TU Delft and UMC Utrecht. This collaborative effort offers a unique opportunity to work on a project with significant social impact. Students interested in technology-driven healthcare are encouraged to apply.

Supervisory team

Sepideh Ghodrat (s.ghodrat@tudelft.nl) expert on the technological part and developing smart material systems.

Mischa de Ridder (m.deridder-5@umcutrecht.nl) expert in radiation oncology and developing brachytherapy techniques

Maarten Kastelijns (m.h.g.Kastelijns@umcutrecht.nl) expert in 3Dprinting of biocompatible applicators for brachytherapy

Johannes Rijken (J.A.Rijken@umcutrecht.nl) expert in head and neck surgery, specifically paranasal and skull base surgery.

Appendix J: Complete List Of Requirements

Requirement	Check	Source
Catheter flexibility needs to be identical to present radii	Yes, but	During pass-through tests and CAD-geometry validation, no radii exceeding the limitation of 15mm were identified. The radioactive source passed through both CTV-orientations without issues. With more testing, situations could arise where this minimum bending radius causes issues
The CTV will be patient specific. The applicator must be adaptable to patient specific anatomies	Yes	The CTV case-studies suggest adaptability to patient specific anatomies. However, more anatomies need to be tested to completely verify this statement. Application to different age groups and genders, would incready validity of this verification.
Catheter orientation must be predictable meaning it can be planned beforehand	Yes	The CTV case studies showed that catheter orientation can be predicted before placement, more practise and case-studies are however needed to improve the skill placement and of pre-planning within applicator constraints.
The applicator must be biocompatible	Yes	Based on the bio-compatibility of the original PORGES catheters (medical silicone) and the application of PEEK in-house 3D-printing the applicator can be made bio-compatible for a 10-day treatment period
Must be deployable endoscopically	No, but	When working with three applicators, the room for an endoscope in the same nostril would need to be tested (four applicators will not leave enough room). When opening the nasal septum, the endoscope can be used to place the applicators through the second nostril. This assumption is shared in collaboration with UMC experts
All materials must be MR-safe (non-magnetic)	Yes	The silicone / latex combination of the PORGES applicator is MRI safe, just like the 3D-printed PEEK material (lock insert connectors and button ends, the catheters, and the stitch-mold
Radiation must not be in direct contact with tissue	Yes	The silicone / latex material completely covers the radioactive source. The button-end prevents the source from escaping the applicator and the balloons filled with NaCl visually cover the 200% isodose lines.
Tolerances for swelling must be taken into account	Yes	This requirement remains theoretical. The balloons should be able to adapt the swelling of tissue, however, the displacement of the catheters remains to be tested in non-rigid environments.
Electronics are a no-go during radiation (possibly placement / removal at low power)	Yes	As no SMAs are used (yet), no activators such as electricity are needed and therefore this requirement poses no threat to further development
The device needs to be able to remain in situ for 2 weeks	Yes, but	With previous uses of the PORGES-14 catheters the balloons remained accurately inflated during a 2-week period, however, displacement of the catheters has not yet been tested.

Must be applied non-invasively	No	Beyond the aspect of surgically removing the Gross Tumor Volume there are some internal structures such as the septum which will likely have to be (partly) opened for accessibility and fixation.
Must remain within stable margins (1mm total (Tiong et al. (2009) -> 3mm. With H&N this margin will be smaller)	No	More validation is needed to provide an answer to whether this requirement can be checked. The catheters seemed visually stable with multiple scans in a rigid phantom environment. However, there are many variables that might change this in a real-life situation.
The applicator must be sterilizable	Yes	Making use of the manufacturing methods of the existing PORGES applicators, we can assume the redesign can be delivered as sterile as the existing applicators.
Application must take no longer than 1 hour	Yes, but	The application of the applicators in a phantom took no more than 5 to 10 minutes, to place the applicators with an endoscope in a real-life situation will be more difficult and time-estimations would need further testing.
Must be visualizable on CT and MRI scans	Yes	The applicator is adequately visible on CT-scans with copper imaging wire for catheter orientation validation. On MRI, the applicator is less visible in a phantom setup. A real-life situation is assumed to be more visible.
Needs to be removable without invasive surgery	Yes	By deflating the inflatables, removal should be as simple as pulling them out of the nostril. With phantom testing this posed no issue, but with real-life testing the requirement could be tested more thoroughly
Needs to facilitate complex patient-specific dosimetry plan (>1 line of dwell points)	Yes	As shown in both CTV's the use of multiple applicators proved to be possible where each applicator served a crucial function in the dosimetry plans.
The expansion ratio of the design should be within the range of 1 : 5 and 1 : 10.	Yes	The PORGES-14 applicators have a minimum diameter of 4.5mm and a maximum (inflated) diameter of 25mm, resulting in an expansion ratio of 5.5. With different dimensions this expansion ratio could be increased if necessary.



Personal Project Brief – IDE Master Graduation Project

Name student Jens Schout

Student number 5,091,802

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT

Complete all fields, keep information clear, specific and concise

Project title Designing a Brachytherapy stabilizer for paranasal sinus applications using shape morphing materials.

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

Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

At the University Medical Center of Utrecht recurrent paranasal sinus cancer remains difficult to treat. Paranasal sinus cancer occurs in the airpockets around the nostrils, a difficult area to treat as it is close to critical organs such as the brain, eyes and throat.

Current treatment happens through surgeries, chemotherapy or photon beam radiation therapy. Each of these treatments are extensive; require multiple long hospital visits and leave lasting side effects such as facial scarring, systemic health decline, or damage to surrounding organs. While other methodologies for treatment are behind in innovation.

An example of such is brachytherapy, where I-192 isotopes in combination with Pt192 are held close to the tumor to radiate it in a concentrated manner without much radiation affecting the surrounding tissue and organs. This therapy, first used in 1901, is used in many other parts of the body such as the lungs or breasts but has not yet been widely applicable to cases in the head and neck (A. Budrukhar et al. (2023)).

The UMC expert in radiation oncology and development of brachytherapy techniques Mischa de Ridder, together with expert in 3D printing biocompatible applicators for brachytherapy Maarten Kastelijns, and nasal surgeon Johannes Rijken have presented the challenge of designing a biocompatible brachytherapy wire stabiliser for the paranasal sinus to treat paranasal sinus tumors more effectively and reduce consequences for patients.

They already show innovative ways of brachytherapy stabilizers on the front of the nasal cavity, but the paranasal sinus seems more difficult to navigate. Likely needing new materials and/or mechanics to reach the targeted area and remain in place for long enough.

introduction (continued): space for images

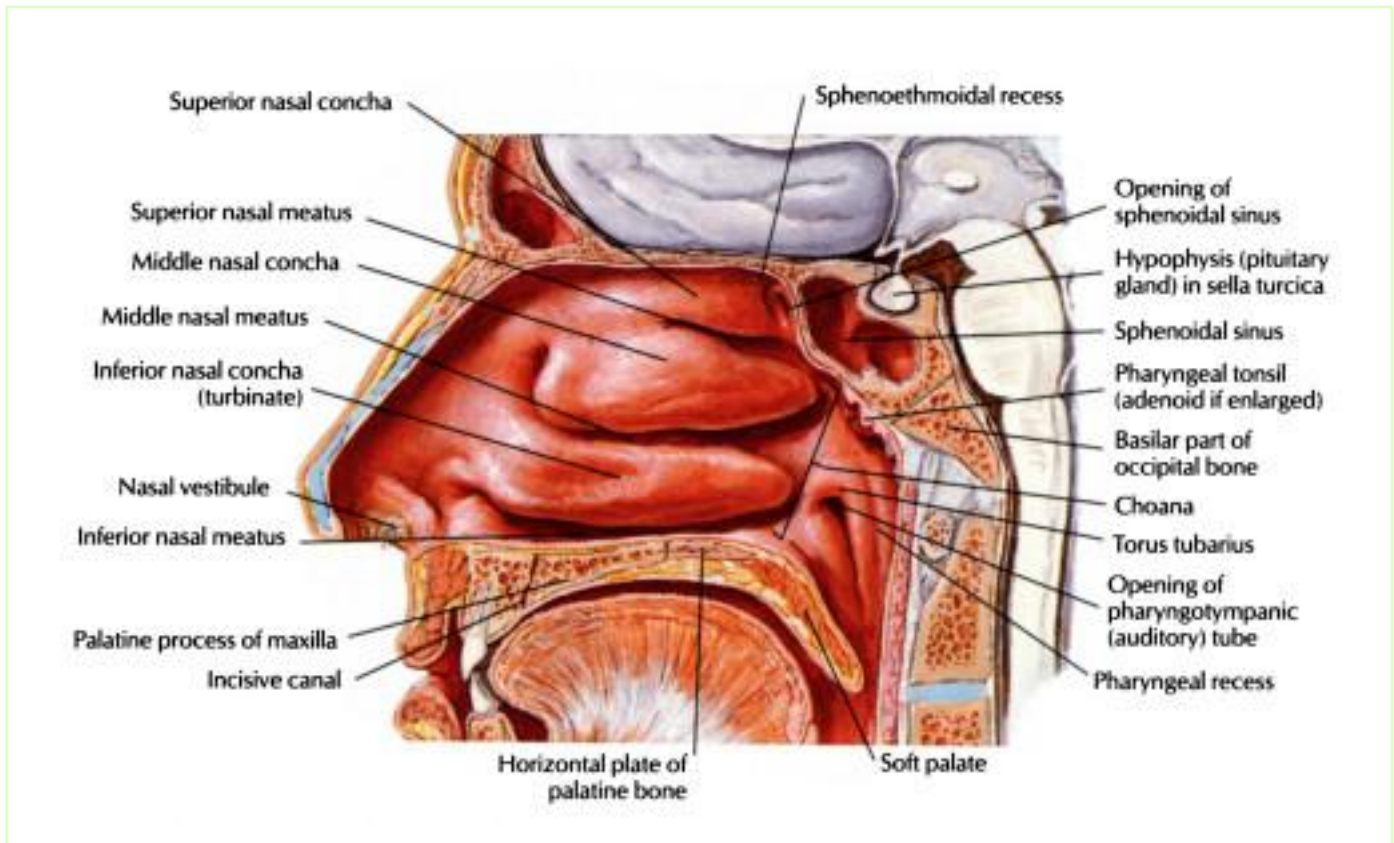


image / figure 1 Anatomical overview of the paranasal sinus structure

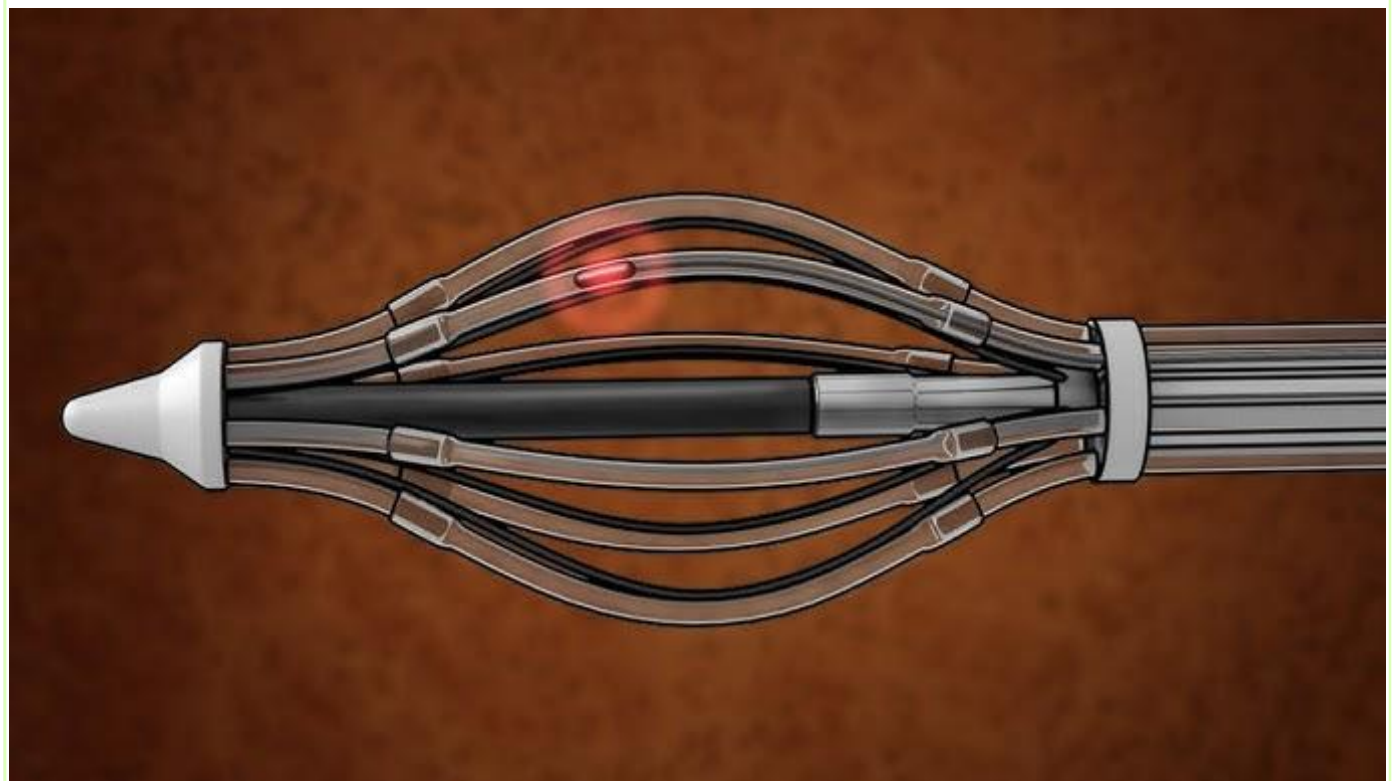


image / figure 2 An exemplary brachytherapy catheter for breast cancer treatment

Personal Project Brief – IDE Master Graduation Project

Problem Definition

*What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.
(max 200 words)*

Existing treatments for paranasal sinus cancer are invasive and often harm surrounding organs. Surgery leaves facial scars, chemotherapy weakens overall health, and photon radiation can damage critical areas near the tumor. All require frequent hospital visits and prolonged recovery.

Brachytherapy could address these issues by placing radioactive catheters directly around the tumor, minimizing exposure to surrounding tissue. In practice, however, stabilizing these catheters in the paranasal sinus is technically challenging. The anatomy involves narrow passages and sharp curvatures, making standard straight catheters impractical without invasive access. A stabilizer must therefore guide and secure multiple ~2 mm diameter catheters through complex geometries while resisting displacement over the ten-day treatment period. It must remain biocompatible, sterilizable, and manufacturable, ideally through additive methods to allow patient-specific adaptation. Furthermore, dosimetry parameters, such as distance from tumor margins, surrounding material density and catheter spacing impose strict constraints on the design.

The opportunity lies in creating a device that balances these medical and technical requirements, enabling minimally invasive brachytherapy in a region where conventional treatments are the exact opposite. Such a solution would reduce long-term side-effects for patients and improve efficiency for clinical staff.

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence) As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:

Create a design to evaluate the possibility of paranasal brachytherapy without large surgical interventions for more effective and less intrusive paranasal cancer treatment for both patient and hospital staff through iterative prototyping.

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

The beginning of the project will be dominantly researching the context and clinical requirements of the final product such as: sterilization standards, anatomical constraints, material constraints (eg. patient-safe shape morphing material triggers) and dosimetry parameters (eg. the density of smart hydrogels).

With these requirements in mind 3-5 concepts will be developed, exploring different mechanisms and (shape morphing) materials that could guide and stabilize the catheters. These concepts will be compared against the previously stated medical and technical criteria to choose the most promising direction of development.

This direction will then in turn be developed through iterative prototyping and testing. Later versions will be evaluated on artificial anatomical models created from anonymized patient data provided by the UMC or ENT training models.

The final stage of the project will aim to deliver proof-of-concept prototypes that demonstrate whether minimally invasive brachytherapy for paranasal sinus cancer can be made technically and clinically feasible without human testing.

Project planning and key moments

To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a **kick-off meeting, mid-term evaluation meeting, green light meeting and graduation ceremony**. 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 course activities).

Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting 19 Sep 2025

Mid-term evaluation 28 Nov 2025

Green light meeting 3 Feb 2026

Graduation ceremony 23 Feb 2026

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	☐
For how many project weeks	
Number of project days per week	

Comments:

Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five.

(200 words max)

After completing a broad range of courses in Industrial Design Engineering and an internship at ManGo Product Design as a product engineer, I discovered that what excites me most in design is the process of problem definition, solution orientation, and concept development. This graduation project combines all three in a highly meaningful way: addressing a complex medical challenge with an equally complex engineered product, while also carrying both societal impact and opportunities for design innovation.

What appeals to me most is the interdisciplinary aspect of the project. It requires close collaboration between material scientists and biomedical experts, integrating knowledge from both expertises into a patient-specific medical device. This aligns well with my experience in collaborative projects at the faculty, where I often took on the role of facilitator: listening to the perspectives of all team members and steering discussions toward effective solutions.

By working on this project, I aim not only to deepen my technical expertise in smart materials, medical product design and product engineering, but also to contribute to a solution that has the potential to improve patient outcomes in cancer treatment.