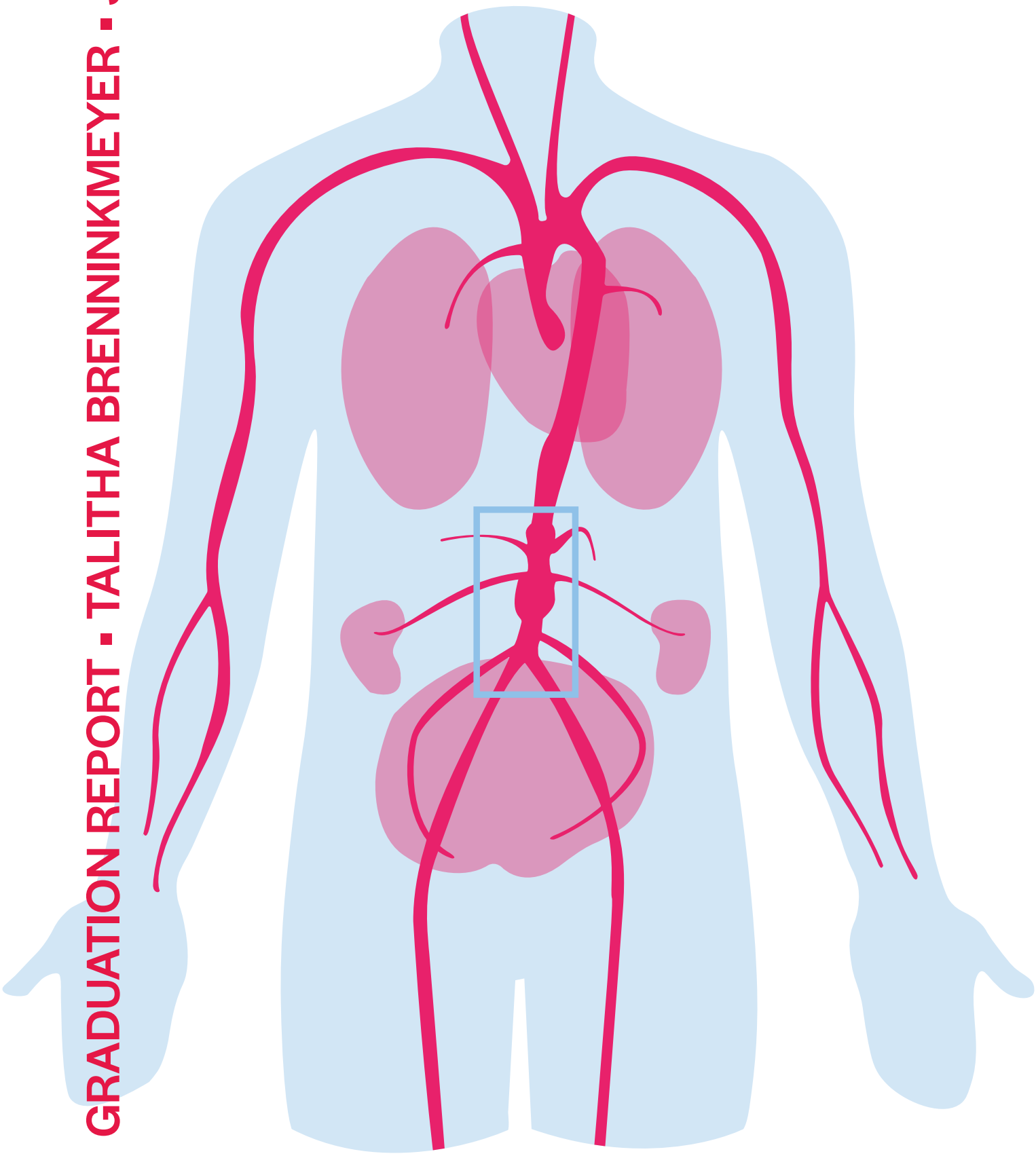
THE PENTAPORT

DESIGNING A SAFE GATEWAY FOR COMPLEX ENDOVASCULAR AORTIC REPAIR

GRADUATION REPORT • TALITHA BRENNINKMEYER • JULY 2021



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DESIGNING A SAFE GATEWAY FOR COMPLEX ENDOVASCULAR AORTIC REPAIR

TALITHA BRENNINKMEYER

GRADUATION REPORT ▪ 02 JULY 2021
MSC INTEGRATED PRODUCT DESIGN ▪ TU DELFT
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INTRODUCTION

PART 1

1. GLOSSARY

AAA	Abdominal Aortic Aneurysm
Aneurysm	A portion of an artery that has weakened and bulged.
BEVAR	Branched Endovascular Aneurysm Repair
Bilateral	Approaching from the right and left sides of the body
Brachial access	Access via the artery in the upper arm
Catheter	A thin tube that is inserted into the body to provide or drain fluids, or to carry tiny surgical instruments and cameras in minimally invasive surgeries.
Dilator	A surgical instrument to expand an opening or passage.
Distal	Located farthest away from the body's centre (opposite of proximal)
Endo	Within / inside
Endoluminal procedure	Procedures performed in a hollow organ.
Endovascular	Within the blood vessel
EVAR	Endovascular Aneurysm Repair, only used for infrarenal (below the kidneys) AAA
Ex vivo	Outside of a living body
Femoral access	Access via the artery in the groin
FEVAR	Fenestrated Endovascular Aneurysm Repair
Hemostasis	The process to prevent and stop bleeding, meaning to keep blood within a damaged blood vessel.
Hemostatic valve	One-way valve that allows instruments such as catheters or cameras to open and pass through the valve and close automatically as soon as the instrument is withdrawn.
IFU	Instructions for Use
In vivo	Within a whole, living organism
Infusion	The slow injection of a fluid into a vein or tissues.
IR	Interventional radiologist
Ischemia	Damage or dysfunction of tissue due to oxygen shortage
Lumen	The hollow part of a tube.
OR	Operating Room
MDD	Medical Device Development
MDR	Medical Device Regulations by the EU
Percutaneous	Performed through the skin
Proximal	Located closest to the body's centre (opposite of distal)
Sheath	Introducer catheter
Stent graft	A synthetic tube-like device used to replace a portion of an artery with an aneurysm, to prevent the aneurysm from bursting. Often a metal tube covered in fabric.
Suture	A stitch / row of stitches holding together the edges of a surgical incision.
TRL	Technology Readiness Level

1.1 READING GUIDE

This report contains nine parts, as presented on the previous pages, including five main parts:
- Medical background: relevant to understand the new device and its design process.
- Synthesis: translation of the essential conclusions from background research into design drivers.
- Concept development: summary of the design process.
- Final design: detailing and validation of the final concept, regarding desirability, feasibility, and viability.
- Future roadmap: benchmark of current level of technology development, and future steps for further design and medical device development.

Appendices can be found in a separate document.

Thank you for reading this report!

* French (F) is the common unit to describe diameter size of minimally invasive surgical tools. Sheaths are sized by their inner diameter, describing the largest size tool that fits through it).

Correspondingly, catheters and dilators are sized by their outer diameter (Kruse et al., 2011a).

DIMENSION UNIT COMPARISON						
Tool	Sheath	Sheath	Sheath	Sheath	Wire	Wire
French*	5	7	20	24	~	~
Inch	0.066	0.090	0.26	0.31	0.014	0.035
mm	1.67	2.33	6.67	8.00	0.36	0.89

Table 1.1 Comparison of frequently occurring dimensions of tool diameters

2. SUMMARY

"A ruptured AAA [Abdominal Aortic Aneurysm] is the 15th leading cause of death in the country, and the 10th leading cause of death in men older than 55" in the United States, states Singh (n.d.), in the Society for Vascular Surgeons. Such Abdominal Aortic Aneurysms (AAA, see Figure 2.2) are increasingly treated by endovascular surgery, during which stent grafts are placed in the ballooned vessel through access sites such as the femoral (thigh) arteries, a procedure called Endo Vascular Aneurysm Repair (EVAR). 10% of patients has an aneurysm near significant arteries (Mayo Clinic, 2019), called a complex AAA, requiring stent grafts fitted with fenestrations (FEVAR, see Figure 2.1) or side branches (BEVAR).

After puncture of the femoral artery, an introducer sheath is placed in the vessel, functioning as a re-usable access point to the arterial system. The sheath prevents blood from flowing out of the artery and enables entrance of tools such as guide wires, catheters and smaller sheaths into the arteries. However, treatment of complex AAA requires introduction of multiple tools (up to 5) through the sheath simultaneously, compared to just one or two during EVAR. With every additional tool being introduced, the valve's capability of adequate closure is reduced even more. This results in leakage that can lead to significant blood loss for the patient.

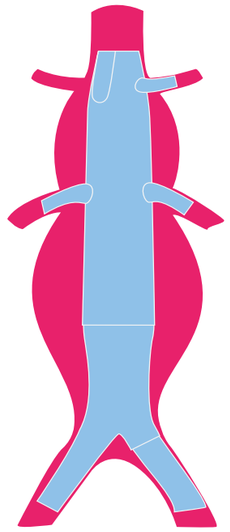


Figure 2.1 FEVAR stent in AAA

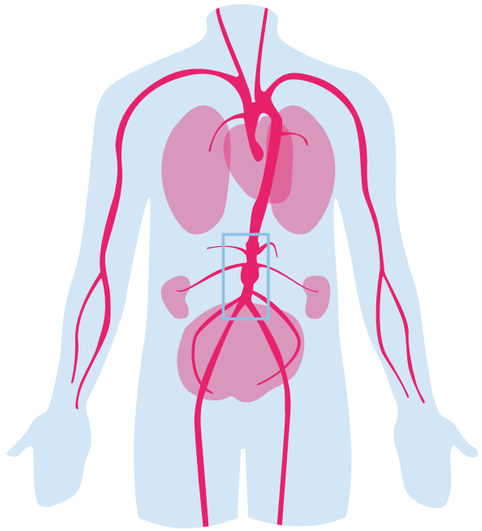


Figure 2.2 Schematic visualisation of an AAA

The Pentaport is a new, safe gateway for complex endovascular aortic repair (Figure 2.3). It functions as an add-on for commonly used sheath models. A leakproof 'plug & screw' connection facilitates safe and easy fastening to the DrySeal by W. L. Gore, which the design was optimised for during this project. The connection's design can be adapted to fit other sheath hubs, such as the Check-Flo by Cook Medical, requiring just one part to change.

The Pentaport minimises blood leakage by splitting the sheath's central lumen into five separate, diverging tool entrances. Each entrance has its own valve, ensuring optimal closure around an introduced tool, even after repetitive movement. Preventing severe blood losses of 2L or even more during one surgery, spares a heavy attack on the patient's condition and eliminates the need for costly consequences, such as cell-saving or blood transfusion.

In addition, the tools can be secured in the five entrances, containing locking mechanisms, to avoid dislocation of the catheters, preventing the need for lengthy recatheterisation efforts (up to 60 minutes) and possible harm to the patient's arteries. The locks also eliminate the need to have a constant grip on the tools, allowing a more comfortable position and better freedom of movement of the user's hand while holding the sheath. The locks' (colour-blind safe) colour-coding helps remembering the tools' locations and improves the medical team's communication.

The design was evaluated and proof of concept was achieved, through functionality tests in simulated environments (Figure 2.5) and usability tests with medical specialists (Figure 2.4). Future development routes are explored and first steps towards IP and publication are in progress.

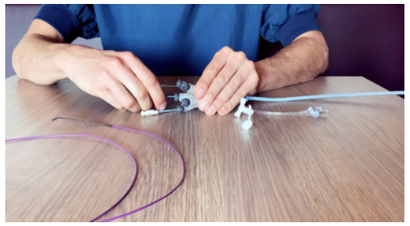


Figure 2.4 Usability test of the final prototype of the Pentaport

Figure 2.5 Functional test of the final prototype of the Pentaport

Figure 2.3 The Pentaport

3. INTRODUCTION

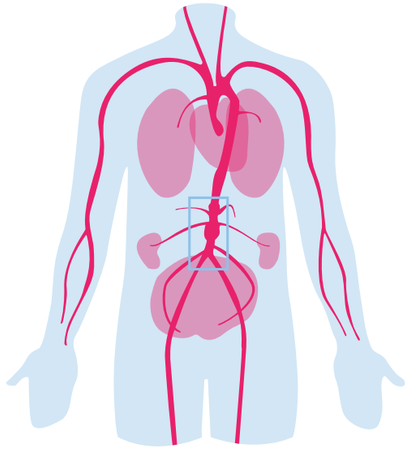


Figure 3.1 Location of (complex) AAA

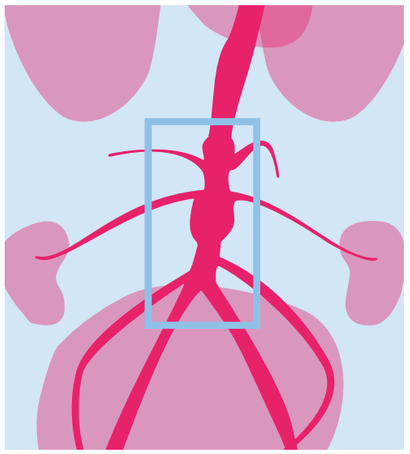


Figure 3.2 Zoomed in location of complex AAA

"A ruptured AAA [Abdominal Aortic Aneurysm] is the 15th leading cause of death in the country, and the 10th leading cause of death in men older than 55" in the United States, states Singh (n.d.), in the Society for Vascular Surgeons.

In 2019, 3607 people were hospitalised due to an Abdominal Aortic Aneurysm in our country (Nederlandse Hart Registratie, 2020). This number is equal to the population of Ameland (RegioAtlas, 2019), an island in the north of the Netherlands. Now, imagine that within a year, every single person on this island has to be hospitalised due to one disease: an Abdominal Aortic Aneurysm, or AAA in short. Consequently, 539 deaths were related to AAA in The Netherlands in 2019 (Nederlandse Hart Registratie, 2020).

Looking at other countries, prevalence is even higher and on a global scale, the number of aortic aneurysm patients is rising (Li et al., 2013 & Research and Markets, 2019).

3.1 MEDICAL TREATMENT

Treatment can lengthen the lives of AAA patients to a life-expectancy of more than 7 years after surgery (Schermerhorn et al., 2002, p. 1115), through open or endovascular surgery. During the latter, stent grafts are placed in the ballooned vessel (Figure 3.3); this procedure is called Endo Vascular Aneurysm Repair (EVAR). These stent grafts are implanted by minimally invasive, percutaneous surgery using access sites such as the brachial (arm) and the femoral (thigh) arteries.

After puncture, an introducer sheath is placed in the vessel, functioning as a re-usable access point to the arterial system. The sheath prevents blood from flowing out of the artery and enables entrance of tools such as guide wires, catheters and smaller sheaths into the arteries. However, a challenging factor for this type of treatment is that approximately 10% of patients has an aneurysm near significant arteries (Mayo Clinic, 2019), called a complex AAA (Figure 3.1 and 3.2). Initially, these patients did not qualify for endovascular treatment, as the stent grafts did not incorporate side branches to the kidneys, intestinal organs, stomach and liver, consequentially blocking these arteries' openings.

Due to technological advances, it has become possible to place stent grafts fitted with holes (fenestrations) or side branches, called FEVAR and BEVAR, respectively. These fenestrations and branches enable stent graft placement for complex aneurysms by incorporating visceral arteries into the treatment zone. Implantation of these fenestrated and branched stent grafts requires insertion of multiple tools through the sheath valve into the patient's arterial system at the same time. This is a lot, compared to just one or two tools inserted during EVAR procedures.

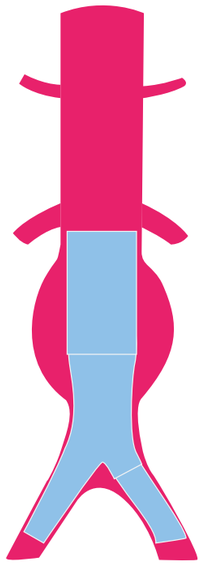


Figure 3.3 EVAR stent in AAA

3.2 CURRENT PROBLEM

Strikingly, sheath designs intended for EVAR procedures are still being used for FEVAR and BEVAR without changing, even though the number of tools used increases. These EVAR sheaths allow a maximum of two tools to be introduced through their valve, before blood from the artery starts leaking through the valve. With every additional tool being introduced, the valve's capability of adequate closure is reduced even more. This results in leakage that can lead to significant blood loss for the patient. During lengthy, complex endovascular procedures, the patient can lose up to 2 litres of blood, making expensive recycling of homogeneous blood (cell saving) or even blood transfusion necessary.

Concluding, sheath development is slacking compared to the improved stent technologies, diminishing surgical quality. Therefore, this project focuses on the design of a new sheath solution to minimise blood leakage.

3.3 DESIGN CHALLENGE

The solution that needs to be developed should enable the use of at least 4 tools and 1 wire in parallel, while minimising leakage to the amount occurring during standard EVAR procedures (50 mL maximum). This can be in the form of a new sheath design or an add-on to existing sheaths.

The most important sub-challenges are:

1. Closing the valve cavity created by introducing multiple tools.
Peak blood pressures of 160-180 mmHg and blood viscosities between 2.5 and 4.5 mPa·s need to be considered.

2. Allowing the tools to be moved in/out through the sheath valve repeatedly.
Tools can be moved in/out around 30-40 times during one surgery, which currently leads to tearing of the valve.
No unintended (torn off) valve material should enter the blood system.

3. Size limitations.
The outer diameter of the sheath should remain as small as possible, with a maximum of 24 French (around 1 cm), while it should allow insertion of 4 tools of 7 French simultaneously (in special cases a fifth tool is used, but only after removing the previous four).

Relevant factors are: smooth handling of tools during introduction and manoeuvring through the sheath and its valve, as well as safety of the device and its operation.

These design challenges are tackled through a structured approach consisting of multiple phases.

4. PROJECT APPROACH

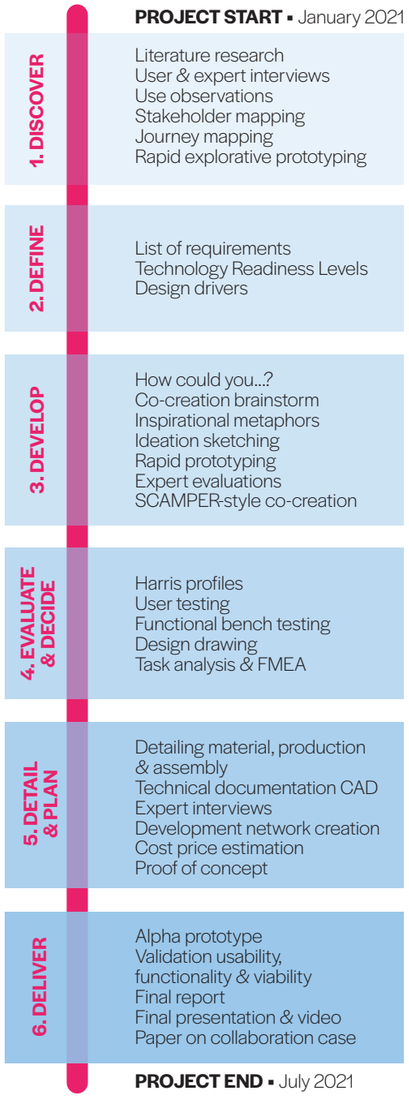


Figure 4.1 Project timeline

The project is divided into six phases based on the stages defined by the Delft Design Guide (Boeijen & Daalhuizen, 2020): discover, define, develop, evaluate & decide, detail & plan, and deliver. A simplified overview of the project's timeline can be found in Figure 4.1. It shows the phases with the applied research and design methodologies, as well as references to the corresponding chapters in this report. A detailed Gantt Chart of the project planning can be found in Appendix B: Project Brief.

The six phases of the project represent a breakdown of the first two steps in the complete Medical Device Development (MDD) process as defined by Marešová et al. (2020). The process by Marešová exists of six steps in total and can be found in Appendix C: Medical Device Development.
Throughout the project, an ongoing analysis and evaluation of the MDD process is performed. This analysis views the MDD steps, regulations to be met, and stakeholders, as well as the experiences with collaboration between the main stakeholders: medical specialists and designers.

Both the device design and MDD analysis are supported by collecting information from various field experts through interviews, observations, co-creation and design evaluations. This group of experts covers backgrounds in design, medicine, engineering, materials, production, medical device development, and business, and is represented in Figure 4.2. Many thanks go out to these experts for sharing their valuable knowledge and experience.

4.1 FINAL GOAL & DELIVERABLES

Finally, the project is aimed at developing a Proof of Concept covering technological feasibility, user desirability (e.g. ergonomics) and commercial viability (e.g. pricing and possible commercialization pathways).

Therefore, deliverables will be a physical prototype (functional & aesthetic), CAD model, project report including a roadmap for future development, presentation, and possibly a paper describing an exemplary case of collaboration between the medical and design disciplines.

Figure 4.2 Project stakeholder network

MEDICAL BACK GROUND

PART 2

This chapter provides the background knowledge for the design project. First, the medical background of the disease and its treatment are illustrated, including its stakeholders and challenges. Second, the market of the introducer sheath, its typical use and functionality are explained. Lastly, a technical analysis is presented of factors relevant for preventing blood leakage, such as blood flow characteristics and valves used in existing sheaths and various other application areas.

5. ABDOMINAL AORTIC ANEURYSMS

5.1 THE DISEASE

The aorta is the body's largest and central blood vessel, running from one's heart through chest and abdomen. Averagely, a healthy abdominal aorta has a diameter between 20 to 30 mm (Mayo Clinic, 2019), Figure 5.1 (left).

Due to health issues, the walls of the vessel can weaken, bulge and cause a balloon-like dilation, an aneurysm (Singh, n.d.), which can grow to a diameter of over 110 mm. Located in the abdomen (Figure 5.2 & 5.3) with a diameter ≥ 30 mm it is called an Abdominal Aortic Aneurysm or AAA (Gezondheidsraad, 2019), Figure 5.1 (centre).

In some cases, the AAA is located near the kidneys (juxtarenal). This increases its complexity, because it incorporates significant side branches of the aorta to the kidneys, intestinal organs, stomach and liver, Figure 5.1 (right).

Oftentimes, an AAA does not lead to any symptoms and remains undetected for a (too) long time, as only 1 out of 4 AAAs causes symptoms of abdominal or back pain, or a pulsating mass in the abdomen. The AAA can be detected (mostly coincidentally) by X-Ray, computed tomography (CT), or magnetic resonance imaging (MRI). Untreated, the AAA will grow, get weaker, and *"is at risk for bursting (rupture) or separating (dissection). This can cause life threatening bleeding and potentially death."* (Johns Hopkins Medicine, n.d.).

Therefore, beginning AAAs are regularly checked and large AAAs (diameter ≥ 50 – 55 mm) are generally surgically repaired to prevent rupture (Singh, n.d.). Possible treatments will be discussed in the next chapter.

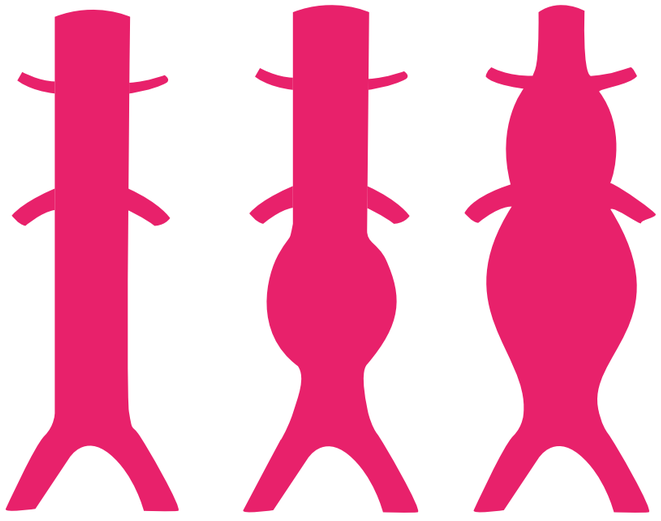


Figure 5.1 Examples of healthy abdominal aorta (left), Abdominal Aorta Aneurysm (centre), Complex AAA (right)

5.2 AAA PREVALENCE

Generally, AAAs are found at least three times more in men than women, according to the Gezondheidsraad (2019). In the Netherlands, 1-2% of men above 65-years are likely to have an AAA. In 2019, 539 deaths were related to AAA in the Netherlands by the Nederlandse Hart Registratie & Hartstichting (2020). On top of that, 62 AAA-patients died perioperatively during preventative surgery (Gezondheidsraad, 2019).

Looking at the US, dominating the global aortic stent market in 2018 (Research and Markets, 2019), every year 200 000 people are diagnosed with an AAA (Singh, n.d.). Singh: *"A ruptured AAA is the 15th leading cause of death in the country, and the 10th leading cause of death in men older than 55."*. Approximately 10% of patients has a complex aneurysm near significant arteries (Mayo Clinic, n.d.).

Overall, in Europe the AAA prevalence decreased from 6,5% in 1990 to 2,8% in 2012 (Li et al., 2013). This can be attributed to factors such as decreasing percentage of smokers, better prevention and treatment of cardiac and vascular diseases, and improved health of the elderly (Nelissen, 2015). However, on a global scale, the number of aortic aneurysm patients is rising (Li et al., 2013 & Research and Markets, 2019).

It is important to emphasize that the numbers in this paragraph concern AAA prevalence in general, including complex cases, because these researches do not distinguish between prevalence of complex and non-complex AAA.

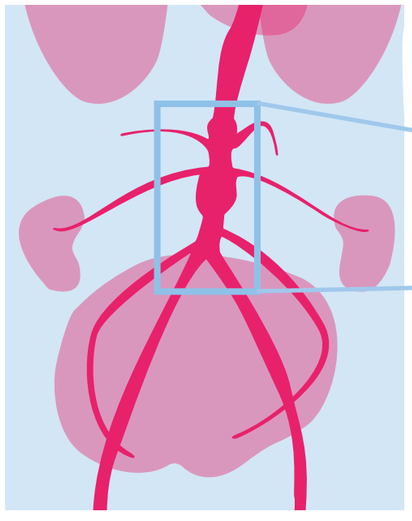


Figure 5.3 Zoomed in location of AAA

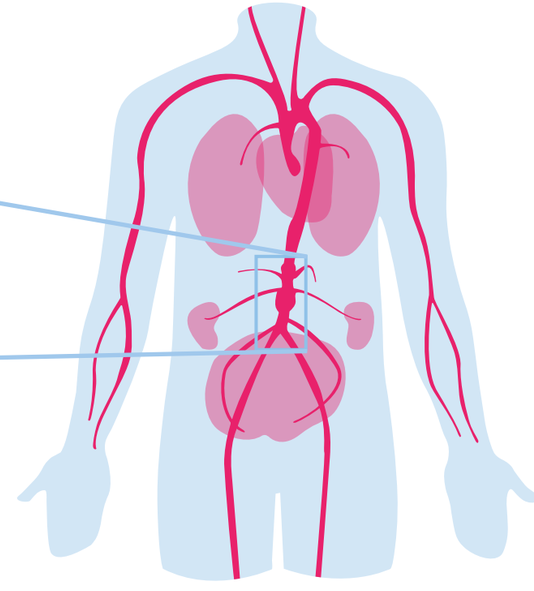


Figure 5.2 Location of AAA, close to the renal arteries

6. AAA TREATMENT

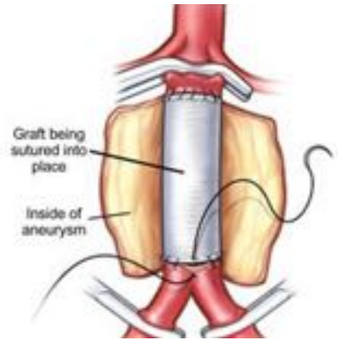


Figure 6.1 Surgical anatomy for open AAA surgery

6.1 TREATMENT METHODS

An AAA can be treated through two main methods: open surgery or minimally invasive, percutaneous surgery. The latter is done from within the blood vessel, thus called endovascular.

6.1.1 OPEN SURGERY

In open surgery, the original repair method (Figure 6.1), the vascular surgeon makes a big incision in the abdomen to access the aneurysm.

6.1.2 ENDOVASCULAR ANEURYSM REPAIR (EVAR)

Endovascular aneurysm repair (EVAR) is preferred in most cases, as it only requires a small incision of around 5-8 cm, using access sites such as the brachial (arm) artery and the femoral (thigh) arteries (Van Schaik, personal communication, January 20, 2021). After puncture, a sheath is placed in the vessel, functioning as a re-usable access point to the arterial system. The sheath prevents blood from flowing out of the artery and enables entrance of tools into the arteries.

Through the access point, a stent graft is implanted in the AAA to reinforce the weakened artery walls and exclude the aneurysm (Figure 6.3). Johns Hopkins Medicine (n.d.) explains the stent graft as: *"a tube made of a thin metal mesh (the stent), covered with a thin polyester fabric (the graft). The tube is collapsed so it is narrow and can fit through the blood vessel."*.

Moving X-ray images show the endovascular location of tools to guide the surgeon during the procedure (see Figure 6.4 for an example). Usually, the procedure takes from 3 up to 8 hours (Schanzer, n.d.).

Overall, EVAR is less invasive than open surgery, allowing faster recovery and shorter post-operational hospital stay (Schanzer, n.d.). It has proven to be very effective in preventing aneurysm rupture and it significantly reduces complications (Mayo Clinic, n.d.).

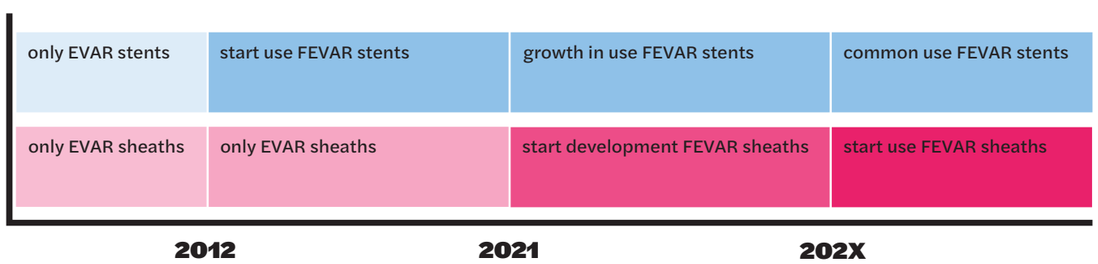


Figure 6.2 Stent graft vs. sheath development

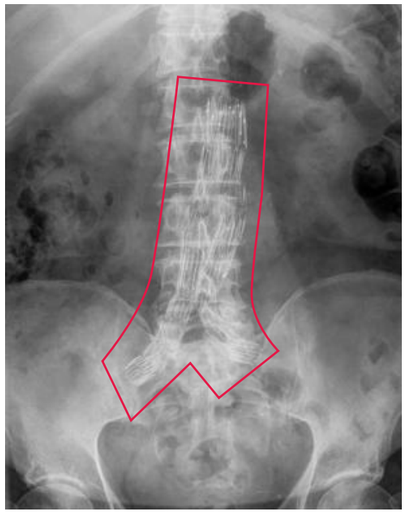


Figure 6.4 Example of X-Ray image of EVAR with highlighted location

6.1.3 FENESTRATED / BRANCHED EVAR

Originally, complex juxtarenal AAAs could not be repaired with a stent graft, as it would close-off significant arteries (Schaik, personal communication, February 3, 2021). However, due to technological improvements (FDA approved in 2012, Johns Hopkins Medicine, n.d.), it is possible to place stent grafts, that are fitted with holes (fenestrations, see Figure 6.5) or side branches (Figure 6.6). These fenestrations and branches enable stent graft placement for complex aneurysms by incorporating surrounding vital arteries into the treatment zone.

Once the main stent graft is located within the AAA, it is rotated to position the fenestrations over the openings of the branch arteries. Next, optional smaller stent grafts are placed in the fenestrations of the main stent graft to form side branches inside the vital arteries. After implantation, blood can flow through the abdominal aorta and surrounding vital arteries without pressurizing the aneurysm. These procedures are called Fenestrated EVAR (FEVAR) and Branched EVAR (BEVAR) (Schaik, personal communication, February 3, 2021).

Strikingly, the sheath development is not keeping up with the significantly developing stent graft technology and corresponding new requirements, see Figure 6.2 for a simplified timeline. These can be related to the increase in stent complexity and number of parts. A representation can be found in Figures 6.5 and 6.6. Therefore, this project focuses on developing an introducer sheath that is specifically designed for use during FEVAR and BEVAR procedures.

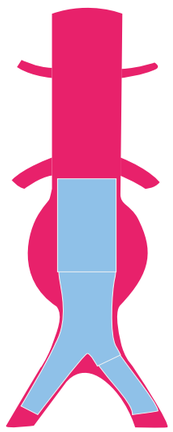


Figure 6.3 EVAR stent in AAA

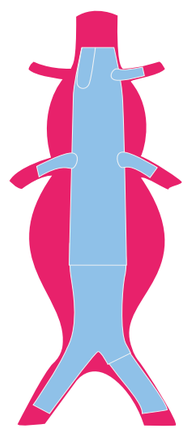


Figure 6.5 FEVAR stent in AAA

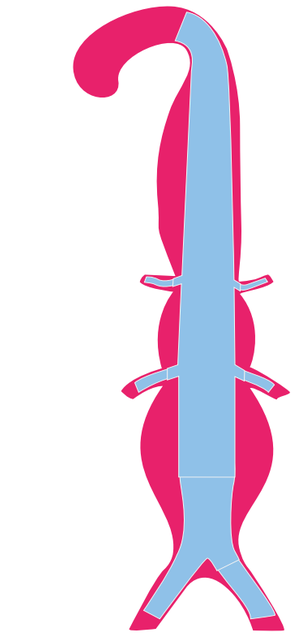


Figure 6.6 BEVAR stent in AAA

Figure 6.7 A view of the OR with the sterile team preparing a FEVAR procedure (large version on p. 24)

6.2 STAKEHOLDERS

6.2.1 THE SURGICAL TEAM

The surgical team is a well-organised structure where every member has a dedicated role and responsibilities to ensure a smooth procedure (covering preoperative care, perioperative procedures and postoperative recovery), high quality and successful outcomes of the intervention for the patient. As vascular surgeon Eefting states: *"The surgeon can be brilliant, but if the team around the surgeon does not function, it is impossible to achieve procedural quality"* (personal communication, February 3, 2021).

In total, around 10-13 people are present in the Operating Room (OR), and another 2-3 people might be in the control room (Figure 6.8). Therefore, strict protocols are in place to guarantee control of the procedure. All staff members wear gowns, plastic gloves, masks, caps, clogs and leaden X-Ray protective wears. The team can be divided into the sterile team and the circulating team. All team members have their own tasks, and corresponding aims and needs for the tools they use.

The sterile team (Figure 6.7) consists of:

- A vascular surgeon, who performs the intervention and aims for perfectionism to execute the procedure as medically effective and neat as possible. Therefore, the surgeon requires the best possible tools, which should allow convenient handling. Other than status, *"personal financial gains"* never influence treatment decisions for these surgeons in Dutch academic hospitals, as concluded by Stevens and Van Schaik (2019).
- A interventional radiologist (IR) closely collaborating with the surgeon and guiding the procedure through real-time imaging techniques. The radiologists require tools that are visible and enable tracking their position on these moving X-Ray pictures.
- A scrub nurse assisting the surgeons, aiming to be 'one-step-ahead' of what tool the surgeon needs and responsible for the surgical equipment on site (Stevens & Van Schaik, 2019).

The sterile team has direct physical contact with the sheath and holds it manually.

The circulating team consists of:

- Circulating nurses monitoring the sterile members' needs, providing any missing tools from storage and performing cleaning and administrative tasks.
- A team of two or three anaesthetists and clinical neurophysiologists keeps track of the patient's vital signs, neuro responses and anaesthesia (LUMC, 2017).
- A back-up vascular surgeon (cautiously watching from the control room), who makes it possible for the sterile team members to take a break and eat/drink something. This switch is necessary due to length of operations and is done at a moment when the surgeon can let go of all tools. Thus, the sheath should remain located in the vessel without holding it. Simultaneously, a circulating nurse becomes sterile and remains at the table, so the scrub nurse can take a break too.

Currently, the vascular surgeons of the LUMC are forming an experienced team of scrub nurses and anaesthetists dedicated to assisting FEVAR and BEVAR procedures. Experience is valuable, because this allows them to anticipate and be prepared for what the surgeons do and need next (Schaik & Eefting, personal communication, January 20, 2021).

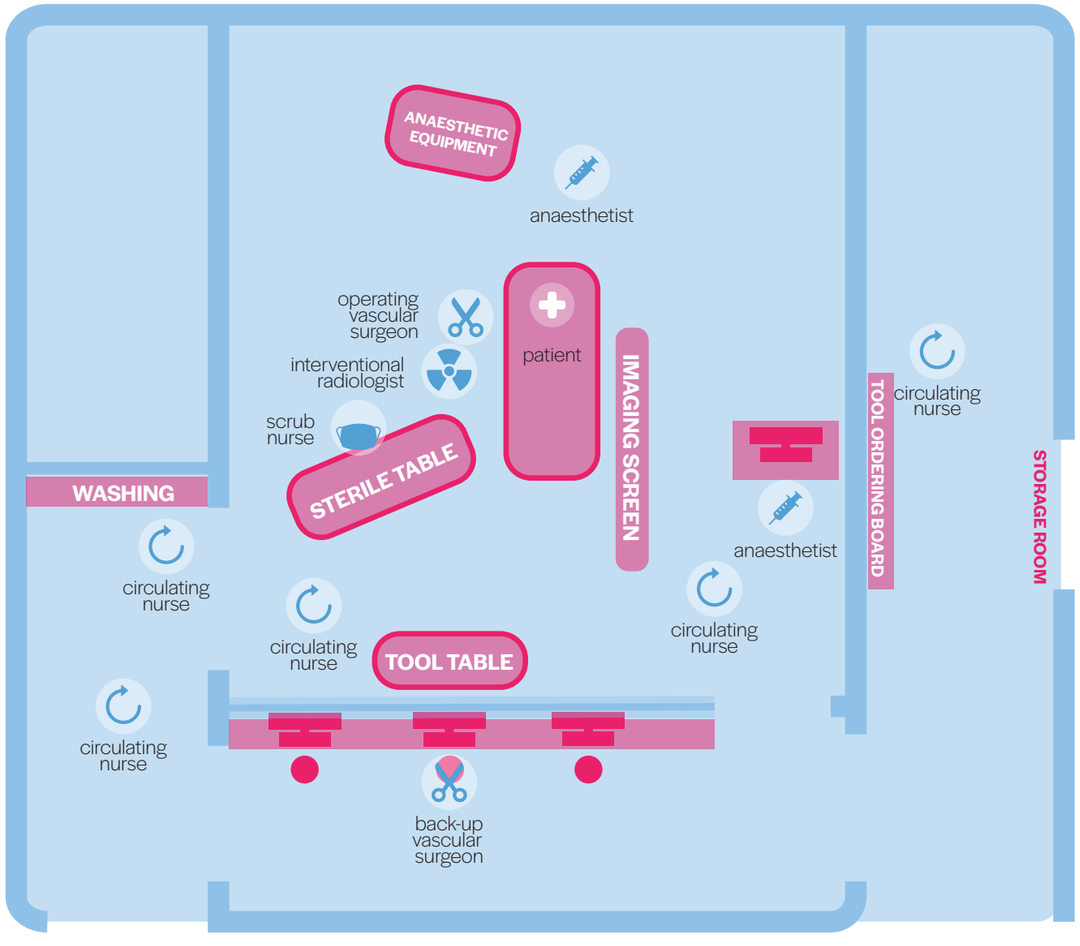


Figure 6.8 Floor plan of dedicated FEVAR operating room with all team members

6.2.2 OTHER STAKEHOLDERS

Around the surgical team, a network of other stakeholders exists that influences the procedure and the sheath's use, directly or indirectly and internally or externally of the hospital. An overview of this network can be found in the stakeholder map in Figure 6.9. Healthcare performance depends on all these stakeholders, united in the quadruple aim as described by Bodenheimer & Sinsky (2014, p. 575): *"improving the health of populations, enhancing the patient experience of care, reducing the per capita cost of health care"* and *"improving the work life of health care clinicians and staff"* (Figure 6.10). The influence and interests of main stakeholders will be explained and related to the quadruple aim.

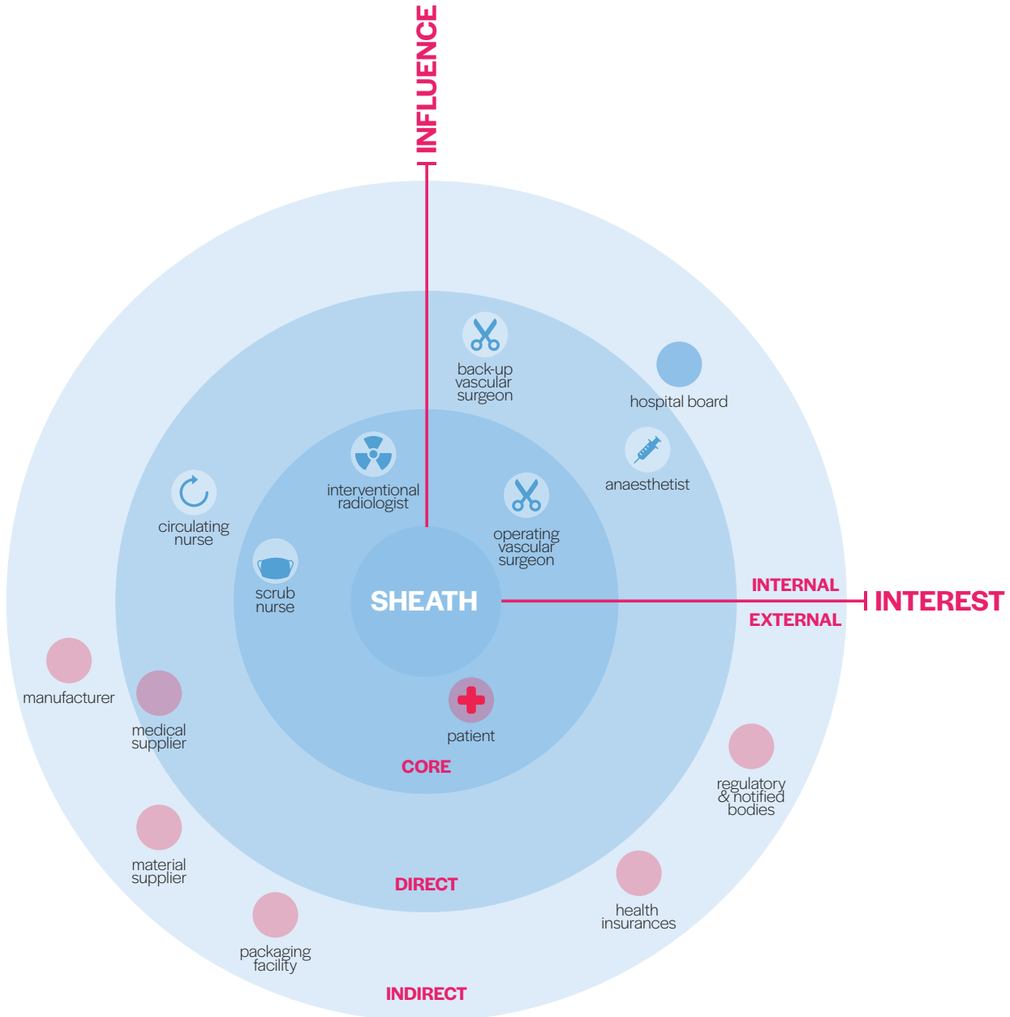


Figure 6.9 Stakeholder map

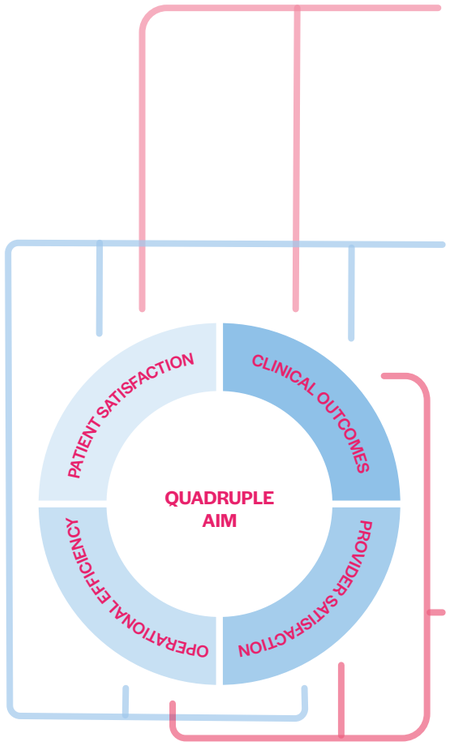


Figure 6.10 The quadruple aim, connected to the stakeholders by interests

6.2.2.1 PATIENT

The patient wants to receive treatment of the AAA and hopes for an improved medical condition without negative side-effects after the surgery. The patient and possibly relatives have an influence on the choice for the procedure. During the surgery, the patient is anaesthetized and does not have a conscious interest or influence. However, the physiology of the patient does have an influence on the choice of tools, execution and achieved outcomes.

6.2.2.2 HOSPITAL

Only a limited number of hospitals in The Netherlands, mainly academic hospitals, can deliver specialised FEVAR treatment as it is a "high complexity, low volume" procedure. According to Dr. J. van Schaik (personal communication, October 26, 2020) approximately 300 to 500 FEVAR surgeries are performed annually in the Netherlands. Various hospital departments are engaged in this procedure:

- The Executive Board aims for efficiency: delivering high quality against minimum resources (money and OR-time), while ensuring a satisfied work life of their clinical staff.
- Other involved departments are hospital procurement, logistics, sterilisation and waste handling.

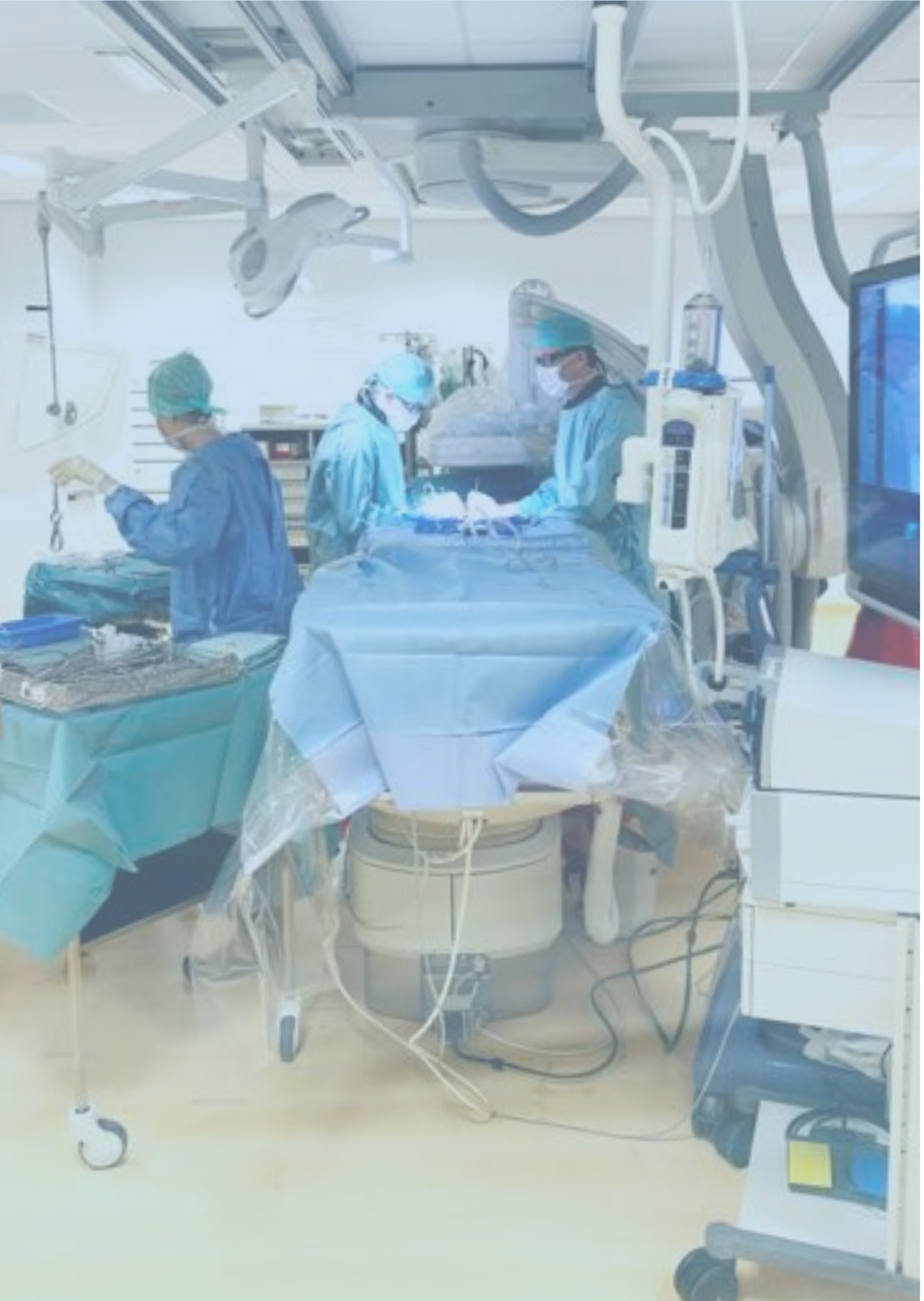
6.2.2.3 MANUFACTURERS & SUPPLIERS

Most importantly, these parties are involved with developing the necessary devices to improve populational health, while creating profit to allow further development of these devices. Strikingly, mainly their financial results are tracked elaborately, whereas neither patient outcomes nor device success rates are recorded (Stevens & Van Schaik, 2019).

The medical supplier of the stent-graft brand oftentimes provides the surgical team with a Proctor (MD) when a new device or technique is implemented. Also, a Sales Representative ensures smooth and intended use of the company's product, strengthening brand trust and loyalty with the hospital and clinicians. Additionally, their devices' ergonomic aspect receives increasing interest to enhance the clinicians' experience.
The medical supplier engages material suppliers, manufacturers, packaging facilities and parties supporting certification to produce and deliver their products.

6.2.2.4 OTHER EXTERNAL PARTIES

Finally, other parties in the healthcare sector are involved. Health insurance companies are involved in financing the procedures. Therefore, their interest is keeping the costs as low as possible and they have considerable influence on the pricing. Also, regulatory parties and notified bodies influence the design of the device and the inherent hazards through their regulations and certification.



6.3 THE FEVAR PROCEDURE

The surgical team introduced above is responsible for executing the complete FEVAR procedure. According to Van Schaik (personal communication, January 04, 2021) the steps of FEVAR procedures are standardised along different hospitals, as the stent grafts always require the same technique to be placed in the patient, allowing only little variety in the rest of the procedure.

Understanding this procedure is important to identify specific problems and design flaws that might influence the access sheath's use and therewith its design. Therefore, the focus of this procedure's analysis lies on parts relevant for the sheath's use and these are described in more detail. Consequentially, not only the peri-operative stage (during surgery) is analysed. Also, the pre-operative stage is included, as this is the moment when a specific sheath type is chosen and ordered from the supplier. However, just a few post-operative steps are added, because current sheaths are disposables. As sterility and safety of the product's design are of significantly larger gravity for this product in respect to improving its ecological footprint, especially viewing the high complexity, low volume extent of FEVAR procedures, topics concerning resterilising and recycling the materials will receive less attention in this project.

The journey map presented in Figure 6.11 forms an overview of all relevant stages and steps of the FEVAR procedure. These have been analysed regarding multiple factors: their duration, active stakeholders with their needs, and the step's emotional effect on them and, finally, the insights relevant for the design process.

The journey map has been developed with information gathered through literature, after which it was enriched and verified through user interviews and observations during FEVAR and BEVAR procedures at the LUMC (2021). Due to patient privacy, it was not possible to photographically document these procedures in detail.

Characteristics of the product's use are further elaborated along the (sub-)stages in the Journey Map. Along with these characteristics, the main pain points* that emerge during this journey are identified. Finally, conclusions, relevant to designing a new sheath solution, are deducted from the characteristics and pain points.

*
Pain points refer to unpleasant interactions with the device, negative feelings experienced by the device's users, and moments of frustration during the device's usage.

STAGES	**PRE-SURGERY**																				
SUB-STAGES	SURGERY PLANNING					SURGERY PREPARATION			SURGERY INTRODUCTION					GA							
STEPS	1 INITIATE PROCEDURE PLANNING	2 CREATE PERSONAL STENT	3 ORDER TOOLS	4 BECOME FAMILIAR	5 STORE TOOLS	6 PATIENT INTAKE	7 PREPARE SURGICAL KIT	8 PREPARE PROCEDURE	9 PATIENT & TEAM BRIEFING	10 COLLECT & POSITION TOOLS	11 UNPACK STANDARD TOOL KIT	12 START ANAES - THESIA	13 PREPPING PATIENT	14 OPEN SHEATH PACKAGING	15 FLUSH & JOIN SHEATH & DILATOR						
DURATION	8-12 weeks in advance					1 day in advance			1.5 - 2 hours					30 - 60 s.							
STAKEHOLDERS																					
DESCRIPTION	decide patient's suitability, discuss & plan procedure	patient specific stent is designed & produced	IR creates tool list, nurse checks stock of standard tools & orders missing tools	surgeons familiarise with stent specific deployment procedure	tools arrive at hospital and are stored nearby OR	patient taken in for pre-tests	tools for surgical kit are gathered from storage and collected in tray	performing surgeons discuss patient specific approach of upcoming surgery	team briefs procedural steps with patient to make sure the patient is familiar with procedure and gives consent	tools are collected from OR storage and positioned on the OR tool table	wrapping of tool kit containing standard surgical tools is removed	after starting anaesthesia, vital signs of patient are constantly watched	positioning patient & free up and disinfect area around access points	circulating nurse pulls of outer wrapping, while scrub nurse or IR pulls out sterile sheath	flushing lumen and wetting ouside of cannula to activate hydro-philic coating						
EMOTION										*"unwrapping everything in advance would be a waste"* - surgeons and nurses			*"Coat gets caught on sheaths lying on table, they fall on to the ground, becoming unsterile. Not enough replacement sheaths are in storage, causing stress. Finally, an annoying alternative has to be used."* - personal observation									
INSIGHTS		required sheath (model, diameter & length) is determined in advance, in general sheaths are a stocked item								extra tools are collected just in case, as they will not all be used, they are not unwrapped in advance	currently surgeons have to do this themselves due to staff shortage, leading to messy kits.		table height can be adjusted to surgeon's preference, disinfection is done with pink-coloured alcohol	much space is required to keep long sheaths sterile while unwrapping, circulating nurse collects sheath wrapping and cuts off label to scan for administration	sheath must remain wet during insertion & full procedure to ensure good lubricity, thus it is flushed before use, every time it is removed and re-inserted to the body and 1-2 timex during use						

Figure 6.11 Journey map of current large-bore introducer sheath use during FEVAR procedures

PERIOPERATIVE

POST SURGERY

AINING SHEATH ACCESS

STENT PLACEMENT

SURGERY CONCLUSION

POST SURGERY

16	17	18	19	20	21	22	23	24	25	26	27	27	28	29	30	31
CREATE FEMORAL ACCESS	INTRODUCE SHEATH UNIT	FIXATE SHEATH BY SUTURE	UNLOCK & WITHDRAW DILATOR	INTRODUCE SMALL SHEATHS	CATHETERS INTO TARGET VESSELS	PLACE MAIN STENT	(PLACE RENAL STENTS)	PLACE ILIAC BIFURCATION STENT	REMOVE SHEATH	CLOSE ACCESS POINTS	AWAKEN PATIENT IN OR	DEBRIEF WITH PATIENT	PATIENT MOVED TO IC	TEAM DISCUSSES OUTCOMES	NURSES CLEAN UP OR	PATIENT DISMISSED

4 - 6 hours

1 - 1.5 hours

1 - 3 days

3 - 4 min.

moment for potential break and (temporary) replacement of sterile team

Seldinger technique used for cannulation: needle puncture, advancing guidewire over needle, removal of needle, entrance using an electrical surgical knife is possible too

sheath is advanced over guidewire with X-Ray guidance into abdominal aorta

suture is placed connecting the sheath's suture loop to the patient's body

dilator is unlocked from sheath hub and pulled out of the sheath over the wire

sheath valve punctured one by one with 1-2 wires and 3-4 small sheaths, sheath assembly should be kept as straight as possible

catheters introduced over wires through small sheaths

fenestrations oriented to patient anatomy and stent is deployed

"frustration can be seen in surgeons when placement ends up differently than intended" - nurse

7F catheters are positioned into renal arteries and stents are oriented and deployed

iliac bifurcation introduced through left femoral access and deployed

wireguide introduced in sheath, dilator advanced over guidewire, sheath & dilator unit removed, wireguide removed

precutaneous access point closed with pre-closing devices

anaesthetists control slow awakening of patient

surgical outcomes are next steps are discussed by surgical team with patient

nurses move patient bed from OR to IC

surgeons discuss surgical outcomes together and determine how the procedural problems can be improved next time

nurses clean up, collect and count surgical tools, dispose of one-time use tools

patient dismissed and returns for regular checks

Sometimes, when annoyed by long preparation time, two surgeons create the two femoral access points in parallel, because this is easier and faster.

dilator should not back out of sheath during introduction, surgeon's left hand holds the wire and right hand pushes sheath over it, a gauze is used to hold sheath's cannula and forward it, because it is slippery

unlocking by turning counter clockwise, locking by turning clockwise

sheath starts leaking, leading to problematic situation for surgeons, anaesthetists, nurses and patient, sometimes bone wax is used to seal the valve

stents supplied in own delivery sheath, deployment by pulling knob or rotating knob counter clockwise

dilator helps to prevent bleeding, vessel damage, and other serious injury; leakage decreases, but valve might need extra tightening; as soon as use of specific sheath has ended, scrub nurse rolls it up, tapes it together and disposes it

if temporary closure of access points is required, a sheath is placed as closure.

- Patient
- Vascular Surgeon
- Interventional Radiologist
- Scrub Nurse
- Circulating Nurse
- Anaesthetist

6.4 THE PRODUCT'S USE JOURNEY

Characteristics concerning the general course of FEVAR surgeries in the OR and concerning typical sheath use can also have an impact on the sheath's design, leading to the following insights and requirements. These characteristics are based on literature, as well as personal observations and communication, and are coupled to the different (sub-)stages in the Journey Map.

It is important to note that not only factual characteristics are taken into account. Similar to the Journey Map, also emotional aspects are included to create a more complete view of the context. This is essential for designing an improved experience, as the product experience does not consist of purely factual functionalities either. Generalisation of these emotional aspects is assumed to be appropriate, as they were confirmed by multiple medical specialists.

The main pain points derived from the product's use journey can relate to possible risks, challenges or negative emotions experienced by the medical team. These are relevant to identify, because they offer opportunities for improvement. The journey map shows three negative phases. First, while ordering the tools and preparing the tray. Second, when gaining sheath access. Third, during introduction of the small sheaths and catheters through the introducer sheath and into the patient's arterial system, and the following stent placement. The last is the most notable, as it carries the highest risks. As explained by De Jong (personal communication, January 20, 2021), the main risks are severe bleeding, difficult access to arteries, obstruction of blood flow, and a worsening patient condition. The last is visible by monitoring vital signs, such as heart rate, blood pressure and neuro-activity.

Occurrence of these problems is strongly patient specific, as well as related to surgical execution and tool functionality, all interlinked and influencing each other. Various factors play a role here, such as: tool insertion difficulties, long operating times leading to exhaustion of the surgical team, and tools that do not function as intended.
These risks, mainly arising during the stent placement sub-stage, are explained in more detail in the following paragraphs.

6.4.1 PRE-SURGERY

In preparation of the surgery, the IR drafts a list of required tools, according to the patient's needs and planned procedure. This has to be done weeks before the procedure, because the development of custom-made stents can take long and is a *"highly salient process"* and a *"bottleneck in the entire treatment process"*, according to Stevens and Van Schaik (2019). It even influences whether the procedure is carried out or not and when. For the stent supplier W. L. Gore, this is a reason to stick with a range of standardised stent sizes, to ensure that the patient can be treated as fast as possible, instead of having to wait for a 3-month production time (S. Schmitz, personal communication, February 22, 2021).

Figure 6.12 Disposable sheath sets, containing sheath, dilator, syringe, guidewire, and wire introduction tool

Figure 6.13 Typically worn leaden protective wear

In contrast, the access sheaths are a standard tool, they are lying in storage or have to be restocked for the planned procedure. Arranging these off-the-shelf solutions is a simple task, that can even be done by non-medical staff (Stevens and Van Schaik, 2019). Mostly, the nurse checks the stock of standard tools and orders missing parts. Also, spare sheaths are available during the procedure in case a tool becomes unusable, or a different size or tool is required.

Some tools are packaged as a set (Figure 6.12), ensuring compatibility between frequently used tool combinations. However, not all the set's contents might be needed during the procedure. Still, they are all unwrapped at once, and must be disposed afterwards, even if unused. This can cause irritation with surgeons, because they think it is a waste of money and materials.

6.4.1.1 MAIN PAIN POINT

The tool list provided by the IR differs per surgery, and can create confusion with the nurse, especially when requiring specific combinations of tools and/or tools that are not standardly stocked. Also, when the surgical kit is prepared shortly before the surgery (mostly one day), stress can arise if certain ordered tools are not in place or damaged and alternative tools must be used, complicating compatibility.

6.4.2 PERIOPERATIVE

On average, preparation times lie between 71 and 123 minutes (Stevens & Van Schaik, 2019). Surgeons and Interventional Radiologists want to start on time and do not like waiting for a slow preparation or conclusion of surgery, thus they are critical about the efficiency and quality of work of nurses.
The operating team composition changes and is very important for smooth and anticipative collaboration.

6.4.2.1 SURGERY INTRODUCTION

Before entering the OR, the sterile team 'washes' and then puts on a sterile robe and gloves.

While in the OR, the whole surgical team needs constant X-Ray protection and this is realised by:

- Wearing a leaden jacket, glasses and thyroid gland protection (Figure 6.13). *"You get used to it, but after a while it starts becoming warm and heavy."* (Van Schaik, personal communication, January 20, 2021). It was observed that everybody puts off the protective wear as soon as possible.
- Positioning a leaden flap and transparent screen between the performing surgeon and the patient's body, leaving an opening around the surgeon's working area.

After unwrapping, all necessary tools are placed on the tool table in a specific order. However, this can become messy during the procedure, especially during staff shortage, when the surgeon must prepare the tool set without help of nurses.

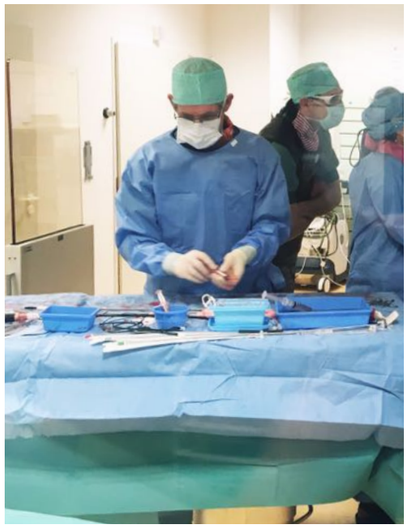


Figure 6.14 Scrub nurse preparing and flushing the tools for the surgeon and IR

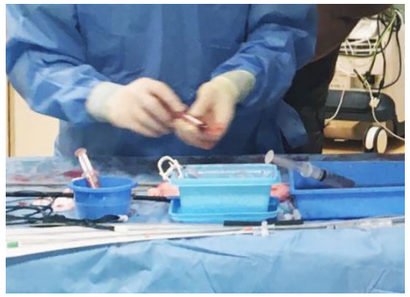


Figure 6.15 Detail of sheath flushing

Figure 6.16 Rotational fixation of DrySeal dilator to sheath hub

To prepare the patient, three different fluids are applied.
- Disinfection of the patient's skin, is done with pink-coloured alcohol. This dries up fast, not leading to stains on the sheath.
- Contrast agent is injected through a perforated catheter to ensure equal distribution in the vessel. This is done repeatedly during the procedure, to make the vessel (walls) visible for imaging. This contrast fluid consists of 3 mL contrast (iodine) in 7 mL saline (Oderich et al., 2014).
- The patient receives blood thinning medication to prevent coagulation. Mostly heparine, however alternatives are ascal, clopidogrel, sintrom of marcoumar.

Lastly, the height of the operating table is adjustable to the surgeon's preference. This means the surgeon is also able to choose the preferred height and angle for introducing and using the sheath.

6.4.3 GAINING SHEATH ACCESS

For introducing the sheath, it is forwarded along three people. The scrub nurse flushes it (Figure 6.14 & 6.15), places it onto the stiff wire and forwards it along the IR and surgeon (Figure 6.17 & 6.18). This makes falling hardly impossible while handing it over to the next user. Also, because the sterile team are used to each other's ways (Van Rijswijk, personal communication, February 3, 2021). Thus, handing over the sheath is no problem.
It differs per operating team whether the introducer sheath is placed in the left or right femoral artery.

Frequently, the dilator is connected to the sheath (Figure 6.16), to prevent the dilator from backing out of the sheath during introduction or removal.

For good lubricity, current sheaths must remain wet during insertion and the rest of the procedure, by flushing saline solution through the valve (2-3 times) and wetting the cannula in advance. Oftentimes, the cannula has a heparin coating that is activated by wetting.

Stevens and Van Schaik (2019) describe that different to open surgery, where visual input and tactile feedback are connected, in endovascular surgery dependency on visual input is higher because almost no tactile feedback is present. Also, *"the visual input does not connect naturally to actions of the hands"*. This combination of minimal tactile feedback and visual input via the screen, is used for correct positioning of the sheath.

If the sheath dislocates during the procedure, the ongoing action has to be stopped at that moment and the sheath is placed back before continuation. For this reason, an extra IR stands behind the scrub nurse and performing IR to support them in watching the positioning of the sheath and detect possible shifting, as the performing team focuses on the action specific location.

In general, no significant bleeding occurs between the edge of the artery access point and the sheath's cannula (Van Schaik, personal communication, January 20, 2021).

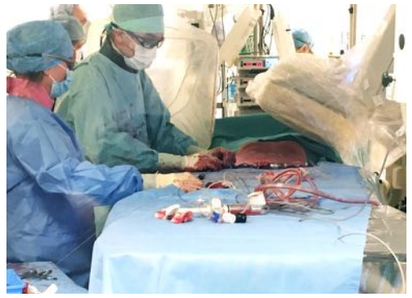


Figure 6.17 Sheath forwarding over the wire along IR to surgeon

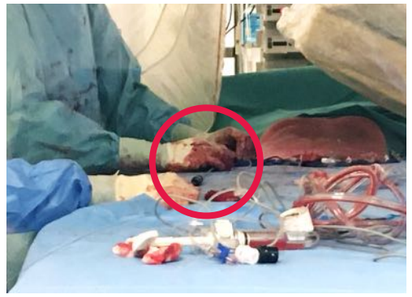


Figure 6.18 Detail of sheath forwarding with highlighted sheath

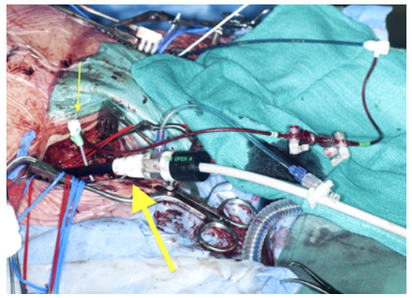


Figure 6.19 External occlusion bypass sheath shunt technique by Hanley et al. (2015)

6.4.3.1 MAIN PAIN POINTS

Difficulties can arise when introducing the sheath through the freshly created femoral access point. The sheath's cannula is slippery, because it is wetted for lubrication, which makes it difficult to grip. As a quick fix for improved grip, surgeons use a gauze to hold the cannula. Forwarding the sheath into the patient's artery and aorta can be complicated by their anatomy. For example, due to arterial kinking (Figure 6.20), small dimensions, flexibility, and calcification. This can lead to longer introduction times and irritation.

Another risk, is reduced or even cut off blood flow in the leg, prevailing in around 10% of cases (Hanley et al., 2015, p. 765). This happens due to the introducer sheath's large outer diameter. Mostly, this is almost as wide or even wider than the femoral artery's inner diameter, obstructing the blood flow from the aorta to the lower limb. In general, this is not harmful for a short period of time. However, after 6-7 hours of operating, this can become a problem (Van Schaik, personal communication, January 20, 2021). This lack of blood and, therewith, oxygen supply results in damage or dysfunction of the tissue, called Ischemia. Techniques to prevent occlusion are applied in exceptional cases (Figure 6.19).

The sheath can also dislocate, which is often prevented by fixation with a suture to the patient's skin. However, this does not always hold, and then requires a pause of procedure and sheath repositioning, again leading to longer procedures. In the worst case, the sheath could shoot out of the femoral access (what happens very rarely), leading to additional blood loss. When it happens, it is mostly after operating for 6 hours. Although not proven, this could be related to exhaustion of the performing surgeons.

6.4.3.2 CONSEQUENCES

In case the sheath shoots out, the operating team needs to adapt to the circumstances without panicking, and follow three steps:
1. Place hand on the blood leakage and regain control.
2. Think in solutions.
3. Call for extra help when required.

Consequences differ per situation, but it can lead to abortion of the procedure. However, sometimes this is simply not possible, when a stent has only been placed half (Van Schaik, personal communication, January 20, 2021). Then, the sheath must be reflushed, rebuilt and reintroduced again.

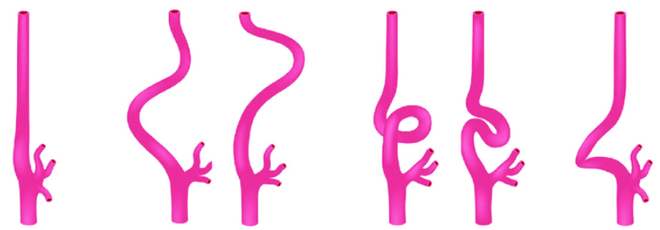


Figure 6.20 Examples of arterial anatomy: straigtht, tortuosity, coiling, kinking

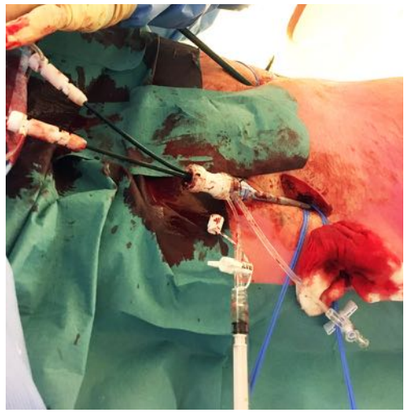


Figure 6.21 Blood loss through sheath after insertion of two catheters

Figure 6.22 Example of DrySeal loaded with a wire and catheter

6.4.4 STENT PLACEMENT

Next, the guidewires, small sheaths and catheters can be introduced, after which the stent can be placed. Through continuous communication, the surgeon and IR alternate who introduces these tools.

Manoeuvring the wires and corresponding sheaths/catheters into the aorta's arterial side-branches is called catheterization and can cost a significant amount of difficulties and time (up to 60 minutes). The surgeon determines the movements via the X-Ray screen and tactile feedback. Interestingly, when the tool is stuck, surgeons dare to push through with more force than IRs in general, because the surgeons have a better feeling of the arteries' strength.

The highest risks, thus also the most negative emotions, are experienced during this sub-stage, and are formed by difficulties during tool introduction, causing severe blood loss and harm to the patient's arteries.

6.4.4.1 MAIN PAIN POINTS

Most important of all, the sheath can cause significant blood loss. Current sheaths allow a maximum of two tools to be introduced through its valve, before blood starts leaking from the artery.. With every additional tool being introduced, the valve's capability of adequate closure is reduced, and continuous leakage occurs (Figure 6.21).

In present designs, the leakage can be attributed to cavities in the valve or in between multiple introduced tools. Manoeuvring the tools through the valve can occur around 30-40 times during one surgery and it is difficult to anticipate whether it increases or decreases leakage. Especially with frequent manoeuvring, the valve material can rupture or even tear off. In those cases, there is a risk of torn off material entering the blood system.

When using the Gore DrySeal, its valve is tightly inflated around the tools (Figure 6.22), to minimise blood loss. However, this makes introduction of more tools increasingly difficult. The user has to fiddle the next tool in between the previously inserted tools. Therefore, the optimal degree of valve inflation must be found, shifting between leaving enough space to insert the next tool and achieving enough closure against leakage. This is a delicate balance, achieved by varying the valve's inflation with a syringe, taking time and effort. Tightening the valve too much can also cause tool damage, in that case the resisting force by the blocked valve is too high. Besides, the valve presses the tools against each other, causing the tools to obstruct each other's ways.

A tight valve also reduces the user's tactility during movements, because the cylindrical compression of the balloon around the tools creates friction between the balloon's surface and the tools themselves, as the surface area of the valve is relatively long. Additionally, when moving one of the tools, the others move along. This is problematic because dislocation can cause losing access to catheterized arteries (Figure 6.26). In that case, they must be recatheterised, significantly increasing procedural time. Likewise,

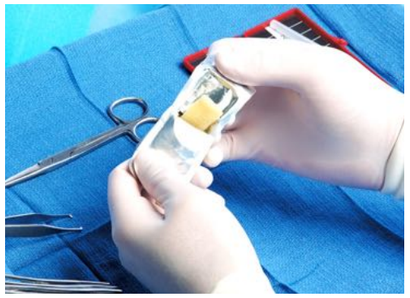


Figure 6.23 Bone wax

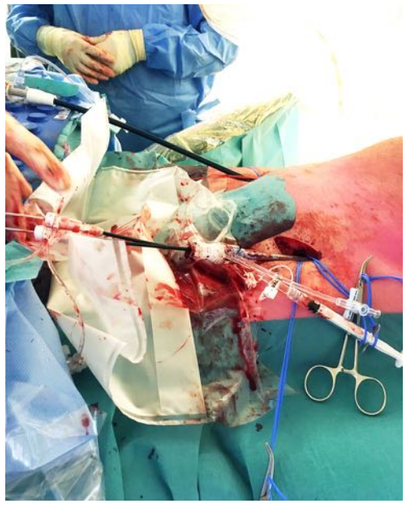


Figure 6.24 Blood collection pouches

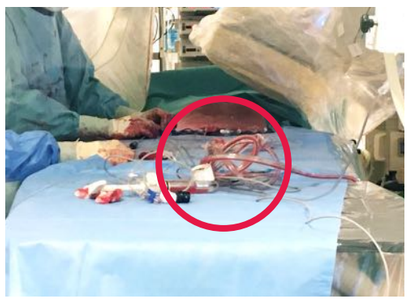


Figure 6.25 Intraoperative blood salvage tubing, leading the blood from the collection pouch to the equipment

when moving the renal stents through the small sheaths, the internal movement and change in stiffness can dislocate or shift the small sheath as well. Consequently, the user has to constantly hold all introduced tools with one hand, to prevent accidental shifting, limiting the freedom of movement with that hand. Again, while removing the tools from the introducer sheath, the above problems can occur.

Specifically, during BEVAR procedures, a stiff guidewire is inserted through the sheath's valve and runs through the patient's body to another percutaneous access point. Pulling of this wire can result in a dysfunctional valve. Often, the pulling direction is not in line with the valve, but angled, forcing the valve open. The amount of force is high, as the surgeon can hang onto the wire with his full body weight. This results in leakage mainly during traction (Van Schaik, personal communication, January 20, 2021).

In some cases, bone wax (Figure 6.23) is used to close a leaking valve, according to a circulating nurse at the LUMC. Consequentially, the inserted sheaths and catheters move very stiff and difficult, and wax particles can be pushed into the blood system. Besides, the use of bone wax on sheaths is outside of the official Instructions for Use, IFU in short (Van Schaik, personal communication, January 20, 2021).

6.4.4.2 CONSEQUENCES

During lengthy, complex endovascular procedures, the patient can lose up to 2 litres of blood. Then, expensive recycling of homogeneous blood (cell saving) or even blood transfusion necessary. The most harmful consequences of severe blood loss are deterioration of the patient's condition, lengthening of post-operative regeneration time or even putting her/his life at risk.

Next to this, leaked blood can lead to an untidy working area. To prevent this, circulating nurses stick collection pouches (plastic bags with an adhesive strip) to the bed to collect the leaking blood (Figure 6.24). According to Van Schaik (personal communication, February 3, 2021): "These pouches always lead to fiddling around". Sometimes, these are used for intraoperative blood salvage. Then, the anaesthetist starts the cell-saver and the surgeon or IR holds it into the pouch, so it can 'suck out' the blood and filter it (Figure 6.25). However, this cell-saving system is expensive. Besides, a circulating nurse explained that *"often, the pouches do not stick well and the situation is impractical. Blood drips onto the ground and unsterile, circulating nurses try to cover wet spots with towels. As a result, the surgeon stands in sludge, and the working area might even become unsterile too."* (personal communication, January 20, 2021).

Finally, bleeding increases cleaning work for the nurses after surgery. Especially, when the blood runs into (small openings in) equipment, where it is difficult to clean.

6.4.5 CONCLUSIONS FOR THE SOLUTION'S DESIGN

6.4.5.1 PRE-SURGERY

The new design should preferably not require creation of a tool set specific for a patient, sheath or procedure. Such specific tool sets often cause longer ordering times with the supplier, and complicate ordering and restocking of the OR's supplies. It also complicates compatibility with other tools, in case alternative tools have to be used spontaneously or it forces waste of possibly unused, but unwrapped other tools in the set.

6.4.5.2 SURGERY INTRODUCTION

- The sheath should allow easy handling by the surgeon, IR and scrub nurse while wearing gloves.
- The use of the sheath should be ergonomically pleasant while surrounded with protective gear and its use should not require notable physical effort.
- The sheath must facilitate handling without looking directly at the sheath. It must give enough tactile feedback and security of its hub's position and entrances to allow the surgeon and IR to watch the on screen visual input.
- The sheath should be well visible, even on messy tool tables, and easy to pick up when lying on the table. It should also not 'roll off' the table.
- The disinfectant's pink colour should not lead to decreased visibility of the sheath's parts.
- The sheath must be resistant to iodine (iodixanol and iohexol).
- The sheath must be resistant to blood thinning medication: heparine, ascal, clopidogrel, sintrom of marcoumar.

6.4.5.3 GAINING SHEATH ACCESS

- It differs per operating team whether the introducer sheath is placed in the left or right femoral artery. This means that the sheath should be usable in both directions and by both hands.
- The solution should not increase the chance of sheath dislocation or even shooting out of the access point.
- The solution should not increase the chance of obstruction of the femoral artery.

6.4.5.4 STENT PLACEMENT

- The valve should be leak proof and allow an (angled) pulling force.
- The valve should be proof to rupturing and tearing, and prevent material from moving into blood circulation.
- As the tools are constantly moved in and out of the valve, it should maintain its functionality when moving tools up to 40 times.
- Smooth introduction and manoeuvring of tools through the sheath should be enabled.
- The surgeon should have a feeling of control over the tool movements and how smooth tool advancement is going.
- It is essential that the sheath does not move out of the access point when pulling the wire or other tools out. Thus, the sheath and its valve should not create a cumbersome level of friction with the tools.

- The surgeon's focus on the operating task should be maximised, by increasing the manual control over the sheath with good tactile feedback and easy, familiar handling actions.
- It could also be interesting to identify methods that require less handling to achieve and maintain good lubricity.

CONCLUSION

A new sheath design should only improve surgical outcomes and reduce procedural risks that can harm the patient's life. It could provide a cleaner, easier, and more worry-free procedure for the surgeons, IR's, nurses and anaesthetists. To achieve this, the design should prevent blood leakage and occlusion of the blood flow, as well as allow smooth introduction and manoeuvring of tools.
The identified requirements are included in the List of Requirements in Chapter 10.

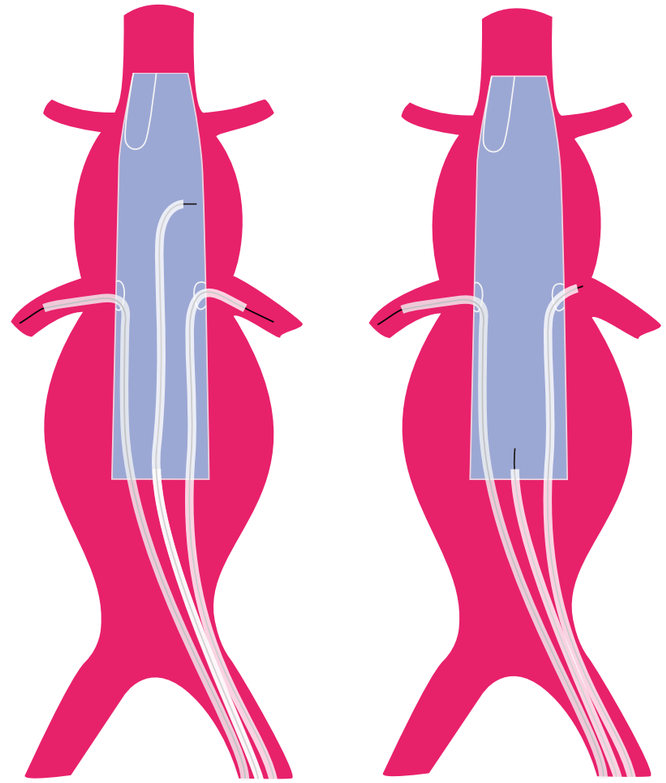


Figure 6.26 Schematic of wires being moved out of artery origins unintendedly

7. THE MARKET

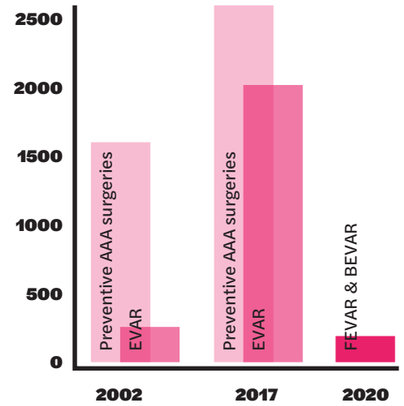


Figure 7.1 Schematic comparison of prevalence total preventive AAA surgeries, and its percentage EVAR, FEVAR and BEVAR

7.1 PREVALENCE OF SURGERIES

In the Netherlands, 2.600 preventive AAA surgeries have been performed in 2017, of which 2002 were EVAR procedures. This is a percentage of 77% of all AAA surgeries, which has grown from only 17% in 2000 (Gezondheidsraad, 2019), see Figure 7.1.

Looking at Dutch national healthcare data provided by Nederlandse Zorgautoriteit (2021), a total of almost 350 procedures for multiple stent placement in the abdominal aorta can be found for 2015. However, this is a rough estimation, as the healthcare codes associated with these procedures have broad descriptions and categorisation can depend on interpretation by the documenting medic. Also, the data for following years is not complete.

According to Dr. J. van Schaik (personal communication, January 20, 2021), in 2020 between 100 and 150 FEVAR and 40 BEVAR procedures were performed, of which 20-25 FEVAR surgeries took place at the LUMC. The LUMC is *"one of eight to ten hospitals in the Netherlands where endovascular reconstructions with custom-made stents of the entire aorta are being performed"* according to Stevens & van Schaik (2019). These complex EVAR procedures are expensive, as they require custom-made stents, costing between €30,000 and €40,000 per procedure (Stevens & Van Schaik, 2019).

In the US, an even steeper growth curve can be seen in the number of EVAR, FEVAR, and BEVAR procedures. Since introduction of the fenestrated and branched EVAR technique in 2011, the number of cases has been rising. For example, looking at the first two years, growth was over 600% (Suckow et al., 2018, p. 10452).

This growth of EVAR, and specifically FEVAR procedures can be attributed to various factors.

- The globally rising number of aortic aneurysm patients (Research and Markets, 2019 & Data Bridge Market Research, 2019), which might be caused by the growing aging population and new government screening programmes for the elderly population. Also changes in people's lifestyle influence the number of AAA patients. Increasing obesity, a global phenomenon, also seen in rapidly developing economies, heightens the AAA prevalence (Grand View Research, 2019), just like smoking.
- A high preference for minimally invasive aneurysm repair over open surgery has established (Data Bridge Market Research, 2019). Simultaneous, commercialisation of fenestrated stent grafts and advancements in this technology make it increasingly possible to treat patients with complex anatomies (Research and Markets, 2019).

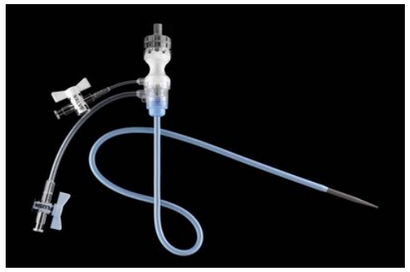


Figure 7.2 DrySeal introducer sheath by W. L. Gore, a commonly used model

Figure 7.3 Extra-Large Check-Flo sheath by Cook Medical, a commonly used model

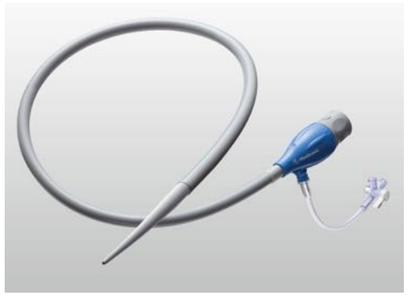


Figure 7.4 Sentrant Introducer Sheath by Medtronic, less common alternative

- As FEVAR and BEVAR procedures are highly complex procedures, they are mainly performed in advanced healthcare centres. Due to global improvements of healthcare facilities, it can be expected that countries with a previously less developed healthcare system will start performing these procedures as well in the future (Grand View Research, 2019). Opening a new market also allows for relatively easy introduction of new tools, because the medical specialists have little working experience with and preferences for longer existing tools, which they are used to working with.

Overall, this can be seen as a continuous cycle of the increasing number of patients, leading to more surgeries, strengthening skills and experience of medical specialists, and stimulating technological development of tools, making it possible for more patients to receive this treatment.

7.2 MARKET AND COMPETITORS

According to a report by Research and Markets (2019), a market research organisation trusted by Medtronic and others, the aortic stent graft market is expected to be worth over $3.7 billion by 2024, a 6% growth since 2018. For this reason, vendors are focusing on and extensively investing in R&D activities to develop further develop FEVAR devices (Research and Markets, 2019).

As the market for large-bore introducer sheaths is specific, competition is limited to a small number of dominant medical device companies. For example, currently, two sheath-models are used for FEVAR-surgery in the LUMC (Schaik, personal communication, January 20, 2021): the Dryseal introducer sheath by W. L. Gore & Associates (Figure 7.2) and the Extra-Large Check-Flo sheath by Cook Medical Inc (Figure 7.3). Besides these, the Medtronic Sentrant Introducer Sheath (Figure 7.4) with large bore sizes, is also used with regular EVAR procedures at the LUMC. However, it cannot be used as large-bore access sheath during FEVAR, as the valve remains open when more than 2 tools are inserted, causing heavy leakage (Rutger van der Meer, vascular surgeon at LUMC, personal communication, January 20, 2021).

One company, Lamed GmbH, supplies a large-bore introducer sheath onto which a multiple-access device can be coupled: the X-Cath - Multiple Access Device for the H.Q.S sheath (Figure 7.5). This device has four separate entrances. Its main drawback is that it is only compatible with Lamed's own sheath. Most surgeons and IR's are already used to a specific tool and/or have their preferred sheath model, making it difficult to gain trust in and experience with the completely new device.

Next to FEVAR and other EVAR procedures, these large-bore introducer sheaths are used for a few other surgeries. As far as identified, these are percutaneous liver perfusion of hepatogenic metastatic carcinomas (Schaik, personal communication, January 04, 2021) and, sometimes, introduction of new cardiac valves in cardiovascular surgery (S. Schmitz, Field Sales Associate at W.L. GORE, personal communication, January 06, 2021).

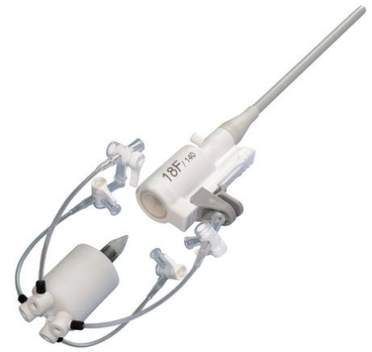


Figure 7.5 Lamed X-Cath add-on for the H.Q.S. sheath

Both, W.L. Gore and Cook Medical Inc., have a wide geographical presence. Especially Medtronic has a very broad range of medical specialisations they cater their products to, from surgical tools to therapy management software. Whereas Gore Medical and Cook Medical are more focused on vascular surgery and other surgical treatments.

Besides these market leaders, a handful of emerging, innovative companies arise on the market.

The strong market position of the major players is a consequence of the high threshold to enter the market, formed by:

- The strict medical requirements for CE- and FDA-marking (regarding design, development, production, materials, sterilization) leading to long time-to-market and high development costs.
- Brand-loyalty by surgeons and hospitals, based on experience and quality trust.

CONCLUSION

The high threshold to enter the market for products newly developed by the industry, in combination with the growing prevalence of FEVAR surgeries, lead to the main opportunity for this industrial design project: to look at the problem, context and design opportunities from a fresh perspective, without being restrained by risks influencing market position, a high market-entrance threshold or acquired working habits. In the case that this fresh perspective results in a functional and desirable product design at the end of this project's timeline and the possibility of realistic development arises, its viability in the market described above should be tested.

8. LARGE-BORE INTRODUCER SHEATH

8.1 DEVICE FUNCTIONALITY

As explained in previous chapters, introducer sheaths are used to gain minimally invasive access to the vascular system to enable a reusable access point for introduction of other tools into the vessel. Sheaths exclude the vessel puncture site from these activities, instead of letting every individually introduced tool form *"a risk of localised hematoma formation or vessel trauma (enlarging the puncture site, dissection of an intimal flap, tearing of vessel walls, etc.)"* (Kruse et al., 2011a).

By using an introducer sheath, one moves the entry point from the femur to the tip of the sheath, for example located in the abdominal aorta (Van Schaik, personal communication, January 20, 2021). This means the new entry point (Figure 8.1) should be used for reasoning which other tools to advance, regarding their stiffness, size and lubricity. Additionally, the sheath should prevent blood from flowing out of the artery and air from entering, while it enables the entrance of these tools.

In a healthy femoral artery, the sheath can be larger than the artery, stretching its walls. However, calcified arteries lead to narrowing and less flexible walls. In those cases, the fitting of the sheath must be checked. Risks of stretching are: vessel rupture, difficult advancement, and pulling back vessel intima when removing the sheath (Van Schaik & De Jong, personal communication, January 20, 2021).

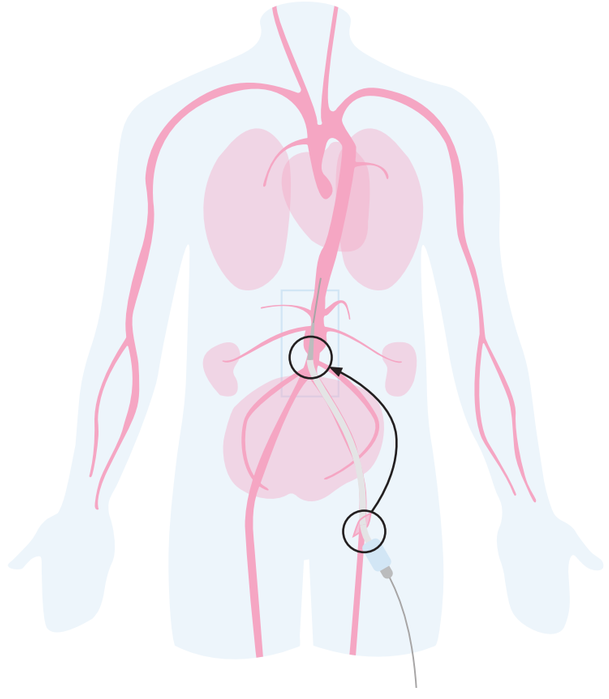
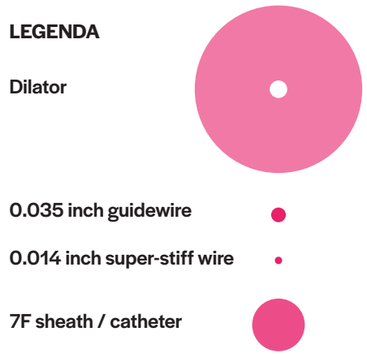


Figure 8.1 'Re-locating' tool entry point from femur to sheath tip



Van Schaik and De Jong determined the following factors for good functionality of sheaths:

- leakage prevention,
- bendability without kinking,
- motion smoothness inside the vessel and manoeuvring smoothness of inserted tools: the sheath should not move out of the point of access when pulling the wire or other tools out,
- minimal material wall-thickness: the inner diameter should allow maximum space for tools, while keeping the hole in the vessel as small as possible.

8.2 TOOLS USED WITH THE SHEATH

The sheath's requirements are strongly dependent on multiple tools that are introduced through the valve during FEVAR procedures (Table 8.1). Mainly because their parallel introduction, manoeuvring and withdrawing should not lead to leakage or breaking of the valve.

These introducer sheaths have a relatively large-bore (inner diameter) between 20-24 French* (Kruse et al., 2011a and Schaik, personal communication, October 26, 2020), compared to most standard sheath sizes, ranging from around 4 to 11F. This large-bore is necessary to fit all tools that must be introduced, which are the following:

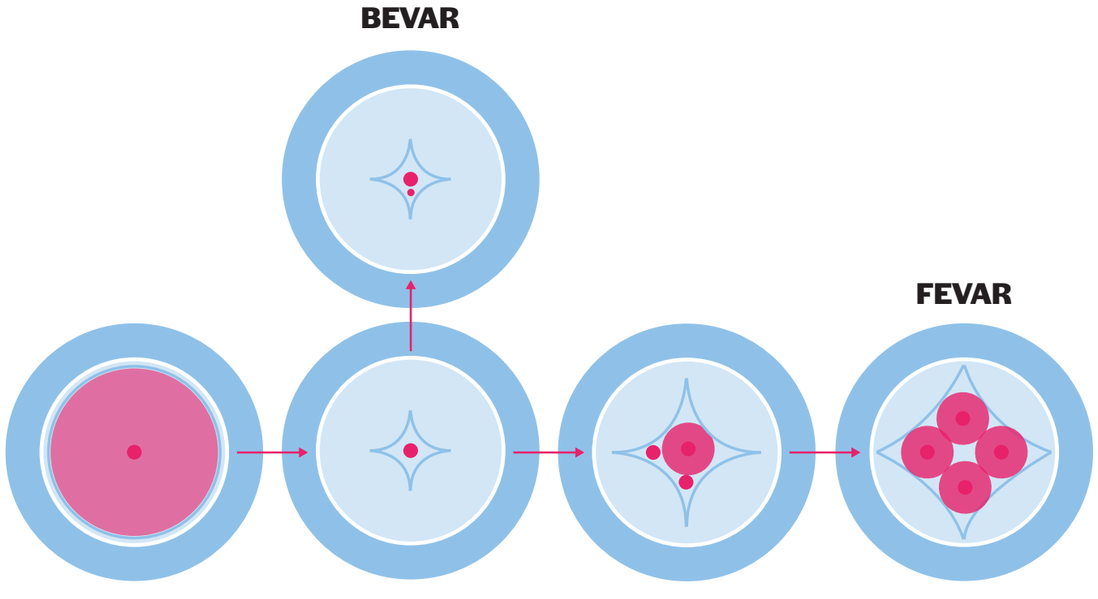


Figure 8.2 Schematic of tool positioning and build-up in valve of DrySeal sheath, during FEVAR and BEVAR

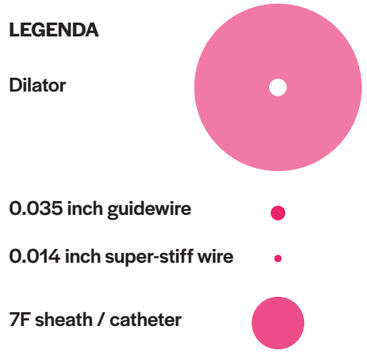
- Needle (e.g. 21 gauge, 0.819 mm diameter).
- Stainless steel 0.035 inch (0.889 mm) super stiff guidewire, with a PTFE coating reducing friction along the wire and a (mostly) 1-cm flexible tip (Boston Scientific, n.d.). E.g. Rosen wire guide (Cook Medical Inc.).
- Small sheath between 5F - 7F, for advancement into the renal arteries, e.g:
    - 5F Kumpe catheters (Cook Medical Inc).
    - 7F hydrophilic Ansel sheaths (Cook Medical Inc).
- Stainless steel 0.014 inch (0.3556 mm) guidewire, for extra stiffness of the initial guidewire.

Figures 8.2 and 8.3 depict the tools' location in the valves of the DrySeal and Check-Flo sheath models.

In general, the sheath's length to gain access to the abdominal aorta is 33 cm for femoral puncture (Schaik, personal communication, January 20, 2021). However, 25, 28 or 30 cm are available as well.

When introducing the smaller sheaths into the introducer sheath's valve, it would be preferrable to maximise the distance between the small sheaths to allow good freedom of movement, while making sure their manoeuvrability is not limited by the cannula wall (Van Schaik, personal communication, January 20, 2021).

Next, the sheath's usage steps during FEVAR are described in more detail, supported by Figure 8.4.



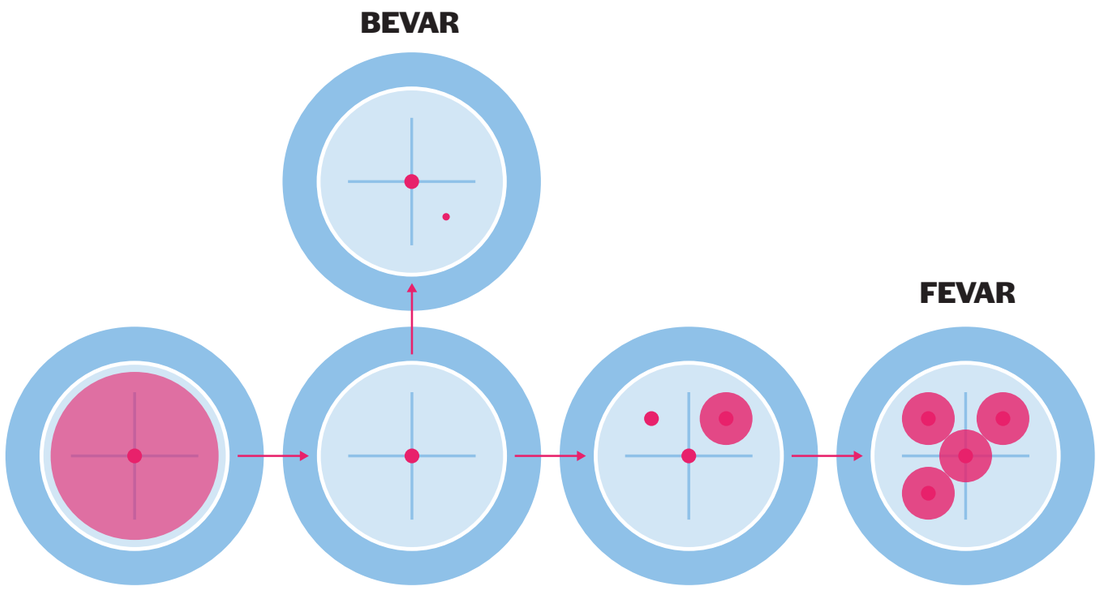


Figure 8.3 Schematic of tool positioning and build-up in valve of Check-Flo sheath, during FEVAR and BEVAR

8.2.1 FEVAR

Incision of around 5-8 cm is made to expose 2 cm of the artery. A small sheath and flexible wire are introduced through access point. Next, the large-bore introducer sheath is placed and used:

1. Flexible wire exchanged for a 0.035 inch wire.
2. Large-bore introducer sheath and dilator unit introduced, tip moves along iliac bifurcation into aorta. Thus, the dilator's lumen should allow movement over this 0.035 inch wire size.
3. Dilator is removed.
4. Optionally a needle is used for puncturing the valve (for example 21 gauge, 0.819 mm diameter). Insertion tool used to minimize friction when introducing second wire through valve.
5. 7F sheath follows, dilator introduced to catheterise first renal artery. Dilator removed and stent introduced to sheath.
6. Step 5 is repeated. Valve starts leaking individual drops of blood. Adhesive plastic pouch is placed below valve to collect blood. The surgeon / IR needs to hold the cell-saver tube in the pouch, to suck up the blood into the system.
7. 3rd 7F sheath is placed over stiff guidewire that is still in place from introducing the large sheath. This is enabled by the two wires and sheaths located in the renal arteries, ensuring the system's stability. Leakage starts becoming severe.
8. Potential 4th sheath would be placed next to the other three. Leakage increases even further.
9. First 7F sheath is removed from large sheath. Immediately, leakage decreases.
10. Other 7F sheaths are removed too.
11. Iliac bifurcation stent is located in own specific sheath (12F) through the introducer sheath (left femoral artery), here leakage is no problem.
12. Introducer sheath is removed.

Material	*Manufacturer*
One hydrophilic-coated J-tip guide wire, 0.035 inch/180 cm	Terumo
One hydrophilic-coated J-tip guide wire, 0.035 inch, 260 cm	
Two Lunderquist extra-stiff guide wires, 0.035 inch, 260 cm	Cook Inc
One Amplatz super-stiff guide wire, 0.035 inch, 1-cm floppy-tip, 260 cm	Boston Scientific
Two Rosen guide wires, 0.035 inch, 260 cm	Cook Inc
Two Sheaths, 9F, 11 cm	Alternative options
Two/three sheaths, 5F, 11 cm	Alternative options
One sheath, 20F, 25/30 cm or	Cook Inc
one Dry-Seal sheath, 18F, 28 cm	Gore
Two guiding sheaths, 7F-ANL1, 55 cm	Cook Inc
One straight metric angiocatheter, 5F, 100 cm	Alternative options
One Berenstein catheter, 5F, 65 cm	Alternative options
One Cobra catheter, 5F, 65 cm	Alternative options
One aortic molding balloon	Alternative options
iCast V12 balloon-expandable covered stents (according to preoperative CTA measurements)	Atrium Maquet
One balloon dilation catheter, 12 mm × 2 cm (flaring of the covered stents)	Alternative options

CTA, Computed tomography angiography; *F-EVAR*, fenestrated stent grafting for endovascular repair.

Table 8.1 Standard endovascular materials used for FEVAR (Verhoeven et al., 2014)

8.2.2 BEVAR

For BEVAR procedures, a percutaneous access point is created in brachial artery and a small sheath and flexible wire are introduced through the access point. Next, the large-bore introducer sheath is placed and used:

1. Flexible wire exchanged for stiff wire.
2. Sheath and dilator unit introduced, dilator is removed.
3. Insertion tool used to minimize friction when introducing second 0.014 inch wire through valve as complement to stiffness of first 0.035 inch wire. The tip of the 0.014 wire is 'caught' and pulled all the way through the aorta and out of the femoral access point.
4. Wires can be added one by one if advancing of the single wire is difficult. In that case, the surgeon should determine what factor is missing: push, stiffness, or hydrophily. When adding a wire, the stiffness of the wires together can be added up and increases.
5. 0.014 inch wire pulled from both ends (brachial and femoral) by surgeon and IR. The traction force is mostly exerted under an angle and can be compared to pulling a tightly fixed cork from a wine bottle.
6. Maintaining pressure, the wire is clamped with a dandy, which is pressed against the sheath hub.

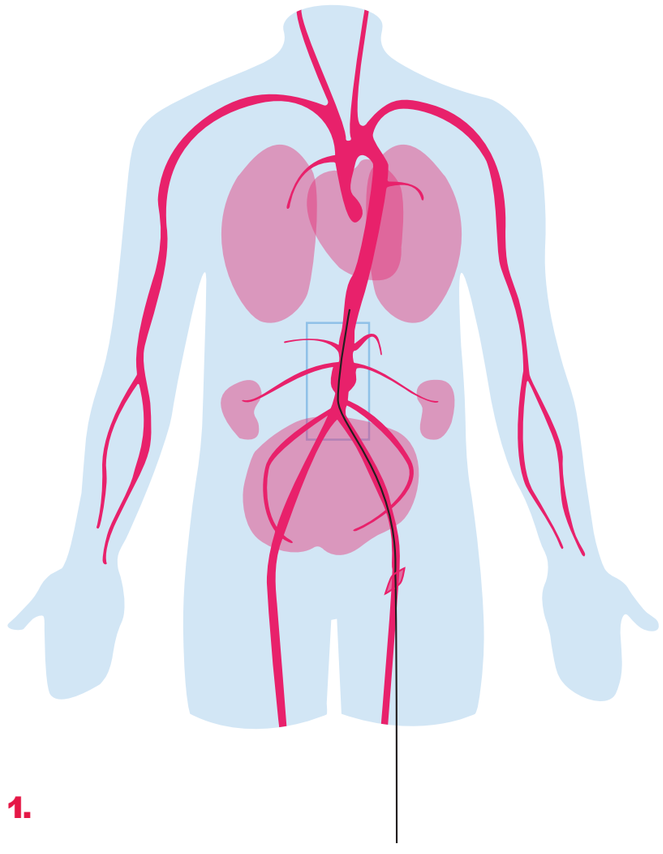
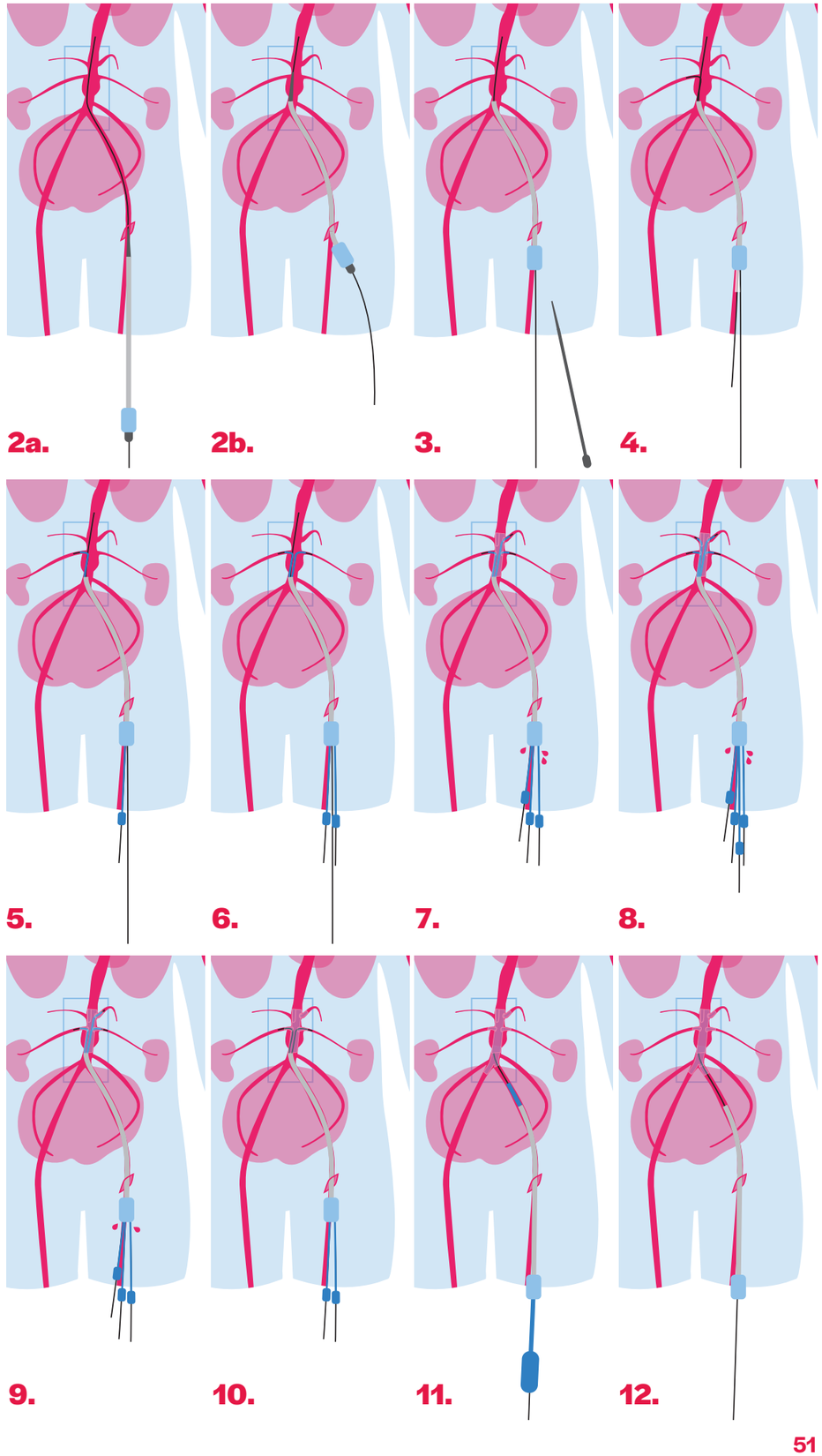


Figure 8.4 Schematic of the sheath's use steps during FEVAR



8.3 FUNCTIONAL SYSTEMS MODEL

The functional model in Figure 8.5 shows a breakdown of the different functional systems and sub-systems. This separation helps to get an understanding of the sheath's composition and functions. The sheath's two main systems are its hub and cannula.

The hub forms the entrance for tools. It contains a valve that allows these tools to enter. Simultaneously, it should prevent the blood from flowing out and prohibit air from entering the blood circulation, to prevent embolisation (Ferretto & Irsara, 2016, p. 69). This is called a haemostatic or haemostasis valve. Next to this, a flush port is connected to the hub below the valve. This port is used to flush the inside of the sheath cannula with a heparine solution for lubrication and to prevent coagulation. The heparine is injected through an on/off valve and enters the sheath via a connected tube.

The valve and flush port parts are embodied in the hub's housing, which also contains a suture loop on its outside at the side of the cannula, near the patient's body. This is used to safely fixate the sheath to the patient's skin next to the access point, preventing movement of the sheath out of the vessel.
The sheath is mainly handled by the surgeon holding its housing. Therefore, it must give the surgeon enough grip and feedback of movements.

PRODUCT	SHEATH					
SYSTEM	SHEATH HUB					
SUB-SYSTEM	VALVE	EMBODIMENT				
PART	HAEMOSTATIC VALVE	GRIP	CONNECTION TO DILATOR e.g. luer taper fitting and/or thread	SUTURE LOOP	HOUSING	

SHEATH					
	SHEATH CANNULA				
PORT	COMPOSITE TUBE				
FLUSH PORT	RADIOPAQUE MARKER BAND platinum iridium located in tip within tube material	OUTER TUBE e.g. Pebax & hydrophilic coating	FLAT WIRE REINFORCEMENT e.g. stainless steel	LINER e.g. PTFE (Teflon)	STRAIN RELIEF RING

Figure 8.5 Functional systems of commonly used sheaths

Every sheath comes with a compatible dilator, to guide the introduction of the sheath into the vessel. It is important that the dilator does not move out of the sheath while advancing the unit into the vessel. Therefore, the dilator is often connected to the sheath hub.
The dilator is longer than the sheath's cannula, letting the tapered end stick out beyond the cannula's tip. This taper enables the tips flexibility while advancing.
The dilator will likely be left outside of the scope in this project, as no challenges have been identified regarding the current use of dilators.

The cannula is a composite tube, connected to the hub. The tube generally consists of a plastic outer tube with a hydrophilic coating, which can be activated by wetting. The coating facilitates easier advancing into the vessel and prevents blood coagulation. The tube is reinforced by a (mostly stainless steel) flat wire. The inner surface of the cannula is lined with smooth material, such as PTFE, for easy advancing of tools. The composite has an integrated radiopaque marker band at the cannula's tip, which is visible on guidance imaging to view the position of the sheath. The connection between the sheath hub and cannula is reinforced with a ring to relieve strain during manoeuvring.

8.4 ANALYSIS OF COMMONLY USED SHEATHS

According to Drs. J. van Schaik (personal communication, January 04, 2021) two sheath models are used for FEVAR surgery in the LUMC: The GORE Dryseal introducer sheath (W. L. Gore & Associates) (Figure 8.6) and the Cook Medical Extra-Large Check-Flo sheath (Cook Medical Inc, Bloomington, Ind) (Figure 8.7).

The Medtronic Sentrant Introducer Sheath is used with regular EVAR procedures too. However, it is not suitable for FEVAR, as the valve remains open when punctured with 4 smaller sheaths, causing leakage (Dr. D. Eefting, vascular surgeon at LUMC, personal communication, January 20, 2021).

Outside the LUMC's walls, the same two models are typically used for FEVAR surgery (Tsolakis et al., 2019, Greece; Verhoeven et al., 2014, Germany, Portugal, Italy, Belgium; Oderich et al., 2014, Minnesota; and Kruse et al., 2011b, USA).

Officially, these sheaths are designed and sold to be used in regular EVAR procedures, and originally are not made for FEVAR (S. Schmitz, Field Sales Associate at W.L. GORE, personal communication, January 06, 2021). However, their use for FEVAR has evolved, as they are currently the best existing option. Schmitz assumes this to be the reason that the use of these two models for FEVAR has not been researched and published by their suppliers. Besides, the number of articles specifically describing the use of either sheath model for FEVAR execution is limited. This can also be related to the relatively low number of performed FEVAR procedures and performing institutions.

Nevertheless, these two sheaths are analysed here on the basis of their functional parts and materials, as well as their benefits and challenges.

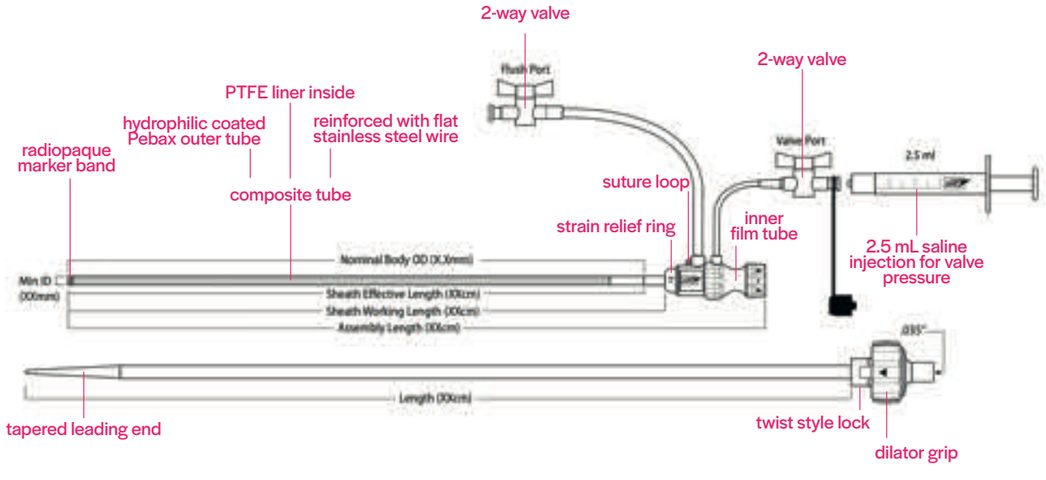


Figure 8.6 Part and materials overview of DrySeal

8.4.1 PARTS & MATERIALS

Both sheath models consist of three main parts (the valved sheath hub with connected side ports and a cannula) and a separate dilator.

Images with annotation of individual parts and materials of the DrySeal (W. L. Gore & Associates, Inc., 2016, pp. 1–11) and Extra-Large Check-Flo (Cook Medical Europe Ltd., 2019, pp. 1-3 and Jeltje Zijsltra, Cook Medical Customer Support Representative Dutch Market at EMEA Support Centre, personal communication, January 28, 2021) can be seen in Figures 8.6 & 8.7.

Little uniform handling actions or usecues are in place for different sheath models, as suppliers compete and do not communicate their methods with each other (Van der Meer, personal communication, January 20, 2021). However, for opening / closing something, rotating respectively counter clockwise and clockwise is the rule of thumb. This can also be translated to unlocking / locking and deploying / constraining. For example, when looking at typical stent deployment mechanisms, initiated by turning a knob and then pulling it. Simplicity is crucial here, as it leads to less handling actions and less faults (Schaik & de Jong, personal communication, January 20, 2021). The rotating and pulling works intuitive and in 'layers': the layers are ordered according to deployment sequence and reveal the next layer when used (and removed).

8.4.2 BENEFITS & DISADVANTAGES

To know what to improve, it is essential to know how current designs work and what does not. Both models are compared to identify their beneficial aspects that can function as inspiration, as well as their disadvantages that should be prevented and/ or improved in the new design. The findings are based on expert opinion of the vascular surgeons J. van Schaik and D. Eefting, and interventional radiologist R. van der Meer, all active at the LUMC (personal communication, January 20, 2021).

Mainly the DrySeal is used for femoral access during FEVAR procedures at the LUMC (Figure 8.9). According to the interviewed experts, the DrySeal works better than the Check-Flo. This could be due to the way how the Check-Flo is being punctured with the tools at the LUMC. Likewise, Verhoeven et al. (2014, p. 250) recognise this preference, because the DrySeal has less leakage compared to the Check-Flo when punctured with multiple tools (Figure 8.8).

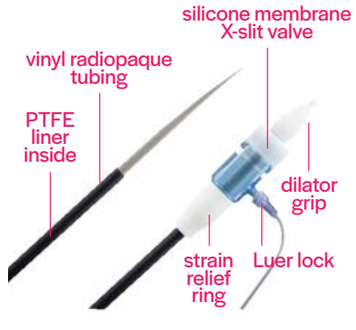


Figure 8.7 Part overview of Check-Flo

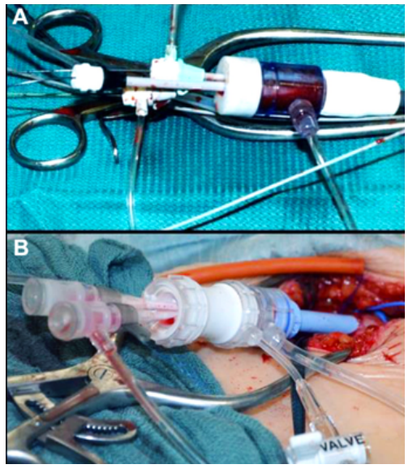


Figure 8.8 Images of Check-Flo (A) and DrySeal (B) by Verhoeven et al. (2014) during introduction of 3 small sheaths

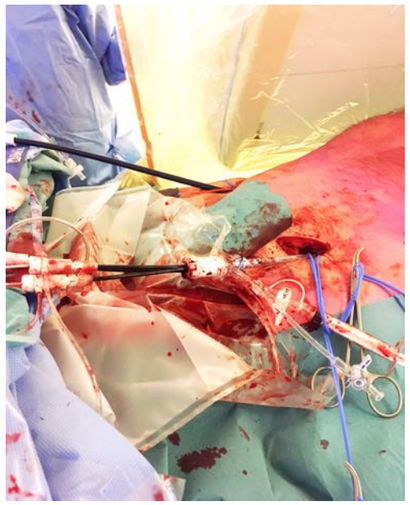


Figure 8.9 Leakage after introduction of the third catheter

8.4.2.1 THE DRYSEAL

\+ The DrySeal's main advantage can be attributed to its balloon valve. The balloon is inflated by injecting a saline solution with a syringe through the additional valve port. Then tools can be inserted through its centre and the balloon can be additionally inflated to fully enclose the tools. This pressure can always be adjusted during surgery.

\- The balloon valve system requires an extra tube, valve and syringe connected to it for saline injection, which can be inconvenient and in the way during operating.

\- Problems arise when inserting three tools, as a cavity appears between the tools, which the balloon cannot close off. With every additional tool, the cavity grows and causes more leakage.

\- In general, the balloon pressure does not decrease unintendedly during operation, but occasionally it is partly deflated and re-inflated by the surgeon, causing extra handling steps and annoyance. This is done because the tools are pressed together by the valve, leaving restricted freedom of movement.

\- The DrySeal's valve can influence the tactility when placing a catheter, by creating too much friction on the catheter or squeezing it too much. The surgeon wants to feel whether the tool enters the side-artery's origin or whether it collides with the artery's edge. This feeling should not be eliminated by the valve.

\- Also, if the valve is too tight, it presses the 7F sheaths against each other. Consequentially, if one small sheath is moved outwards, the other sheaths follow as well. Thus, when pressing the sheaths together in the valve, control is lost at the small sheath's tips located in the renal and SMA arteries. As a result, the tips can back out of these arteries, costing additional time and effort to re-catheterise.

\+ Lastly, the (amount of) grip on the sheath's hub is good when holding it and does not cause any problems (Van Rijswijk, personal communication, February 3, 2021). The current way of holding the sheath is shown in Figures 8.10 and 8.11.

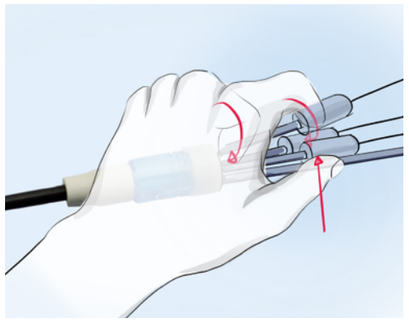


Figure 8.10 Typical grip of the sheath, index and middle fingers clamping around tools

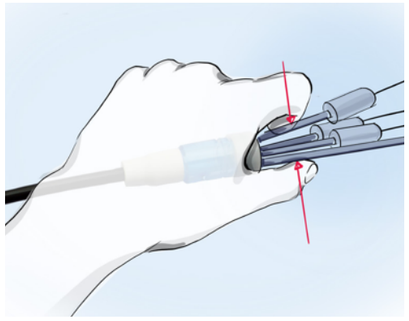


Figure 8.11 Typical grip of the sheath, thumb and index finger pressing tools together

8.4.2.2 THE CHECK-FLO

\- The Check-Flo's siliconet cross-slit valve only has one X-shaped cut in its centre, requiring the surgeon to puncture the silicone membrane around the cut for additional entrances. This is generally done with a needle, risking damage of the valve and sheath.

\+ The puncturing does allow the surgeon to choose a preferred positioning of tools.

\- The silicone membrane wears off and stiffness diminishes with more punctures, tools, and tool movements. It can rupture and ruptured parts can even tear off and land in the patient's vascular system.

\- Lastly, the Check-Flo does not have a suture loop, allowing the sheath to move out of the artery.

CONCLUSION

Both the W. L. Gore DrySeal and the Cook Medical Check-Flo introducer sheaths have their own differing (dis)advantages, especially regarding (the handling of) their valves.

Distinguishing between parts that do not lead to significant problems in these sheaths and parts that are problematic, requiring an intrinsic redesign, leads to the following division.
The first category consists of the cannula, as its radiopaque marker band, outer tube, flat wire reinforcement, liner, and strain relief ring currently function as intended. On the contrary, the haemostatic valve is the part causing the highest functional criticality. Forming the most important part for improvement, it also receives the focus during concept creation. As the valve design directly influences other parts, such as the housing and flushing system, these lie within the scope of the new concept development as well.

Overall, the project's aim is to design a sheath with a valve that improves functionality, especially by minimising blood leakage and other risks for the patient's condition, and reduces handling steps and difficulty.

8.5 CERTIFICATION & REQUIREMENTS

8.5.1 USE OF THE MDR

Although medical devices are intended to improve the patient's health, they can also present safety risks for the patient and medical staff. To ensure that all devices used in European healthcare are safe enough, their quality and safety must meet the standards of the European Medical Device Regulation, in short MDR (EU MDR 2017/745). These standards are incorporated into this design project from the beginning to ensure inherent compliance and safety with the design.

It is not realistic nor necessary to subject all medical devices to the strictest and most extensive regulations. Therefore, medical devices are classified according to the corresponding level of potential hazard. *"The classification of medical devices is a 'risk based' system based on the vulnerability of the human body taking account of the potential risks associated with the devices."* (European Commission, 2014).

In general, it can be said that the higher the risks, the higher the device class, and the more control is needed. The classification categories are based on the duration of use of the device in the patient's body and the intended use of the device, whether it is non-invasive, invasive or active.

MDR, Annex VIII, Rule 7:

All surgically invasive devices intended for short-term use are classified as class IIa unless they:

— are intended specifically to control, diagnose, monitor or correct a defect of the heart or of the central circulatory system through direct contact with those parts of the body, in which case they are classified as class III

— are intended specifically for use in direct contact with the heart or central circulatory system or the central nervous system, in which case they are classified as class III

8.5.2 SURGICALLY INVASIVE DEVICES

According to Van Schaik (personal communication, January 20, 2021), the introducer sheath enters through the access in the femoral artery and it is advanced until its end is positioned through the iliac bifurcation into the abdominal aorta. This far introduction is intentional, as there is a chance that other sheaths or tools moving through the access sheath go 'the wrong way' into a different vessel.

Annex VIII – 2.6 of the MDR sees the *"aorta descendens to the bifurcation aortae"* as part of the central circulatory system. The aorta descendens runs down from the aortic arch, through the thorax and abdomen to the iliac bifurcation. Thus, it can be concluded that the sheath is a surgically invasive device in direct contact with the central circulatory system and consequentially is a class III medical device according to Rule 7 in the same Annex (see left). This conclusion was consolidated with A. Loeve, expert in BioMechanical Engineering, Clinical Technology, and Medical Device Regulations (personal communication, January 18, 2021).

8.5.3 DIFFERENCES IN CLASSIFICATION

It is striking that the DrySeal is classified as a IIa device. This classification difference can be attributed to the fact that notified bodies are susceptible to human interpretation and, therefore, do not always act consistent (Degens, personal communication, February 2, 2021). In parallel, classification is the medical suppliers' responsibility, and they often look for grey areas and define their intended use vaguely (Aniba, personal communication, February 5, 2021). The DrySeal's IFU (W. L. Gore, Inc., 2016, pp. 5) states its intended use as *"...to be inserted in the vasculature..."* and does not define the exact location in the vasculature. Besides, it can be related to the change from the previous European Medical Device Directive (MDD) to the new MDR, which will occur on May 26, 2021 (Degens, personal communication, February 2, 2021). This is indeed the case, as the DrySeal is CE-marked according to the MDD 93/42/EEC (W. L. Gore, Inc., 2016, pp. 6). Also, the intended use only describes insertion to the vasculature in general, not (any part of) the central circulatory system. This could be a 'smart' way to achieve lower classification and, therewith, easier certification.

8.5.4 REQUIREMENTS

8.5.4.1 DEVICE CLASS

There are little differences between the basic design requirements for class IIa and class III devices. This can be found in Article X and Annex IX of the MDR. However, the classification routes (conformity procedures) do differ, stricter evaluation for certification is needed for class III. When a medical device company possesses an approved Quality Management System (QMS) in general, most of its class IIa devices can be automatically certified and assessment by a notified body is only done on a sampling basis. This is different for class III devices, as they always have to be assessed by a notified body (Degens, personal communication, February 2, 2021). Even after certification, Aniba (personal communication, February 25, 2021) explains, every change must be reassessed by the notified body.

8.5.4.2 STERILISATION

As sheaths enter sterile tissue and the central circulatory system, they are class III devices and must consist of biocompatible materials and be sterile (Aniba, personal communication, February 5, 2021). Consequentially, the device must be designed for sterilisation, aiming to kill all microorganisms on its surface. The chance of leftover microorganisms after sterilisation is expressed by the sterility assurance level, SAL, which must be 10^{-6} for this type of device (Starfish Medical, 2020). This is achievable through different methods: steam, dry-heat, Ethylene Oxide (EO), or radiation sterilisation. The latter two are commonly used for sheaths, as these can be sterilised in industrial settings at the packaging facility. However, both methods can influence material properties of plastics, such as embrittlement or colour changes. Thus, suitable materials should be chosen for the design of the device.
Finally, in case of required sterilisation, the device's sterility protocol or QMS must always be assessed by a notified body (Aniba, personal communication, February 25, 2021).

MDR, Annex VIII, Rule 3.2:

If the device in question is intended to be used in combination with another device, the classification rules shall apply separately to each of the devices.

Accessories for a medical device and for a product listed in Annex XVI shall be classified in their own right separately from the device with which they are used.

8.5.5 DESIGN CHOICES INFLUENCING CERTIFICATION

Design choices influence the classification and, consequently, lead to easier certification. For example, when designing an add-on valve component for existing, certified sheaths. According to Loeve (personal communication, January 18, 2021), in many cases collaborating components of a device receive the same, highest necessary class. However, in some cases individual certification is possible, such as for parts of infusion systems. This is described in Rule 3.2 of Annex VIII. Aniba (personal communication, February 25, 2021) confirms that a sheath add-on can be viewed separately for classification and can be graded as a class Is device. The 's' indicates sterility, thus requiring assessment of the device's sterility protocol, as stated in the previous paragraph. Such assessment is not required for all other documentation of class I devices, significantly reducing the certification process' duration, forming a large benefit. Still, the supplier is responsible to meet the requirements and provide the documentation for random checks.

Next to direct requirements for the device, the MDR also describes requirements concerning the device's Instructions for Use (IFU), packaging and labelling. These aspects are left out of scope during this project as they are time consuming and detail specific and, therefore, often supported by specialised, consulting parties during professional medical device development. Besides, these aspects do not directly contribute to the sheath's functional design and have to be constructed based on the final product, instead of the proof of concept which will be developed during this project.

CONCLUSION

Duration and costs of the certification process can be decreased, by designing a device in a low certification class. This can be the main benefit of development of an add-on over a complete sheath. As an add-on can follow the route for class Is, whereas a complete sheath needs to meet requirements for class III devices and follow a longer route with more extensive assessment.

9. DESIGNING FOR BLOOD FLOW

The sheath will be used in direct contact with the arterial system, making it essential to understand the blood flow and its characteristics, as these influence the valve's closure.
The flowrate of blood depends on the pressure and viscosity, which is *"a measure of a fluid's resistance to flow"* (Princeton, n.d.). Viscosity is created by the internal friction of a moving fluid. The lower the internal friction, the lower the velocity, the easier it flows and vice versa.

9.1 CHARACTERISTICS OF BLOOD FLOW DURING SURGERY

Comparing water at 20° Celsius with untreated blood, viscosities are respectively 1 mPa·s and 4.5±0.3 mPa·s (Hitosugi et al., 2001, p. 373). However, there is another difference. Water is a Newtonian fluid, it has a constant viscosity, whereas blood is a shear thinning fluid, as its viscosity can change (Figure 9.2). Here the viscosity decreases under shear strain down to a factor of 10 times (Poelma, personal communication, January 13, 2021). The smaller the vessel diameter, the more blood contacting the vessel wall, thus the higher shear strain and viscosity, and the lower velocity and flow rate (Figure 9.3).

Figure 9.1 Anaesthetic patient monitoring, peak and mean blood pressure values can be seen in red (116/63)

As vessel diameter is patient dependent, the viscosity of blood is too. Additionally, blood viscosity is influenced by temperature and addition of blood thinning, anticoagulants (Khnouf et al., 2019, p. 2). During surgery, mostly heparin is added, or an alternative, such as ascal, clopidogrel, sintrom or marcoumar (Van Schaik, personal communication, January 13, 2021). When adding heparin, viscosity decreases depending on the anticoagulant dose to a minimum of 2.5±0.3 mPa·s (Hitosugi et al., 2001, p. 373).

Peak blood pressures during surgery at the femoral access point are estimated between 160 and 180 mmHg by Van Schaik (personal communication, September 02, 2020) and this is constantly tracked throughout the surgery by the anaesthetists. Also, Fung et al. (2008, p. 487) describe peak blood pressure at 180 mmHg, which is a severely high blood pressure level. In comparison, mean arterial pressure is maintained between 80-90 mmHg (Juszczak et al., 2020, p. 439). Peak and mean pressure are constantly monitored during the surgery (Figure 9.1).

CONCLUSION

The sheath's valve must form closure when subject to blood flow with a maximum pressure of 180 mmHg and a viscosity between 2.5 and 4.5 mPa·s.

9.2 DESIGNING FOR BLOOD FLOW

Designing a product that should be resistant and leakproof to blood flow, comes with its own challenges regarding the specific viscosity and pressures, explained above. Recommendations have been gathered from literature and expert interviews, as well as existing valve designs that can be found in medical, industry, and household applications (Appendix F). These are categorized into: form design, fluid management components, and testing.

9.2.1 FORM DESIGN

- According to Poelma (personal communication, January 13, 2021), the effect of hydrophobic versus hydrophile materials only works on a very small scale. That means that the type of material has little effect on the amount of leakage.
- In this project's case, the form is the decisive factor (Poelma, personal communication, January 13, 2021). Instead of using complicated and expensive materials, focusing on the design of the valve is more effective according to Poelma, for example by placing multiple valves behind each other (in series).
- The potential for leakage can be reduced by minimizing the number of connections (Hydraulics & Pneumatics, 2011). As these are all potential points for leakage and can be omitted by integrating multiple components into one pre-joined assembly.

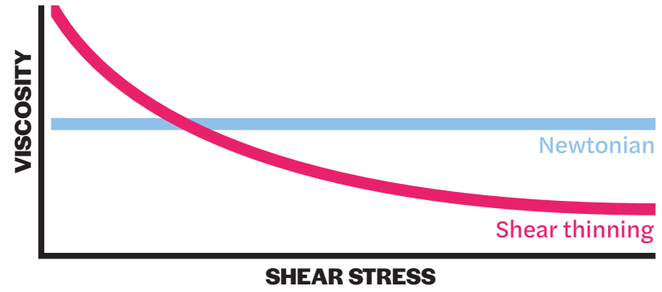


Figure 9.2 Characteristics of shear-thinning fluids

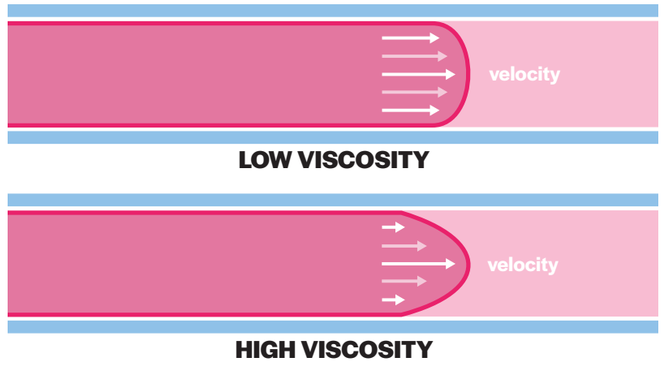


Figure 9.3 Viscosity influences blood flow

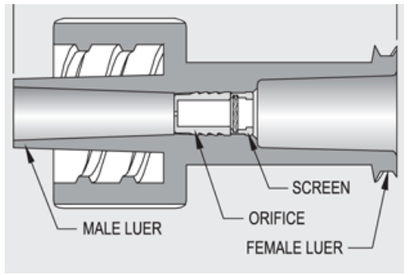


Figure 9.4 Luer lock

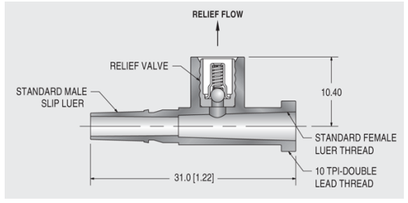


Figure 9.5 Luer slip

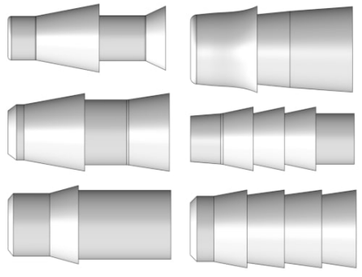


Figure 9.6 Various alternatives of multi-barb fitting designs

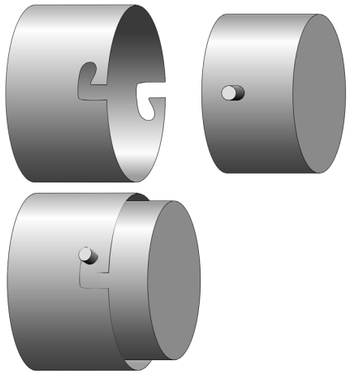


Figure 9.7 Open and closed bayonet-style connector

9.2.2 SUITABLE FLUID MANAGEMENT COMPONENTS

- Luer connections are typical medical fluid management components based on the 6% tapered cone Luer standard. This type of connection is used worldwide and results in reliable and inexpensive components (Nordson Medical, n.d.). They exist of a female and male part and are available in two forms:
    - Luer-locks have a threaded sleeve (male) that can be screwed into a tabbed hub (female) and provide a secure connection (Nordson Medical, n.d.), Figure 9.4.
    - Luer slips are plug-connectors conform to Luer taper dimensions. By pressing them together, they are held by friction, without a thread. This form is used for less critical applications, such as flushing, Figure 9.5.
- Single- or multi-barb fittings (Figure 9.6) are frequently used for blood pressure resistant connections and are suitable in use with tensile forces (Binder, n.d.).
- Bayonet-style connectors (Figure 9.7), sometimes used in combination with snap-in connections, have a cylindrical male part with radial pins or notches and a female connector with corresponding slots. The parts are slid together and rotated for fixation.
- Threads are a typically used joining method for medical connections, mostly requiring a single rotation. They are a strongly preferred temporary connection method, because *"you can feel that the thread is completely fixed and cannot move anymore, this gives confirmation"* (Van Rijswijk, personal communication, February 3, 2021). Sometimes an extra closure is added on top of the thread, to withstand the high blood pressure.
- Click-fits would rather lead to impractical and clumsy handling when the user wears gloves (Nijenhuis, personal communication, January 8, 2021). Also, the user has less security regarding correct fixation and click-fits can get stuck in a wrong position.

9.2.3 TESTING

According to Poelma (personal communication, January 13, 2021), it is difficult to exactly calculate the shear thinning rate caused by a valve, especially because the calculations will become very patient specific (depending on the patient's blood values and anatomy). He concluded that an experimental approach is more suitable for this project.

Poelma expects relatively low blood flow velocities for this project's application; thus, the occurring viscosity differences will be small. He assumes that the viscosity will remain between 3 and 4 mPa·s. Therefore, testing with different viscosities of, for example, 3, 3.5 and 4 mPa·s will not lead to significant differences of leakage of the model.

As testing with human blood is complicated, especially at the beginning of the project during rapid prototyping, alternatives are required to mimic the characteristics of blood. Looking at viscosity, comparable viscosities can be found with milk (3 mPa·s (Global Pumps, n.d.)) and grape juice (2-5 mPa·s (Bürkle GmbH, 2021)).

Patent search parameters
Search engine:
Google Patents

Search keywords:
(one-way valve solution) language: ENGLISH

(hemostatic valve) language: ENGLISH

However, a fluid typically and easily used for testing is water mixed with glycerol (Poelma, personal communication, January 13, 2021). A dynamic viscosity of 3.0 mPa·s can be achieved with a water to glycerol mixing ratio of 1:0.43, a viscosity of 4.0 mPa·s with a ratio of 1:0.57. This was calculated with a tool developed by University of Reading (2018), based on the parameterisation in Cheng (2008), and Volk and Kähler (2018).

9.3 EXISTING SHEATHS, PATENTS, AND VALVES

Next to the large-bore introducer sheaths that have been discussed, competitor sheaths used for other types of catheterisation are analysed (Appendix D), as well as relevant patents (Appendix E). This is important to prevent reinventing the wheel or even (unaware) copying of these solutions. Hereto, a selection of sheath designs with interesting aspects is evaluated. Next to existing sheath solutions, valves for other applications were researched and evaluated as inspiration for possible application. The analysis includes valves intended for medical, household, and industrial products.

The main insights gathered through existing commercial sheaths can be summed up:

- Instead of forcing all tools through the same entrance and valve, these separated entrances are each provided with separate valves which can be numbered to track the inserted devices. However, again no more than two separate entrances can be found (Figure 9.8).
- Coupling add-on valves to the hub of a separate sheath by using Luer connections (threaded or form fitting) (Figure 9.8).
- Creating double valve systems existing of two (types of) valves in series can be done, for example by combining a Touhy valve and a simple split valve (Figure 9.9).
- Providing valve with adjustable passage positions (Figure 9.13) to:
    - open / close, by rotating the outer housing part or compressing two housing parts.
    - loosen / tighten, by pressing the outer housing part over the hub's centre.
- Locking dilator with a ¼ turn lock mechanism, as seen in the DrySeal by W. L. Gore.

The patent search lead to the following relevant valve solutions:

- A silicone valve with a plurality of holes can reduce surface tension when inserting a catheter or dilator, configured to provide a softer sense of insertion feel to the user (Figure 9.10).
- A trailing ridge and knob for locking of the dilator to the sheath hub (Figure 9.10).
- Layering of rotated (single) slit valves to ensure that slits are arranged in differing directions (Figure 9.11).
- Use of pin-hole valves to ensure centre alignment of the guidewire. The pinhole slits have no width but can have a length of 2-15 mm (Figure 9.12).

Figure 9.8 Sheath with corresponding add-on separating the tools, connected by Luer, by Merit Medical

Two other distinct sheath functionalities were considered too, but neither is found to be suitable:

- Steerable, used for better approach into origins of branching arteries. However, a steerable tip has no advantages for an introducer sheath as it does not need to enter perpendicular artery origins (Schaik, personal communication, January 04, 2021).
- Pre-loaded, used in sheaths that are loaded with a stent graft and which are specifically intended for this stent's deployment. Again, this functionality is not required in the introducer sheath (Schaik, personal communication, January 04, 2021).

Most patented designs have a smaller bore, preventing introduction of four 7F-sheaths. Freudenberg Medical and Medtronic both do sell a large-bore introducer sheath. However, these are also limited to a single, round entrance for all four tools, allowing the familiar problem of leakage between these tools.
Combinations of valves appear in different designs, either in parallel or in series. Also, rotational fixations are used for multiple purposes, such as coupling add-ons and dilators, or adjusting the valve passage's position. The last can also be achieved by pressing two housing parts together.

CONCLUSION

A leak proof design can be achieved by reducing the number of connections to a minimum, and using common fluid management components, such as Luer-locks and slips, barb fittings, bayonet-style connectors, and threads.

Figure 9.9 Double valve system: Touhy valve and split valve, by Merit Medical

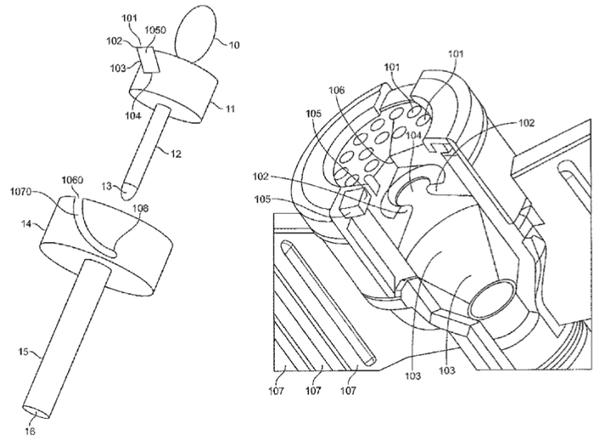


Figure 9.10 Locking ridge for dilator (left) and valve perforated with plurality of holes (right), from patent: US 10258771

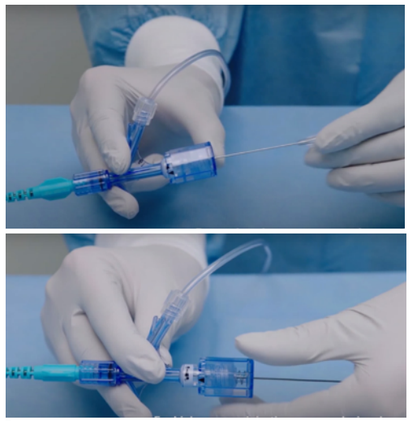


Figure 9.13 Valve opened by pressing, rotation prevents pressing the valve open, seen in the WatchDog by Boston Scientific

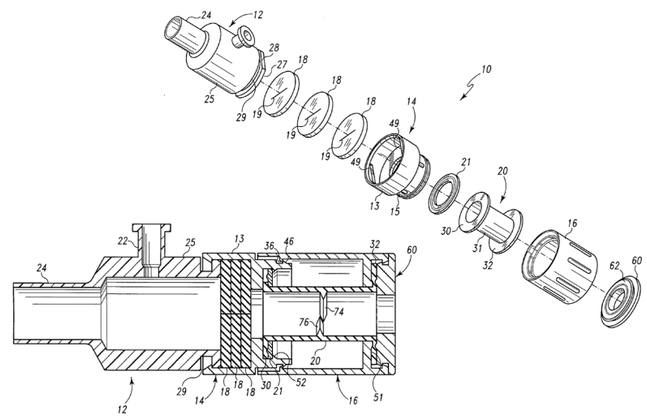


Figure 9.11 Layering of multiple slit valves in assembled (left) and exploded view (right), from patent: US 7,172,580 B2

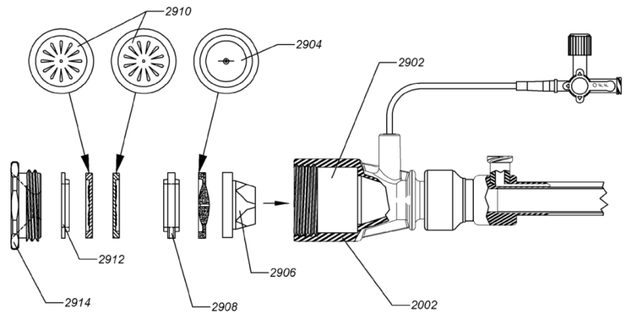


Figure 9.12 Layering of pin-hole valves in combination with cross-slit valve, from patent: US 9,387,314 B2

SYNTHESIS

PART 3

This chapter covers the synthesis step between gathered research findings and creation of the final solution. Here, the research conclusions are translated into specific requirements and prioritised drivers, forming guidelines for the future design. A summary of the concept development process is included too, from ideation to three concepts tested for functionality and usability.

10. LIST OF REQUIREMENTS

(Synthesis of) the above described research leads to numerous requirements for the new sheath solution design that are gathered in this List of Requirements, covering aspects from functional performance to ergonomics and sterilisation. Besides, wishes are identified for creating the optimal sheath solution. Completeness of the List of Requirements is verified with support of the Delft Design Guide (Boeijen & Daalhuizen, 2020) and the MDR Usability Requirements Checklist by Johner Institut (2021).

10.1 PERFORMANCE

1. The sheath solution should form a reusable access point for introduction of other tools into the vessel (Paragraph 8.1 Device functionality).
2. The sheath solution should exclude the vessel puncture site from insertion activities of other tools (Paragraph 8.1 Device functionality).
3. The sheath solution should remain located in the vessel without holding it by hand (Paragraph 6.2 Stakeholders).
4. The sheath solution should have a haemostasis valve (Paragraph 8.3 Functional systems model).
5. The valve should be leak proof when inserting three or four 5-7F sheaths or catheters (Paragraph 6.4 The product's use journey).
6. The valve should be leak proof when exerting an (angled) pulling force on an inserted 0.014 inch (0.036 mm) super-stiff wire (Paragraph 6.4 The product's use journey).
7. The valve must prevent blood from flowing out of the sheath solution during mean pressure of 80-90 mmHg and even during peak blood pressures of 160 up to 180 mmHg (Paragraph 9.1 Characteristics of blood flow during surgery).
8. The valve must form closure when subject to blood flow with a viscosity between 2.5 and 4.5 mPa·s (Paragraph 9.1 Characteristics of blood flow during surgery).
9. The valve should be resistant to tearing (Paragraph 6.4 The product's use journey).
10. The valve should resist moving the individual tools in and out sequentially for at least 40 times, while keeping its intended functionality (Paragraph 6.4 The product's use journey).
11. The valve should not allow rupturing and tearing and prevent its own material from moving into blood circulation (Paragraph 6.4 The product's use journey).
12. The dilator must be connectable to the introducer sheath hub during introduction and removal (Paragraph 6.4 The product's use journey).
13. The sheath solution should be lubricous during the whole procedure. For example, it should enable saline flushing and have wet-activated heparine coating on its cannula (Paragraph 6.4 The product's use journey).
14. The cannula's tip should be visible on radiography imaging (Paragraph 8.3 Functional systems model).

10.2 DIMENSIONS

1. A cannula inner diameter between 20-24F should be available (Paragraph 8.2 Tools used with the sheath).
2. An introducer sheath length of 25, 28, 30 and 33 cm should be available (Paragraph 8.2 Tools used with the sheath).
3. The sheath solution's dimensions must allow at least four tools of 7F and one central guidewire to enter in parallel (Paragraph 8.2 Tools used with the sheath).
4. The dilator should be longer than the sheath's cannula (Paragraph 8.3 Functional systems model).
5. The dilator's lumen must be compatible with a 0.035-inch (0.89 mm) guidewire (Paragraph 8.2 Tools used with the sheath).
6. Dimensional accuracy: the production methods must provide dimensional accuracy and a tolerance of max. 0.05 mm for the device's parts (Paragraph 23.3 Manufacturing processes).

10.3 CONTEXT OF USE

1. The sheath solution must be resistant to alcohol (Paragraph 6.4 The product's use journey).
2. The sheath solution must remain well visible when positioned next to pink coloured disinfectant (Paragraph 6.4 The product's use journey).
3. The sheath solution must be resistant to iodine (iodixanol and iohexol) (Paragraph 6.4 The product's use journey).
4. The sheath solution must be resistant to anti-coagulant heparine, and its alternatives ascal, clopidogrel, sintrom of marcoumar (Paragraph 6.4 The product's use journey).
5. The device must be able to withstand a fall from 1.5m height (standing table height with 50% margin) without breaking (Paragraph 6.4 The product's use journey).
6. The device must be functional at a temperature between 5° and 60° Celsius (Paragraph 6.4 The product's use journey).
7. The device must be resistant to temperatures between -15° and 80° Celsius (Paragraph 6.4 The product's use journey).
8. The device must withstand an axial traction force of 50 N (Fischer, 2013) (Paragraph 6.4 The product's use journey).
9. The device must withstand an axial compression force of 20 N (Paragraph 6.4 The product's use journey).
10. The device must withstand a tilting / kinking force of 10 N (Paragraph 6.4 The product's use journey).
11. The device must withstand an in plane (over its width) compression force of 80 N (based on the pinching force with 3 fingers and a thumb) (Ng, 2015) (Paragraph 6.4 The product's use journey).
12. The device must consist only of biocompatible materials (Paragraph 8.5 Certification & requirements).
13. The materials used in the device must meet ISO 10993-1:2018 Biological evaluation of medical devices (Paragraph 8.5 Certification & requirements).

10.4 STERILISATION

1. The sheath solution must have a SAL (sterility assurance level) of 10-6 (Paragraph 8.5 Certification & requirements).
2. The sheath solution should be sterilisable by gamma irradiation (Paragraph 8.5 Certification & requirements).
3. The materials used should be sterilisable by gamma irradiation (Paragraph 8.5 Certification & requirements).

10.5 ERGONOMICS

1. The sheath solution must be usable while wearing a gown, plastic gloves, mask, cap, and clogs (glasses, coat, thyroid gland protection) (Paragraph 6.2 Stakeholders).
2. The use of the sheath solution should be ergonomically pleasant while surrounded with X-Ray protective gear and its use should not require notable physical effort (Paragraph 6.4 The product's use journey).
3. The sheath solution should be well visible and easy to pick up at its hub when lying on the table (Paragraph 6.4 The product's use journey).
4. The sheath solution should not be able to 'roll off' the table (Paragraph 6.4 The product's use journey).
5. The sheath solution should be usable in both directions and by both hands (Paragraph 6.4 The product's use journey).
6. When incorporating rotatable mechanisms, the sheath solution's design should adhere to the rule of thumb: counter clockwise is opening / unlocking / deploying, clockwise is closing / locking / constraining (Paragraph 6.4 The product's use journey).
7. The connection between the sheath and dilator unit should be ergonomically easy to lock and unlock (Paragraph 6.4 The product's use journey).
8. The connection between the sheath and dilator unit should give a confirmation of correct closing for a secure feeling (Paragraph 6.4 The product's use journey).
9. The valve should create minimal friction on tools moving through it, this friction force must be smaller than the force required to pull the introducer sheath out of the vessel (Paragraph 6.4 The product's use journey).
10. The friction during tool manoeuvring should give the user a feeling of control over tool movements (Paragraph 6.4 The product's use journey).
11. The sheath solution's housing must give the surgeon grip and feedback of movements (Paragraph 8.3 Functional systems model).
12. The sheath solution should facilitate ergonomically pleasant introduction of tools through the valve, for example with good visibility of the entrance or a shape guiding the tool in the right direction (Paragraph 6.4 The product's use journey).
13. Good visibility of the sheath solution's separate parts, usecues and tool positioning in the valve from a minimum distance of 40 cm, which is assumed to be the maximum distance between the user's hands and eyes (Paragraph 6.4 The product's use journey).

10.6 LIFE IN SERVICE

1. The sheath solution should not force disposal of unused parts or tools (Paragraph 6.4 The product's use journey).
2. The sheath solution must allow replacement when it, or a part of it, becomes unusable (Paragraph 6.4 The product's use journey).

10.7 LIST OF WISHES

1. The sheath's production costs should be kept as low as possible (Paragraph 11.2 Hospitals, the customers).
2. The sheath's design could prevent occlusion of the femoral artery and enable blood flow to the leg (Paragraph 6.4 The product's use journey).
3. The sheath should enable the best possible surgery outcomes (Paragraph 11.1 Surgeons, the users).
4. The sheath should enable as easy as possible handling (Paragraph 11.1 Surgeons, the users).
5. The sheath should be as compatible as possible with other tools it is used with (Paragraph 11.1 Surgeons, the users).
6. The sheath should decrease the procedural time as much as possible (Paragraph 11.1 Surgeons, the users).
7. The sheath must limit entrance of air to the vascular system as much as possible (Paragraph 8.1 Device functionality).
8. The sheath must prevent leakage of blood as much as possible (Paragraph 8.1 Device functionality).
9. The sheath should be as bendable as possible, while kinking as little as possible (Paragraph 8.1 Device functionality).
10. The sheath should move into the vessel as smooth as possible (Paragraph 8.1 Device functionality).
11. The wall-thickness of the cannula should be as little as possible (Paragraph 8.1 Device functionality).
12. The inner diameter of the cannula should allow maximum space for the tools (Paragraph 8.2 Tools used with the sheath).
13. The outer diameter of the cannula should be as small as possible (Paragraph 8.1 Device functionality).
14. The distance between the small sheaths should be maximised to allow good freedom of movement (Paragraph 8.2 Tools used with the sheath).
15. Freedom of movement of the inserted tools should be as good as possible (Paragraph 8.4 Analysis of commonly used sheaths).
16. The number of connections of the sheath should be minimised to decrease leakage (Paragraph 9.2 Designing for blood flow).

11. USER'S & CUSTOMER'S INTERESTS

Simply designing a new leakproof sheath does not mean that it will be used by surgeons in hospitals. There are various factors and parties that influence whether the device will be bought or not.

11.1 SURGEONS, THE USERS

First of all, surgeons must be convinced to use the tool. De Jong, Surgical Resident Vascular Surgery at Leiden University (personal communication, January 20, 2021) explains that above all trust in the new concept's functionality is guiding. Therefore, it should be supported by enough trustworthy research and testing. Before trusting and using the device yourself, you want that other places test it and find its problems, especially because there are a lot of unfunctional devices on the market nowadays. For example, when a new, cheaper wire is procured and the functionality is worse than previously used wires, surgeons often complain about it (Circulating nurse at the LUMC, personal communication, January 20, 2021).

11.1.1 EASY HANDLING

It is essential to realise that changing the complete procedure is practically impossible (and unwanted), because it is seen as golden standard. It is possible, though, to make it safer for the patient and easier for the surgeon, or the change the way that existing tools are used (M. Chmarra, personal communication, January 04, 2021). Design for easier handling increases the surgeon's focus on the main task. Intuitive and automated tool use can be achieved, for example, by using familiar parts and mechanisms, designing an ergonomically comfortable and secure shape and grip, and providing necessary feedback.

11.1.2 GOOD COMPATIBILITY

Acceptance of new surgical tools also depends on their compatibility with existing tools (Nijenhuis, personal communication, January 08, 2021). Good compatibility makes their acceptation and introduction into the procedure easier, because the surgical team is familiar with the working principle or design. On top of that, good compatibility ensures lower investments, because the new device can be used with tools that are already in use and/or are stocked.

Looking at compatibility, some suppliers choose to sell their tools in patient specific sets (Nijenhuis, personal communication, January 08, 2021). This guarantees compatibility, is financially beneficial for the suppliers and easy for the hospital's procurement staff. However, one of the tools could break, get lost, or fall and become unsterile. In that case, a complete new set must be opened, wasting money and tools, leading to frustration and annoyance with the medical staff.

11.1.3 HIGH EFFICIENCY

Time is a very important factor during surgical procedures, as it influences the effect of the surgery on the patient's blood circulation and blood loss and, consequentially, the patient's recovery (Nijenhuis, personal communication, January 08, 2021). Besides, the shorter the procedure, the more time the surgical team has left for other tasks or even the less (un-paid) overtime they make (Van Schaik, personal communication, January 20, 2021), as Dutch academic hospitals currently have a staffing shortage.

11.2 HOSPITALS, THE CUSTOMERS

The factors mentioned above influence the surgeons' attitude towards a new tool and whether they recommend buying it to the procurement department. Nevertheless, the choice of tools mostly depends on a hospital's financial plans and hospital wide agreements with specific suppliers (Nijenhuis, personal communication, January 08, 2021).
Often, it is difficult to switch to different tools, as hospitals have 4-year contracts with suppliers (Circulating nurse at the LUMC, personal communication, January 20, 2021).

A typically used way to introduce new tools is by first 'borrowing' them to the hospital, so the surgical team can get acquainted with and used to them. After the trial period, the hospital can keep the tool by paying the full price for it.

Overall, it can be said that the aim of hospital boards is to achieve the best surgical outcomes with the lowest possible costs. However, this must be seen relatively, as these academic hospital boards put little financial and time pressure on their staff compared to specialised, private centres (De Jong, personal communication, January 20, 2021).

CONCLUSION

The product's users and customers (surgeons and hospitals) consider various factors when deciding to procure a new device. The most determinant (and intertwined) factors can be prioritised as follows:
1. Demonstrated better outcomes
2. Easy handling
3. Good compatibility with existing tools
4. Efficiency
5. Low cost (which is significantly less important in academic hospital settings compared to specialized private centres).

12. DESIGN DRIVERS

1. MINIMISED LEAKAGE

<50 mL per procedure by enclosing every individual tool, even after numerous movements

2. PRODUCT SAFETY

Minimal risk factors, familiar handling actions and clear feedback

The determinant factors are used to prioritise the requirements and to focus the design work on the key challenges, as identified from the procedure (Paragraph 6.4). These factors should not be seen separately, as they are strongly intertwined. For example, when incorporating a commonly used connection mechanism, this might ensure compatibility with other tools, while the medic is familiar with the working principle. (S)he automatically knows how to engage with it, requiring little attention and allowing the medic to concentrate on the main task, leading to better outcomes.

12.1 PRIORITISING DESIGN REQUIREMENTS

12.1.1 MINIMISED LEAKAGE

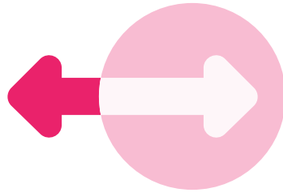
Before the device stands a chance of being used in practice, surgeons, hospitals and procurement departments must gain trust, by demonstrating improved operations and outcomes. Thereto, most importantly, the leakage problem should be solved to ensure optimal surgery outcomes by minimising blood loss. Hereto, fulfilling requirements regarding the valve's functionality is essential. If these are not met, the device is of no significant benefit to the market.

In particular, leakage should be minimised when inserting three or four 5-7F tools (Requirement 10.1.5) with a blood pressure of 180 mmHg (Requirement 10.1.7) and a viscosity between 2.5 and 4.5 mPa·s (Requirement 10.1.8), while moving the tools up to 40 times (Requirement 10.1.10). Leakage should be kept below 50 mL during one surgery, which is the maximum leaked volume with sheath use as intended during regular EVAR surgeries (Van Schaik, personal communication, February 23, 2021).

A second challenge causing leakage, concluded in Paragraph 8.2, is the (angled) pulling force on an introduced 0.014 inch super-stiff wire during BEVAR surgeries (Requirement 10.1.6). However, this causes significantly less leakage according to Van der Meer (personal communication, February 3, 2021) compared to the first challenge. Thus, it has less priority and will be solved only if integration with the main problem's solution is possible.

12.1.2 PRODUCT SAFETY

Also, safety is an inevitable priority. The device's design should inherently ensure safety, as any hazards can severely harm the patients' health, especially due to the high surgical complexity. Hence, risk factors should be minimal, if not completely overcome. Next to physical risk factors, such as a breaking part, also risks related to usage should be prevented by enabling correct use only, implementing handling actions that are familiar to surgeons, providing clear use-cues for these actions, and forwarding feedback of these movements to the user through the valve (Requirement 10.5.11). Additionally, requirements concerning sterilisation, dimensional fit, and environmental influences are important. The latter two are also relevant for the device's compatibility, the fourth design driver.



3. SMOOTH TOOL MANOEUVRING

Enabling either fixation or optimal "Freedom of Movement" when required

4. ERGONOMIC USE

Ambidextrous, comfortable and secure one-hand grip, good visibility for precision

5. TOOL COMPATIBILITY

Dimensional fit and stock adaptability for unexpected problem solving

12.1.3 SMOOTH TOOL MANOEUVRING

The third essential challenge, identified in Paragraph 6.4, is facilitating smooth introduction of tools through the sheath. This relates to requirements of minimising the friction on the tools while inserting and moving them (Wish 10.7.4 & 10.7.15).
Even when pulling out the tools, the sheath should not be pulled back with the tools and remain located in the vessel (Requirement 10.1.3). Thus, a paradox is applicable here of enabling either optimal "Freedom of Movement" when required, or solid fixation when the tool is not in use.

12.1.4 ERGONOMIC USE

Besides smooth tool manoeuvring, other factors also relate to ergonomically easy introduction of the tools through the valve. For example, facilitating precision handling through good visibility of the entrance, an entrance shape that guides the tool in the right direction (Requirement 10.5.12) and enough handling space around the entrance. Besides handling related to the valve, general ergonomic comfort and a feeling of security are a way to convince the surgeon. These are covered by requirements about ambidexterity (Requirement 10.5.5), a secure one-hand grip, comfortable and light (Requirement 10.5.4), even while wearing protective clothing (Requirement 10.5.1), and a confirmation of correct fastening (Requirement 10.5.8).

12.1.5 TOOL COMPATIBILITY

For achieving compatibility, both dimensional aspects (e.g. a fit with other tools) as well as device stock are applicable.

Correct size and form fit is required with the tools that enter the sheath (Requirement 10.2.3 & 10.2.5), but also with existing sheaths in case of designing an add-on. Besides, compatibility with the procuring and storage system in place is needed. It must allow replacement of the sheath or its device components in case they become unusable, by enabling a certain stock of the components to be in place in or near the OR (Requirement 10.2.1 & 10.2.2). Besides, the same counts for catheters or small sheaths becoming unfunctional: the sheath must be flexible for use with stored alternatives for unexpected problem solving.

6. EFFICIENCY

Time and costs should be equal or lower, or proportional to improved outcome.

12.1.6 EFFICIENCY

The last design driver is efficiency of time and money, covering for example OR-occupation, staff availability and equipment costs. This is subordinate to the previous design drivers but must be proportional.

In comparison to the sheath's current preparation time of 30-60 seconds and subsequent introduction of 3-4 minutes, Van Schaik (personal communication, February 2, 2021) explains that *"a solution can function brilliantly, but if preparation takes the scrub nurse 30 minutes, it will never be used."*.

Similar to time, pricing should not be a reason to not use the device. Thus, it should not be significantly more expensive than existing solutions. But if the new device leads to better outcomes and, therewith, reduces revalidation and post-surgical care for the patient, or reduces surgical time and efforts, it could lead to noteworthy cost reductions in other areas. Such considerations should be taken into account when determining the pricing. Thus, the new sheath design's resource use should be least the same as in current situations, and preferably reduced, or it should be proportional to improved outcomes.

CONCLUSION

Six prioritised design drivers are taken along to the next phase of developing ideas and concepts: minimised leakage, product safety, smooth tool manoeuvring, ergonomic use, tool compatibility, and efficiency. They are used both as inspiration for ideation, and as evaluation criteria to compare solutions.

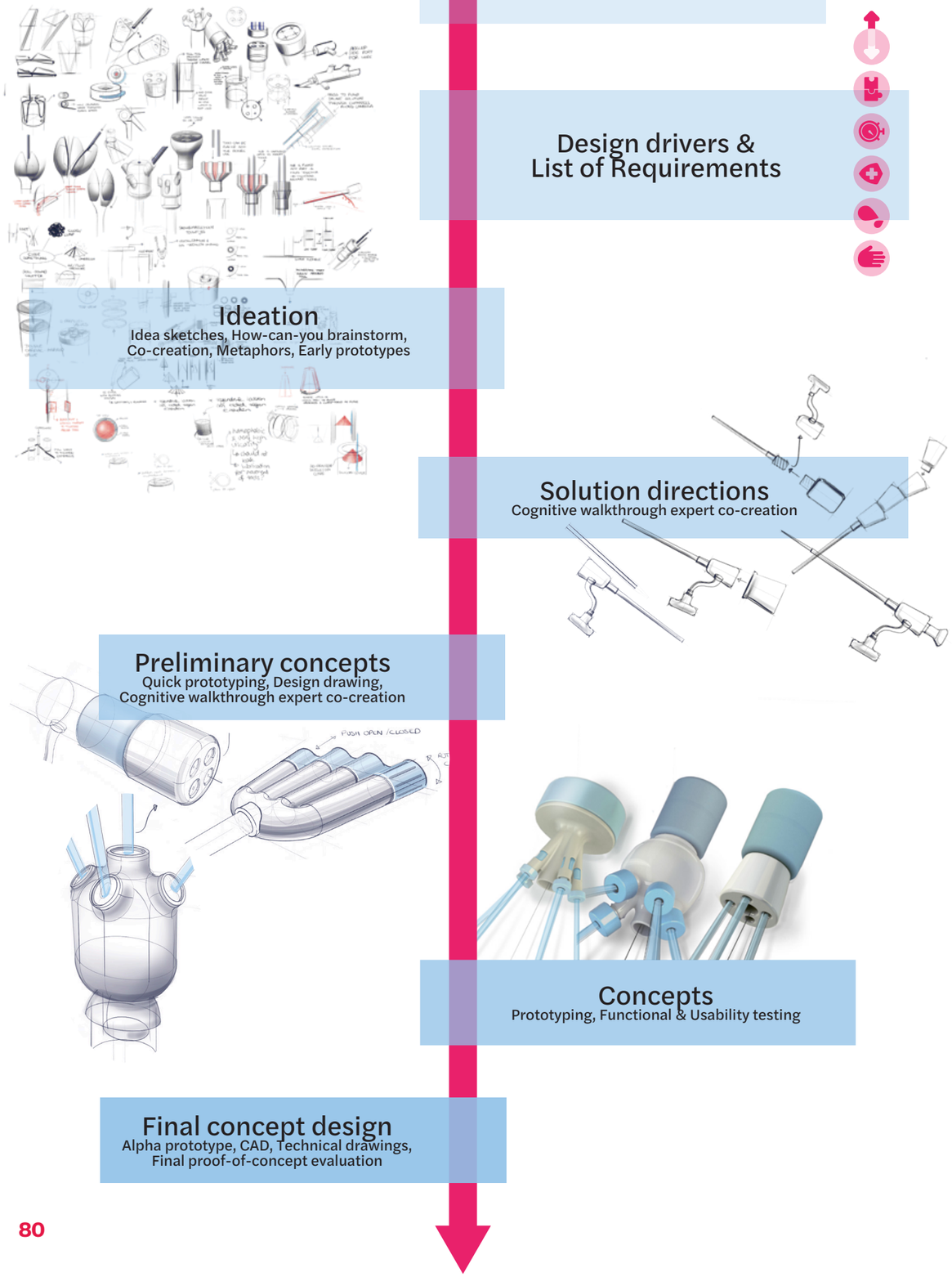


Figure 13.1 Left: schematic of concept development process

13. CONCEPT DEVELOPMENT

The background research (Part 2) in combination with the Synthesis (Part 3) form the basis for concept development. The overview in Figure 13.1 shows the course of this process, started by generating as much as possible ideas and finally crystallising these back to one final concept, which can be found in the next Chapter. Throughout the process, various tests and evaluations were performed to assess and improve functionality, desirability, and product safety. With these evaluations, also possible product risks were identified and mitigated, according to human factors engineering principles and typical usability research studies, to ensure the best possible Design for Safety. As formulated by Hallbeck et al. (2008, p. 148): "*Approximately two-thirds of the incidents related to the [medical] devices can be ascribed to incorrect operation by the user and not to technical faults*".
A more elaborate explanation of the human factors engineering approach can be found in Chapter 17. The following description of the process and main conclusions follows the steps in Figure 13.1.

13.1 IDEATION

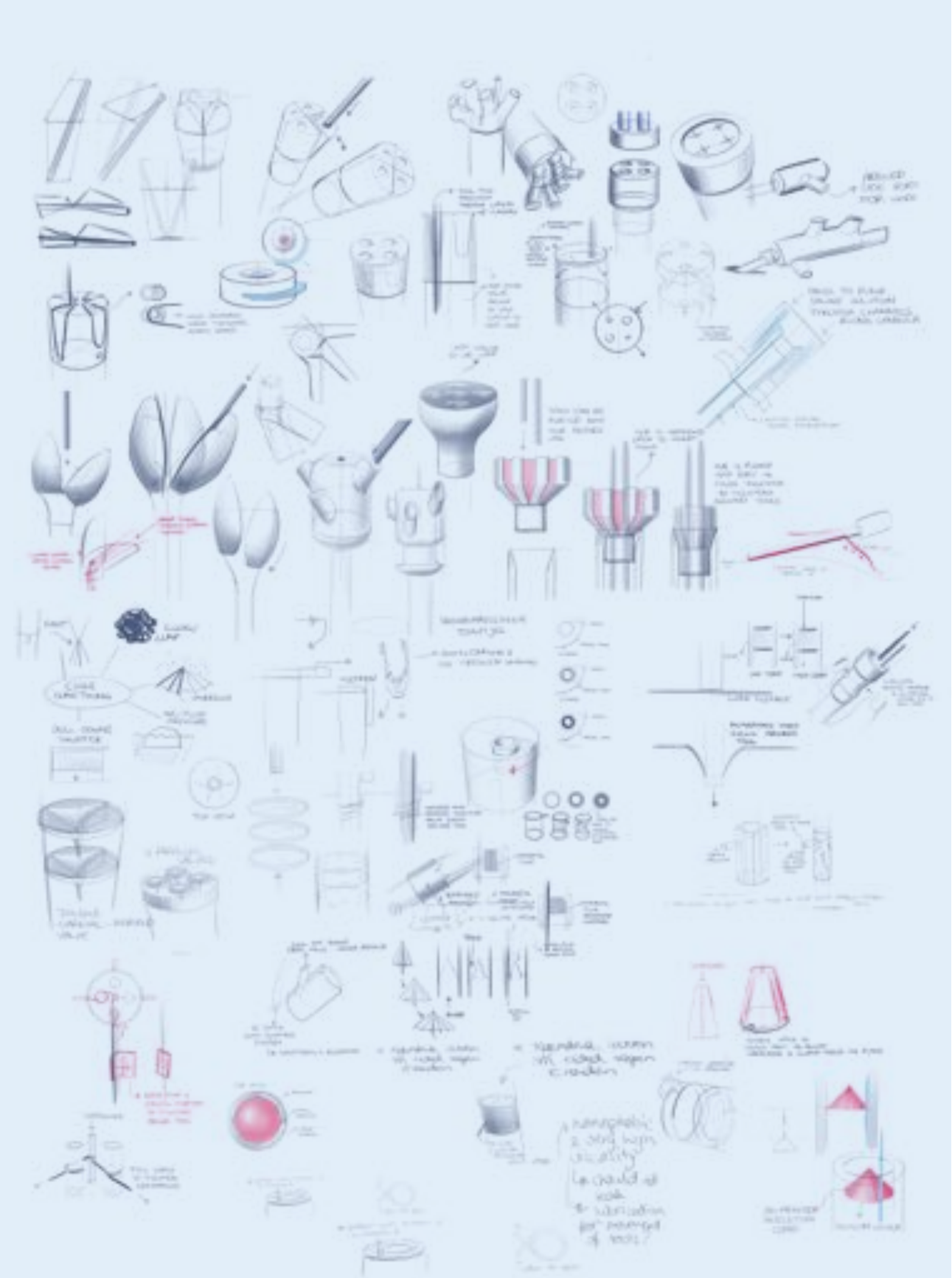
Idea generation was initiated with the help of three brainstorming techniques: a "How Can You...?" (Appendix G) and Analogies Co-creation session (Appendix H) with other students of relevant study backgrounds, as well as a translation of metaphorical solutions to the project's challenges (Appendix I).

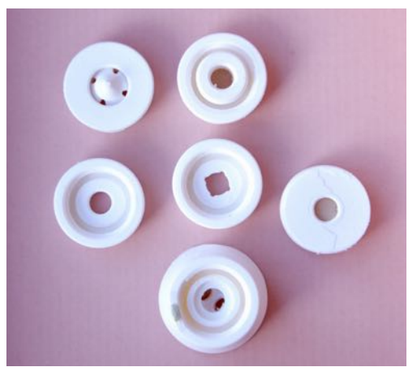
Resulting interesting ideas were sketched out (Figure 13.2) and evaluated early in the process by presenting these idea sketches to medical staff during surgery observations (nurses, vascular surgeons, IR's). Besides, some realistic ideas for valve principles were 3D-printed and tested with both hand-made valves and industrial silicone valves by MiniValve (Figures 13.3 - 13.5).

13.1.1 MAIN CONCLUSIONS

13.1.1.1 IN GENERAL

- The sheath should not become much longer than existing alternatives. "*You can order longer catheters, making manoeuvring more difficult, but it is worth it if you save blood.*" explained R. van der Meer (personal communication, January 20, 2021).
- An add-on could be interesting because it reduces certification requirements.
- A lumen parallel to the sheath's cannula was considered to ensure continuous blood flow into the leg, because this second lumen would not be filled with tools and ends in the femoral artery, behind the sheath. However, according to the medical staff the diameter of the cannula would become too large to fit well into the patient's femoral artery, and it would be a hassle and could harm the patient's artery to position the lumen's end in the femoral artery behind the sheath.
- A flushing system integrated in the sheath's hub was considered, facilitating flushing control directly with the one-hand grip on the sheath, instead of requiring the user to control the syringe with the other hand or even release the grip of the sheath's hub. However, users experience flushing as a small effort, thus focus lies improving aspects that lead to more significant benefits in the procedure.





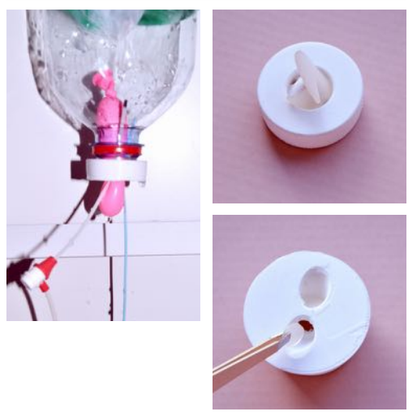


Figure 13.2 Left: Solution sketching ideation
Figure 13.3 Above: Impressions of valve functionality exploration

13.1.1.2 VALVE

- It is difficult to join silicone with glue. Therefore, it is much more functional against leakage to clamp a silicone valve.
- The Shore hardness of silicone is a determinant factor for the functionality and feeling of the valve. The higher the shore, the more friction the valve creates.
- A multiple-entrance valve should be used, instead of introducing all tools through the same valve, to prevent cavities between the tools.
- 3-dimensional cross-slit, duck-bill and dome valves are not suitable as haemostasis seal for this application, because their functionality depends on the size of the introduced tool, which can differ largely in practice.
- A thin, flexible tube could function as a valve, when rotated or pulled tight with a wire, this was further explored.
- A central, inflatable balloon, around which the tools can be introduced, might reduce the freedom of movement of the tools. The surface, pressurised by the inflation, might cause significant friction.

13.1.1.3 TOOL ENTRANCES

- The number of tools is the same mostly and does not differ between procedures, thus the design does not have to offer a flexible amount of tool entrances.
- It would be beneficial to adjust the angles of the entrances to the direction the surgeon is working in.
- A side port to the sheath's hub for the super-stiff wire, used during BEVAR procedures, was considered. It could be placed under an angle, to make sure that the wire still moves straight through the valve, when pulling the wire to the side.

13.2 SOLUTION DIRECTIONS

The most promising ideas were combined into five solution directions (see Appendix J for an elaborate description).

13.2.1 DESIGN CONSIDERATIONS

The following considerations were taken into account while designing these directions.

13.2.2 ONE ENTRANCE VS. MULTI-ENTRANCE VALVE

To prohibit both leakage due to a cavity between multiple tools and unintended moving of the tools due to a compressing force, a design with a single round valve is written off. Separating the valve entrances is a way to decrease leakage and a way to improve tool handling. It maximises the distance between inserted tools, as they are not squeezed together within the same valve, preventing obstruction of tool movement by other tools laying in the way and reducing chance of unintended tool dislocation, leading to re-catheterisation efforts and consequential emotional frustration and time-loss.

Application of mechanical valves (as can be seen in Appendix F) is explored, as well as alternatively actuated valves, think of Shape-Memory-Polymers and -Alloys (SMP and SMA), microfluids and hydrogels.

Figure 13.4 Above: impressions of valve prototyping exploration
Figure 13.5 Right: overview of explorative functional prototypes

13.2.3 SIZE, PATIENT OR PROCEDURE SPECIFIC SETS

Currently, the tool sets are French-size specific. The size is determined according to the patient's arterial anatomy and the tools that must be inserted. In comparison, when designing a patient specific tool set, ensuring compatibility with the procurement and storage system is difficult. Standard sets cannot be stored in bulk, because they are composed for one patient in specific. Also, in case a tool becomes unusable during the procedure (e.g. due to falling), a complete new set must be opened. The other tools in the second set will remain unused but have to be disposed as they are unwrapped.
On top, when sets are patient specific, they must either be ordered in twofold, or the specific item might not be in place when needed.

Developing a procedure specific set is possible and could be interesting, as no sheath has been developed before for the specific use-case of FEVAR and BEVAR procedures. Such a procedure specific set could also be achieved by creating a modular framework that allows combining certain parts to create the optimal configuration for the procedure in question.

13.2.4 MAIN CONCLUSIONS

The solution directions, elaborately described in Appendix J, were evaluated with experts of various relevant backgrounds:
- J. van Schaik, vascular surgeon,
- W. de Jong, vascular surgeon in final stage of training,
- F. Trauzettel, biomedical engineer and PhD candidate specialised in development of minimally invasive surgical instruments,
- J. van der Ploeg and J. Oude Vrielink, engineers at the LUMC Department of Development,
- F. Anuba, consultant for quality management and regulatory affairs of medical devices.

Through discussion, feedback and replacement of critical parts (based on the SCAMPER method: Substitute, Combine, Adapt, Modify, Put to another use, described in the Delft Design Guide (Boeijen and Daalhuizen, 2020)), the directions and their sub-solutions were evaluated.

Table 13.1 compares the evaluation of the 5 solution directions based on the six previously defined design drivers. The complete sheath and hub add-on were chosen as most promising directions, because their overall philosophies are unanimously found most appealing by the experts. They also score highest on the first three, most important design drivers and have little drawbacks compared to the other directions. The concepts developed next, are positioned within the chosen solution directions.

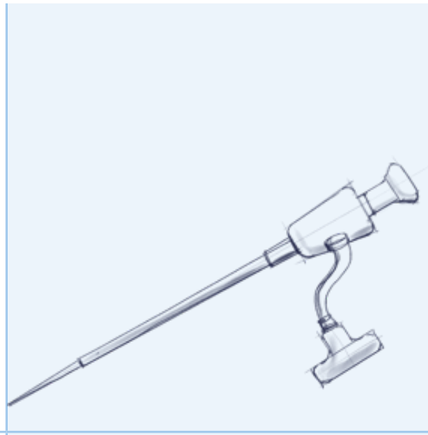
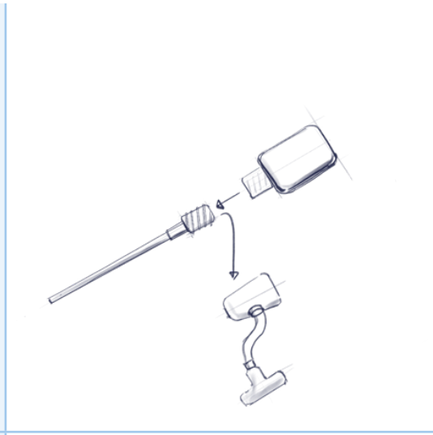
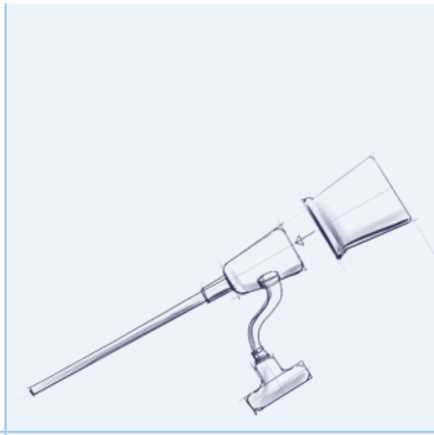
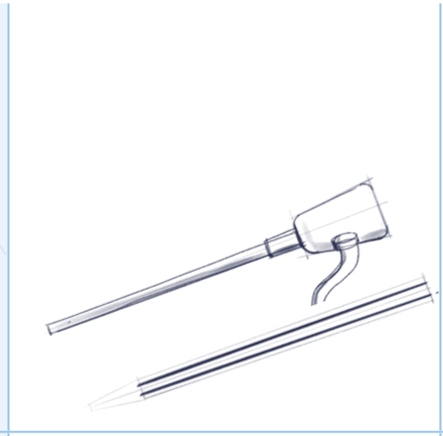
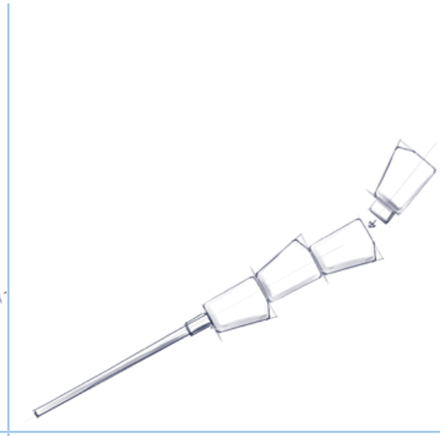
					
CONFIGURATION	**COMPLETE SHEATH**	**HUB EXCHANGE**	**HUB ADD-ON**	**SHEATH ADAPTER**	**MODULAR SHEATH**
Philosophy	**Independence**	**Targeted problem solving**	**KISS (Keep It Simple Stupid)**	**Workload shift**	**Flexibility**
System	4 separate entrances with individual locking mechanisms	Replacement of existing sheath hub, connecting new sheath hub with separate valves and improved grip to existing cannula	Add-on component for one or multiple existing sheaths, Based on combination of individually proven parts	Overtube adapter, loaded with tools by scrub nurse and inserted as unit	Modular set of add-ons with separate valves, cannula components and dilator
Specific for...	French size	Sheath size and procedure	Procedure (FEVAR / BEVAR) and sheath size	Procedure, sheath and tool size	Adaptable to procedure and patient
Expected classification	CLASS III	CLASS IIA	CLASS I STERILE	CLASS III	CLASS III
1. Minimised leakage	+ 4 separately controllable hub entrances - Valve / locking mechanism should not move when pushing tool through sheath	+ Redesign focused on unfunctional parts	+ Well functioning parts can be kept the same and focus can lie on disfunctional parts + Keep it simple stupid: proven functionality add-on component with 4 typically used valves is connected to current sheath's hub + Additional valve in place, forming closed off cavity between both valves - Problems of current valves still occur, such as difficult tool introduction or tearing	+ Filled adapter occludes sheath lumen	- More connections that are prone to leakage + Possibility to integrate solution for blood flow occlusion + Easy possible integration of BEVAR wire-pulling solution + One-way valve is only opened when guide part is pushed through it for tool
2. Security	+ Pre-assembled: little space for human error + Possibility to integrate solution for blood flow occlusion - Mechanisms increase risk points	- Modularity and assembly by clinical staff might reduce trust in functionality - Who does dis- and re-assembly? - Possible breaking due to removal of original hub, snap fits are not designed for disassembly	- Connection is extra point of risk, room for human error - Modularity and assembly by clinical staff might reduce trust in functionality? + The add-on can be removed during procedure as a fail-safe option, relying on original sheath	- Change of routine - Not possible to add a tool or switch to a different one during procedure, prohibiting flexibility required for unexpected problem solving	- Forgetting addition of individual parts is possible - Modularity might reduce trust in functionality? - Connections form many points of risk, room for human error
3. Smooth tool manoeuvring	+ Entrances can slide away / move outwards to open - Bending of tools <30°	+ Not necessary to move tools through original valve of the sheath, but directly into cannula	+ Add-on entrances hold individual tools in position when moving another tool + "Twisting tube membrane principle is interesting" stated F. Trauzettel	+ Overtube adapter could function as dilator - Dilator tip is critical part: must be deployable & constrainable, too complex and expensive	- Many valves stacked
4. Ergonomic use	+ Better visibility & more tool handling space - Too 3D for working field of surgeon	+ Hub entrances guide tools in multiple directions + Improved grip on hub	- Limited possibilities to optimise ergonomics of manual grip, due to combination with existing sheath hub	- Change of routine	- Small separate parts, prone to falling - Requires too much patience to fumble around with connecting individual modules
5. Tool compatibility	- Two separate designs might be necessary for FEVAR and BEVAR or functionality overload for either procedure.	+ Use of existing dilator possible	+ Easily compatible with existing procurement system and supplier contracts - Compatibility with existing dilator might cause difficulties	+ Adapter can be used with existing sheaths and tools + Different overtube configurations are possible: sizes & number of entrances - Range of different sizes and tool configurations is not ideal for production - No flexibility during procedure	+ Surgeon has freedom to choose the optimal configuration for that procedure + Design can even enable adaptability during procedure - Surgeons always opt for maximum number of tools and tool size, flexibility will not be used
6. Efficiency	+ Independence of other tool suppliers	- Highly dependant on sheath supplier and sheath design changes	+ Strong business case: adaptability with multiple existing sheath hub designs - Dependant on sheath supplier and sheath design changes, and variability of hub shapes	+ Adapter can be loaded with tools by scrub nurse before inserting into the sheath, letting surgeon focus on main task - Cost / benefits are not convincing	- Might lead to extra handling steps during preparation or procedure - Only relevant with significant cost benefit of using less parts

Table 13.1 Summary of the comparison of the five solution directions

13.3 PRELIMINARY CONCEPTS

Three preliminary concepts were developed from the two most promising solution directions: one completely new sheath (Figure 13.6) and two hub add-on's (Figures 13.7 & 13.8), also integrating promising aspects from other directions (see Appendix W for larger versions of the design drawings). For example, the granular jamming principle known from the "Hub Exchange"-direction is applied as possible clamping mechanism in the third concept "Add-on deluxe".

Again, these are evaluated with experts, like the approach with the solution directions, but with a special focus on possible risks this time. The risks, explained elaborately in Appendix K, indicate what needs to be tackled to achieve safety by design and can form a tool to identify which concept has the largest chance of succeeding for realistic, safe use.

Other experts were involved for fresh perspectives on the concepts:
- A. Loeve, lecturer TU Delft BioMechanical Engineering & Clinical Technology
- H. van de Stadt, technician at the LUMC Department of Development
- N. Berkhoudt, senior medical designer at IDE Group
- R. Nelissen, orthopaedic surgeon and Medical Delta professor connected to the TU Delft 3ME faculty

On top of that, physical prototyping (Figures 13.9 & 13.10) conclusions concerning individual closing and clamping principles are used to create functionally realistic concepts (Appendices L & M). An overview of the working principles that were tested, can be found in Table 13.2. The blue-dotted principles were found to be the most functional. These are integrated in the next concepts (Paragraph 13.4), which are evaluated through usability tests as well.

Table 13.2 Overview of the tested working principles

PART				
VALVE	multi-layer slit valve	funnel	centre balloon	
CLAMP	granular jamming in tube & syringe vacuum drawing	wring flexible cylinder	slider with round opening	flexible tube compression
CLAMP CONTROL	pressing soft tube & axial pull / push ring	screwing (axial direction)	pull / push for sliding out / in	pressing (axial direction)
ADD-ON CONNECTION	compression screw fitting	lever arm clamp (bottle stopper)	flexible sleeve	applied in next concepts applied in next concepts & tested for usability

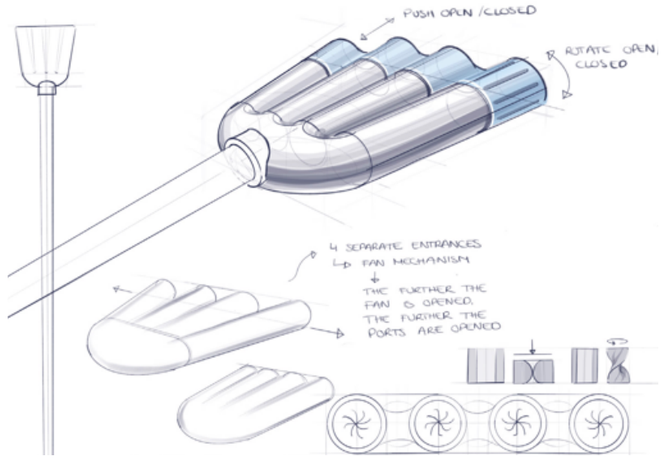


Figure 13.6 Concept 1: Independensheath

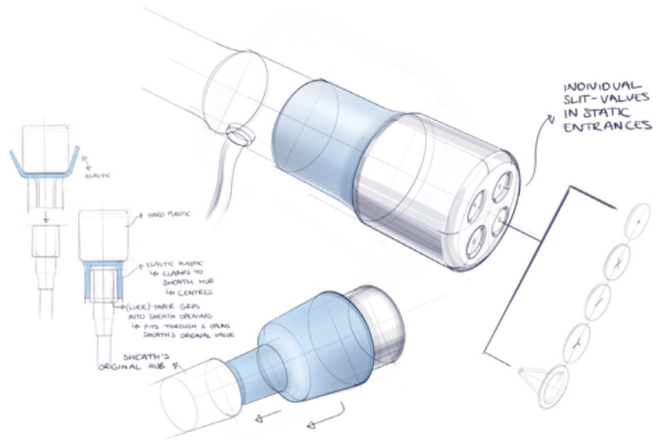


Figure 13.7 Concept 2A: Add a KISS on

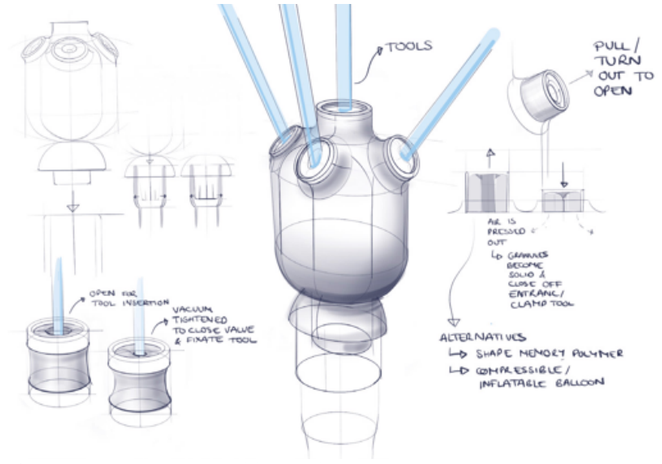
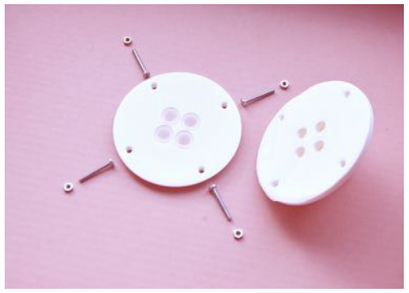
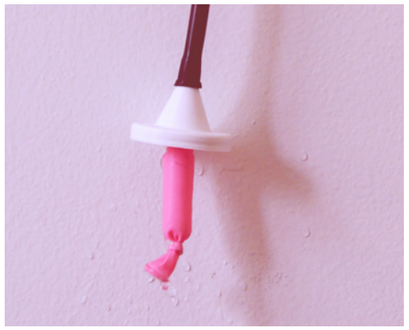
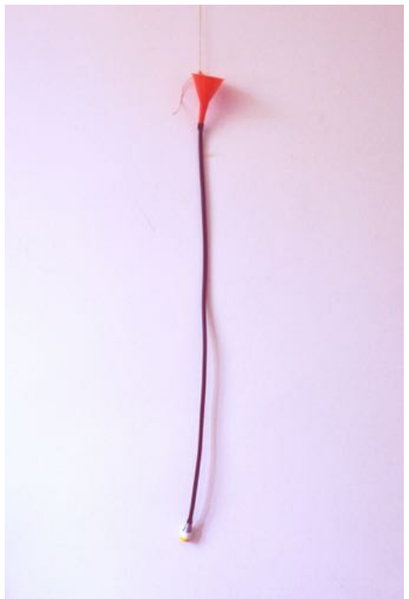


Figure 13.8 Concept 2B: Add-on Deluxe







Finally, the concept evaluations are summed up in Harris Profiles of the three concepts (Figure 13.12), based on the six design drivers. The same conclusions are represented in another way in the radar chart (Figure 13.11). These design drivers are specified to facilitate the comparison (Appendix K.4).

13.3.1 MAIN CONCLUSIONS

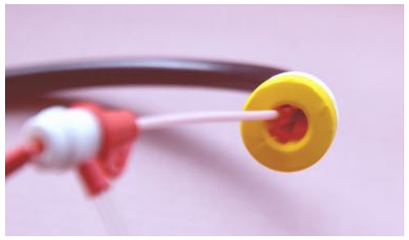
13.3.1.1 IN GENERAL

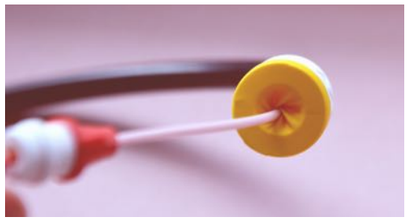
- The guidance from entrance positioning to radial orientation, fitting the sheath's cannula, should be solved in the design of the hub. But the bending radius for tools should not be too sharp (>30°), tools can kink and become difficult to handle.
- (Moving) mechanisms, for example of the fanning entrance "arms", can break and get stuck in position. Therefore, they must be kept to a minimum and require a fail-safe option. For example, removing the locking module or having an extra unlocking button, or even removing the complete add-on.
- The design's number of entrances could be increased to five, for future desirable applications.
- If a patient is obese, bodyfat lies in the way of the sheath and entrances. Then it is practical if the entrances are diverging towards the user, for more space.

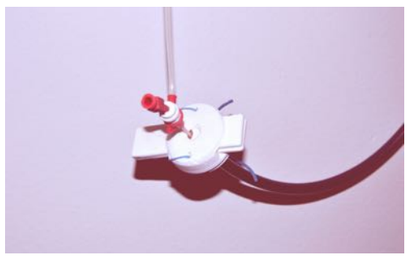
13.3.1.2 CONNECTION TO SHEATH

- The design does not require compatibility with the sheath's dilator, because an add-on can be placed onto the sheath while it is positioned in the artery already.
- Connection of an add-on to the sheath should prevent axial, rotational and tilting movements. Alternative connections, such as to the Luer lock flushing port or cannula were considered as well. However, these are fewer constant factors than the sheath hub itself, as the cannula size varies and the Luer lock is positioned quite differently on sheath models.
- The elastic clamp depends on sheath hub dimensions and might not fit the sheath hub. Also, from a certification perspective, the supplier is responsible to make sure it always fits the sheath, either through the intended use described in the IFU or an adaptable connection.
- Wrong fixation of the add-on to the sheath should be prevented and easily detectable, to ensure that the user is confident about the fixation.
- An outward expanding plug clamping into sheath hub might break / loosen during operation, causing leakage or the add-on to fall off.
- Blood collection and coagulation, for example in ridges of the connection, should be prevented.

Figure 13.9 Photos of functionality testing of the following valve principles (top to bottom): multi-layer slit valve, funnel, centre balloon, and the test setup







13.3.1.3 THE VALVE

- When removing the catheter from the sheath, you do not want an extra action to be needed, for example to close the valve again (such as in the Boston Scientific WatchDog small sheath model). This leads to leakage as long as the valve is open and to more handling steps for the surgeon. Thus, it would be beneficial to separate the closing and clamping functionalities. Also, when reinserting a new catheter, it is easier when the clamp is still open, instead of having to open it again. Besides, the surgeon can forget to perform additional actions, such as closing or opening a valve, or a rotating valve can get caught / jammed. As the valve should always function and the risk that the valve is open unintendedly is not acceptable, the choice was made to separate the closure and clamping functionalities and make the valve a continuously closed, unadjustable part. Also, clamp and valve have different requirements:
  - Valve membrane: low friction coefficient, flexible and tight enclosure of tool.
  - Clamp: high friction coefficient, little flexibility when moving the tool unintendedly.
- Separating the two also makes testing and certification easier, and increases safety, as the clamp can be released / break without reducing the valve's functionality.
- Funnel valve can cause overshoot due to clamping force when retracting tool.

13.3.1.4 THE CLAMPING MECHANISM

- Rotational valve closure / clamping can also cause unintended twisting of the catheter, due to the rotational movement and friction by the surface of the balloon for example. A perpendicular clamping force is preferred to fixate tools. Clamping should prevent rotation, wiggling and axial movements of the tools. The clamping handle should be facing the user, to get an immediate impression of (un)locking.
- When moving a tool through the sheath with an axial force, the mechanism should not move unintendedly.
- An elastomeric clamp is chosen over a solid mechanical clamp, because it is adaptable to different diameters and the chance of damaging the catheter is smaller, due to its flexible surface. Friction of the elastomeric surface can be chosen to fit the intended amount. Clamping could be achieved by pressing down a spring or rotating the cap around a thread. With the latter, a lubricous ring (e.g. PTFE (Teflon) or Nylon) should be placed in between the rubber and the cap, to allow smooth rotating and prevent the rubber from twisting.
- "*This is a creative application of the granular jamming technology*" according to A. Loeve. However, it might be too complex for this application, as it requires many separate parts such as a flexible material, granules, and an air valve. Also, leakage of air can appear from granular jamming sleeves. As a consequence, the valve loosens, blood leaks and tools cannot be fixated.

Figure 13.10 Photos of functionality testing of the following clamp principles (top to bottom): wring flexible cylinder, slider with round opening, granular jamming

- Feedback of locking degree should not rely on tactility alone, this can cause unclarity / insecurity about level of fixation with the surgeon, resulting in overtightening. For example, a visual scale can be added.
- SMPs and ferro-fluids fall into the category of active devices for certification, increasing strictness. However, using a battery makes it easier than using a connection to grid power.

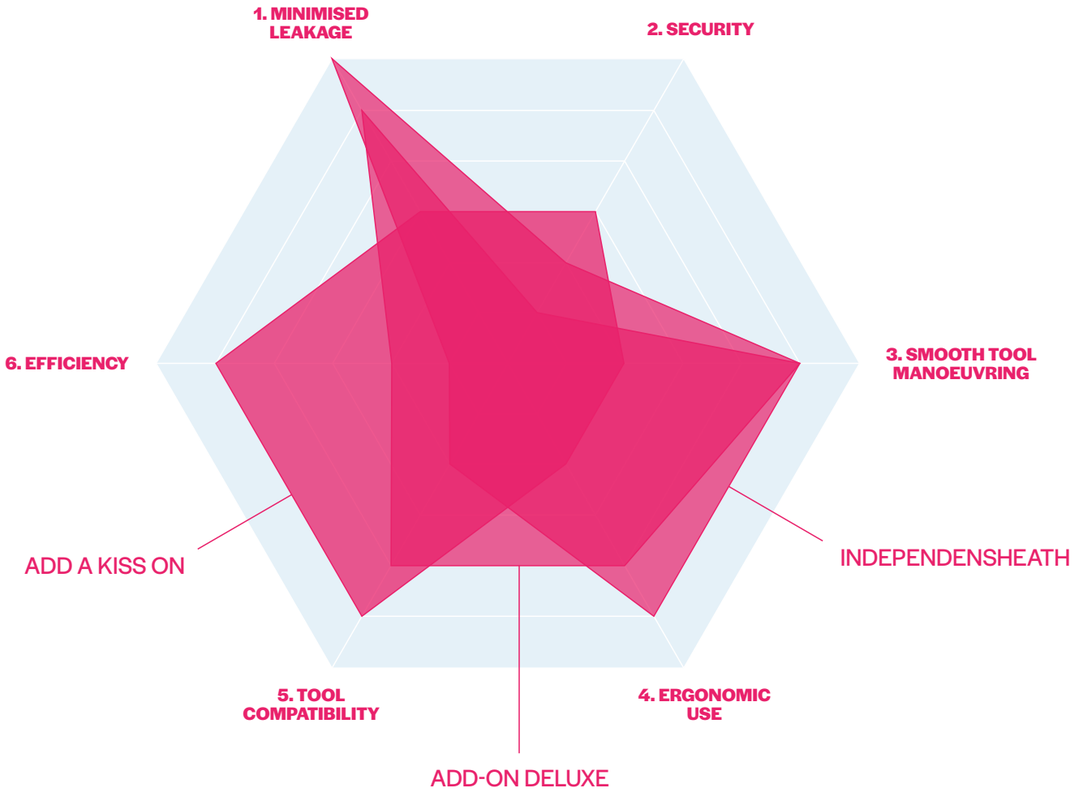


Figure 13.11 Radar chart of concept comparison

13.3.2 CONCEPT CHOICE

A concept comparison in the form of a Harris profile (Figure 13.12) was based on the above evaluations.

"The design must be robust, simple, cheap, and idiot proof" **- Loeve**

Concept 2A stands out for its simplicity. *"The design must be robust, simple, cheap, and idiot proof"* to ensure that it will be used, states Loeve, "*that is the charm of the simple add-on concept"*. On the other hand, the benefit of the other two concepts lies in their extended functionality. Providing individually controllable tool locking, more ergonomically shaped entrances, and better tool guidance into the valve, strongly enlarges the device's added value. A critical point here, are the moving mechanisms, adding to complexity and which must have a fail-safety option. Therefore, the design with the folding-out entrances is eliminated.

"Most danger originates when the surgeon starts using another tool"
- Nelissen

A unanimous preference is found for the add-on. According to Loeve (personal communication, March 1, 2021), *"Surgeons do not like changing the tools they are used to working with, thus an add-on would enable them to keep using their preferred sheath."*. Similarly, Nelissen (personal communication, March 15, 2021) stresses the add-on's practicality: *"Most danger originates when the surgeon starts using another tool. They are all alpha-men, thinking that they know how it works without (enough) training. This is where the most goes wrong in medicine."*. Besides, he explains that ease of using a familiar tool increases the focus on the actual task. Also market-wise, this is preferred, because instead of becoming a competitor trying to 'snatch away' market share, the market of existing sheaths can be used.

Figure 13.12 Harris profile concept comparison

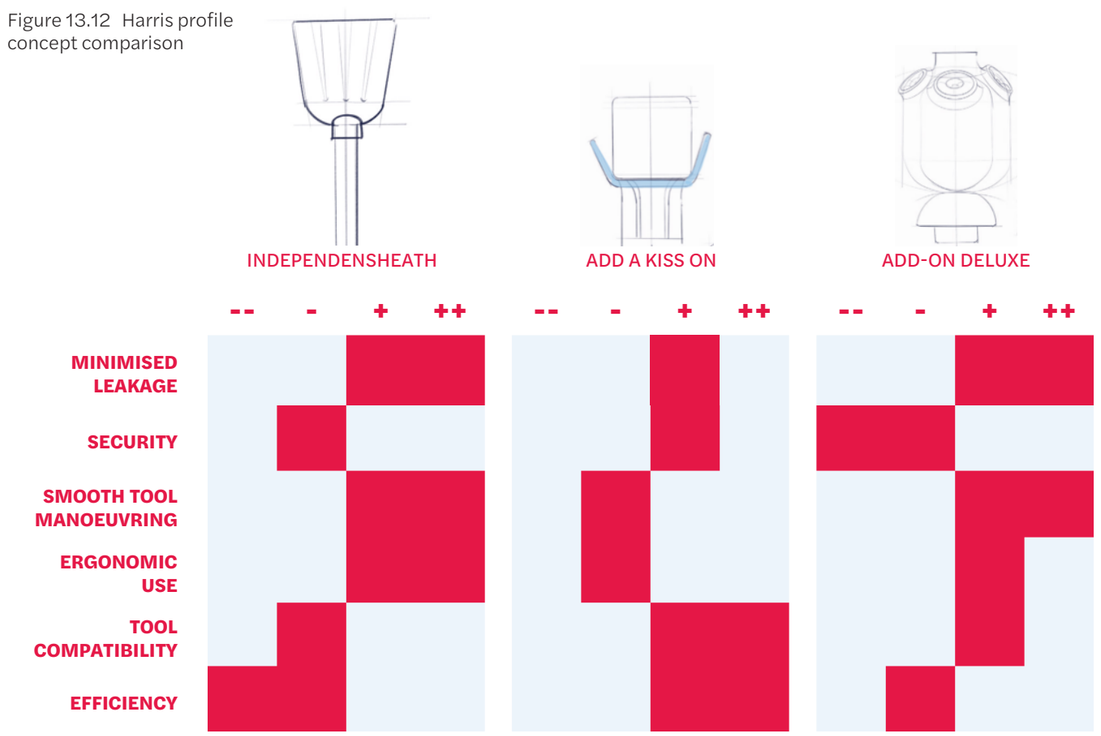


Figure 13.13 Compression screw of Gardena garden hose

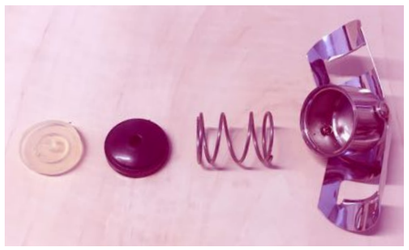


Figure 13.14 Lever-arm and spring mechanism in bottle stop

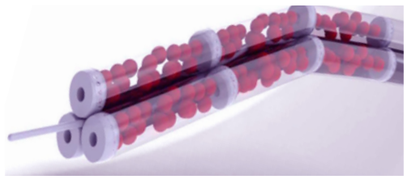


Figure 13.15 Electric actuated granular jamming in surgery tool

13.4 CONCEPTS

The previous insights and identified risks were implemented to create three concepts (Figures 13.16 - 13.18). Working principles of the sheath connection and locking mechanism were detailed, supported by additional research and analysis of relevant mechanisms. For example, a compression screw used in garden hoses (Figure 13.13), an air- and liquid tight stop used on bottles (Figure 13.14), and application of granular jamming in robot-assisted surgeries (Figure 13.15).

Next, prototypes were made for usability testing and functional testing*, these can be seen in respectively Figure 13.19 - 13.21 and 13.25. Both are higher fidelity formative tests, as explained in Paragraph 17.1.

The formative usability study was performed with nine participants: six vascular surgeons (3 LUMC, 3 Haga Ziekenhuis), one vascular surgeon in training (LUMC), 2 interventional radiologists (LUMC). The prototype could be connected to a sheath, positioned in a wooden holder. A depiction of the setup can be found in Figures 13.22 - 13.24. Approach and elaborate findings of this study can be found in Appendix N.

The formative functional study was performed with the help of a flowmodel simulating the blood flow (Figure 13.27 & 13.29). The blood characteristics were imitated by use of Voluven-fluid (similar viscosity and stickiness as blood), and pulsating blood pressure was actuated by an antique heart-lung machine (Figure 13.26). As comparison to the pressure achieved by the heart-lung machine, a drip bag was used afterwards to build up the pressure. Pressure was measured with an anaesthetic machine. All working principles of the device were tested together: the connection to the sheath, the valve, and the locking mechanism. Four alterations of the valve were tested and compared, by varying the layer-thicknesses of the 3-layered valves. This variation was possible, as the fixation of the valves was designed using a threaded connection, enabling tightening of all valve thicknesses (only for prototyping reasons) (Figure 13.28).

The main conclusions of the usability and functional studies are explained below.

*
Both usability and functional tests were consciously performed separately instead of combined to prevent results from cross-influencing each other. For example, technical misfunctioning such as a leaking valve should not influence the user's experience of the concept's use. And vice versa, unintended handling of the user should not compromise the evaluation of the valve's technical functionality. In this way, an objective functionality test can be done, while the usability test can remain more subjective.

Figure 13.16 Concept 1: KISS

Figure 13.17 Concept 2: SCREW

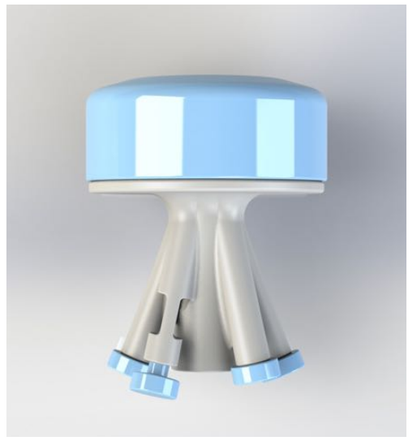


Figure 13.18 Concept 3: VACUUM

Figure 13.19 Usability testing prototype of concept 1: KISS

Figure 13.20 Usability testing prototype of concept 2: SCREW

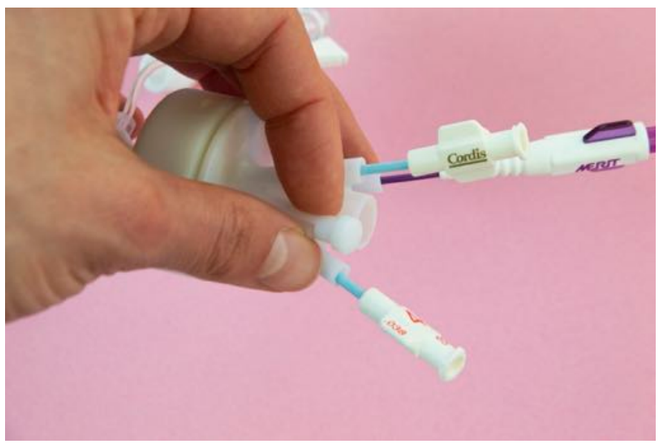


Figure 13.21 Usability testing prototype of concept 13 VACUUM

Figure 13.22 Usability testing with interventional radiologist

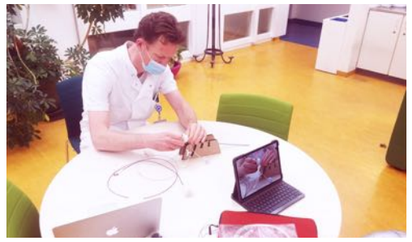


Figure 13.23 Usability testing with vascular surgeon

13.4.1 MAIN CONCLUSIONS USABILITY TESTING

13.4.1.1 IN GENERAL

The add-on's form should be round and symmetric, as well as the position of the entrances, to use the space optimally. "*The shorter the add-on, the better it is for the procedure.*" said Van Rijswijk (personal communication, March 31, 2021), because no switch to longer catheters is needed then.

It should for a sleek, slim, and subtle addition to the sheath. It should form 'one whole' with the sheath, because that feels safer to the user and is easier to use with an obese patient. Thus, the device should look as simple as possible, which is further described in Paragraph 18.2. Simplicity of the design is also found to lead to more confidence of the handling actions. Besides, the add-on should be as light as possible, to prevent bending down or even kinking the sheath, and requiring the user to apply more force when holding it. The preferred grip has two fingers on top, supported by the thumb on the bottom.

The add-on must be removable from and reconnectable to the sheath hub, for example if the sheath must be relocated.

Participants indicated that the designs were easy to understand. However, a concern is that thromboses might be formed in the ridges of the connection between sheath hub and add-on. This must be extensively tested in the future, ideally with real blood.

13.4.1.2 CONNECTION TO SHEATH

The choice between the silicone sleeve connection and the compression screw was tough, because both have clear advantages. The silicone sleeve's simplicity, ease and efficiency of connection make it very interesting. On the other hand, when applying a high axial pulling or tilting force, the sleeve can come off. The chance that such a force is applied in practice, is quite low, as it could harm the patient.

Contrary, the compression screw's connection remains in position and leakproof even at high manual forces. Besides, the user feels more confident about the connection as well, due to the tactile and visual feedback experienced while screwing it tight. As explained by Van der Meer among others: "*The idea is very good, because you screw it tight, that gives you the feeling that it is fixed tightly.*". The same was endorsed by De Jong (personal communication, April 6, 2021): "*it gives a good comforting feeling that you're sure that it is really fixed, then you can focus on other things*". Contrary, "*If connection is too easy, it seems to fall off too easy as well*" Van Rijswijk noted about the silicone sleeve.

It is also more visible to the user whether the sheath hub is positioned correctly within the add-on, compared to the silicone sleeve, which shapes around the hub in any position similar to the correct one. Thus, it can be slightly tilted without the user noticing, risking leakage in the connection. An advantage of the silicone was the soft, rubbery grip. This insight is applied while detailing the ergonomic and aesthetic design (Paragraphs 18.1 & 18.2). As Design for Safety is key for this device, the compression solution was chosen. Also, ease of connection just influences a one-time handling action, whereas safety influences the complete use period of the add-on.

After placing the add-on, among others, Eefting (personal communication, April 6, 2021) "*would deflate the DS balloon, because then you can insert the tools easier*".

13.4.1.3 TOOL ENTRANCES

The radius the catheters must make in the device's lumen to enter the sheath's central lumen, should be kept to a minimum. Also, the outward guidance should be into the length, as much as possible in parallel, instead of forwards to the user. The tools should not diverge too much on the table, as they should not slip off the table, making them unsterile.

At the same time, "*it is really handy to be able to reach the entrances easily, like here, you have more space*" as complimented by De Jong (personal communication, April 6, 2021) regarding the outward bending entrance design. He concluded that a finger-width in between the entrances is enough distance.

A fifth entrance is practical, especially for future applications, or the situation that a fifth fenestration must be done. This hardly occurs, but "*you could imagine that it would be practical to place them all through one sheath*" explains Eefting (personal communication, April 6, 2021).

Coding makes it easier to locate the tools in the entrances. Eefting elaborated his preference for the type of coding: "*I would use numbers instead of letters or colours. Many people are colour blind. With numbers you can agree upon a number for a specific artery.*". The coding should not be predefined for a specific artery, as the flexibility is valued to pick the entrance that is closest by or most practical.

"it [the locking mechanism] gives you the security that you can focus on the tool you are working with"
- De Jong

13.4.1.4 LOCKING MECHANISM

The participants were very much in favour of adding a locking mechanism. "*It is very practical; it gives you the security that you can focus on the tool you are working with. I think it really is an addition! And you have enough space for screwing it. You have done your procedure and move forward to the next step and can simply fixate the previous tool.*" explained De Jong. Another benefit, according to Van Rijswijk, is that "*If you can fixate it, you don't have to hold the tools all the time with your first few fingers to make sure they remain in place. That would be very nice.*".

It makes sense to start with open clamps and close them when the tool is in position, instead of the other way around. Eefting: “It is unpleasant to manoeuvre while having to press something open simultaneously”. The largest part of the time it can be open, and then it can be locked if the user switches to the next catheter.

It is ideal if tool retracting is still possible when the clamp is in locked position, because this means that in case of spontaneous incidents, the tool can be pulled out directly. However, a certain level of locking is required, to overcome the movement actuated by movements of other parallel tools.

The screw locking mechanism is preferred because clinicians are used to screws. Also, pressing and pulling the granular jamming alternative feels unhandy with big fingers and can happen accidentally when pushing in a tool. “*Most movements are in the axial direction, so it is risky to have locking control in that direction as well.*” emphasised De Jong. Additionally, the sheath can lie in different directions. If the pressing and pulling controls are facing downwards, they are difficult to use. This is less problematic with the screws. Besides, “*with a screw you always feel how tight you fix it, with a button or pressing you have less control and tactile information. In that case you depend a lot on what you feel.*” says Eefting.

Still, it must be very clear whether the screw is open or closed. Existing sheaths often have a line or dot to indicate this, “*but then you have to look at it precisely, to see whether it is open or closed, especially causing difficulty when it is located on the backside*” argues Van Rijswijk.

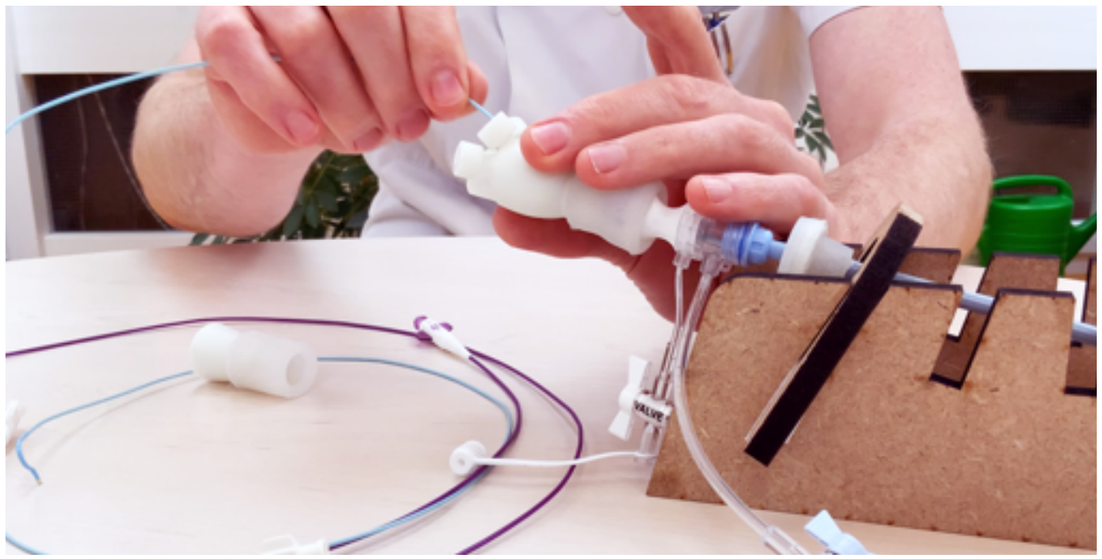


Figure 13.24 Close-up while testing the locking mechanism’s usability of Concept 2: SCREW

Figure 13.25 SLA 3D-printed prototypes for functional testing: five separate valves and compression connection (above) & central valve and 40 Shore A silicone sleeve connection (below)

13.4.2 MAIN CONCLUSIONS FUNCTIONAL TESTING

13.4.2.1 CONNECTION TO SHEATH

Connection to sheath was completely leakproof. Only, when sliding the compression teeth onto the sheath's hub, they were quite tightly fitted around it, requiring considerable effort and force to place the add-on. The effort and force are too much for a real usecase. Partly, the problem lay in the compression ring as well because its inner diameter did not offer enough space for the compression teeth to bend outwards when sliding them over the hub. Therefore, the inner diameter of the compression teeth and ring are slightly increased in the final design.

13.4.2.2 MULTI-LAYERED VALVE

- 3x 0.5 mm: leakage occurs quite soon in the form of wetting and little droplets, no heavy leakage, becomes stronger when tool in moved
- 3x 1.0 mm: this valve did not leak at all, also after frequent tool movements. Regarding the amount of friction experienced on the tool, this composition is ideal as well.
- 3x 1.5 mm: this valve did not leak at all, also after frequent tool movements. However, this valve is very tight, creating high friction on the tool and the tool must be pushed in with a too high force.
- 1.0 – 1.5 – 1.0 mm: after being leak proof most of the time and moving the tool around frequently, this valve started leaking very slightly too. This was visible due to minimal wetting of the locking mechanism. It is assumed that this can be attributed to the different layer thicknesses of the valves. The thicker middle layer is stiffer as well, which might cause a difference in deformation with the two lining layers, creating openings for fluid to leak through.

Because the valve and clamp functionalities are separated, material damage of the clamping mechanism is less critical than material damage of the valve. Especially, because it is behind the valve, thus torn off parts are blocked from entering the blood system by the valve.

13.4.2.3 LOCKING MECHANISM

The locking mechanism was tested on the lumen carrying the last valve (1.0 – 1.5 – 1.0 mm). It was a practical coincidence that this valve started leaking slightly, because it enabled testing of the locking mechanism's functionality while leaked fluid had entered. The locking functionality was not reduced noticeably and functioned as intended before and after the leakage.

CONCLUSION

The fluid pressure achieved by the heart-lung machine varied strongly, reaching peaks far over 180 mmHg. Even during these peak pressures, the prototype remained functional and leakage was significantly minimised. The combination of the sheath connection and 3x 1.0 mm valve was even found to be completely leakproof!

Figure 13.26 Antique heart-lung pump

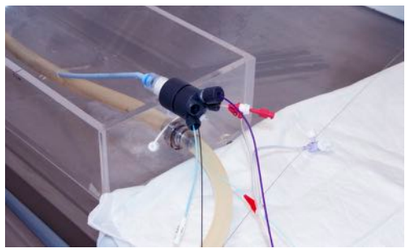


Figure 13.28 Sheat with add-on and introduced tools, placed in a flexible rubber tube

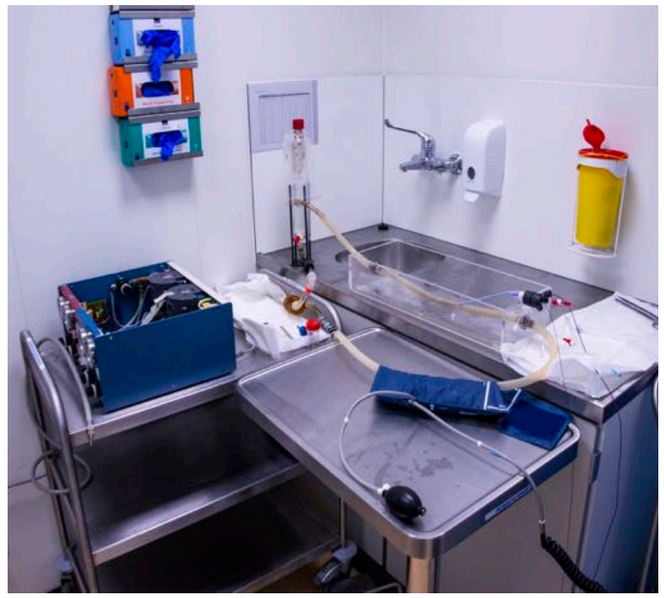


Figure 13.27 The test setup pulsating pressure flow model

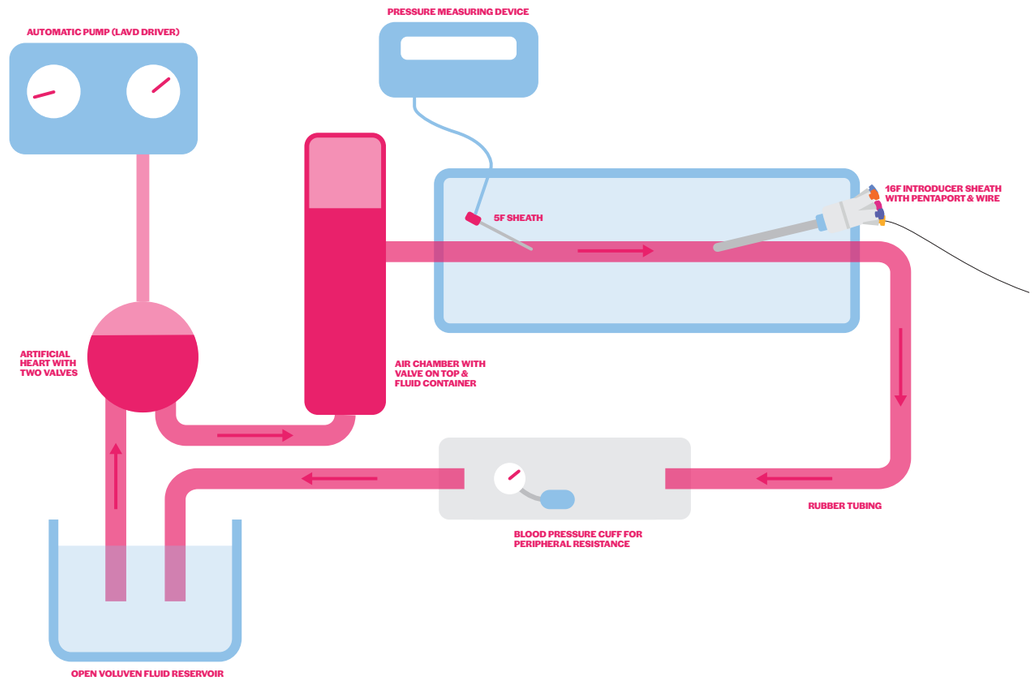


Figure 13.29 Schematic of functional test setup of pulsating flow model

THE DESIGN

PART 4

This chapter presents the device’s final design and prototype, how the device is used, and its Unique Selling Points.

MINIMISED LEAKAGE

5 separate valves (one per tool) ensure closure, preventing severe blood losses of 2L or more.

Sparing a heavy attack on the patient's condition and eliminating the need for costly consequences, such as cell-saving or blood transfusion.

the safe gateway for
complex endovascular aortic repair

the PENTAPORT

WORRY-FREE MANOEUVRING

The 5 tool locks avoid unintended dislocation of the catheters, preventing the need for lengthy recatheterisation efforts (up to 60 minutes) and possible harm to the patient's arteries.

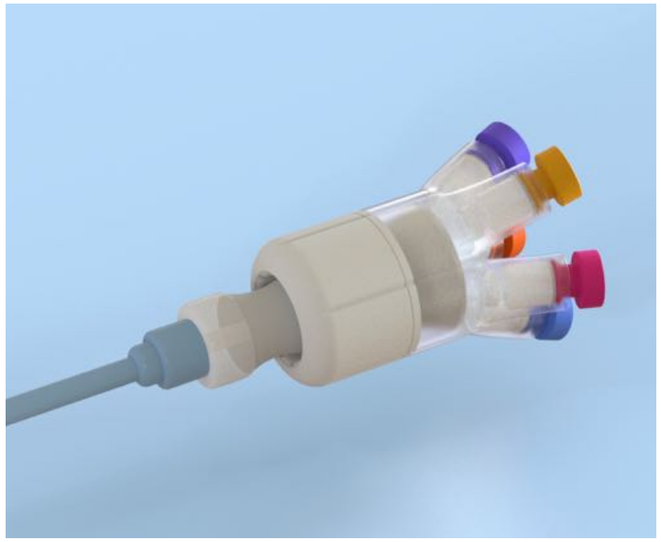
Eliminating the necessity to have a constant grip on the tools, allows a more comfortable position and better freedom of movement of the user's hand holding the sheath.

(Colour-blind safe) colour-coding helps remembering the tools' locations and improves the medical team's communication.

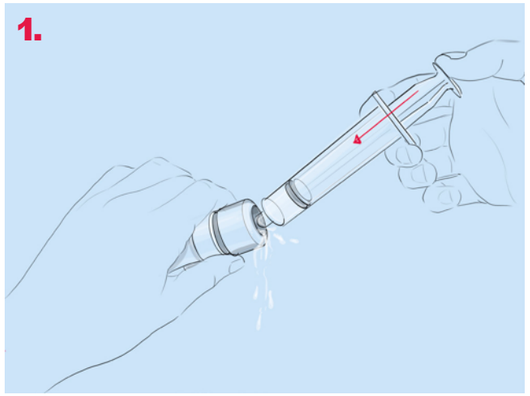
ADD-ON FOR COMMONLY USED SHEATHS

A leakproof 'plug & screw' connection facilitates safe and easy fastening to the DrySeal by W. L. Gore.

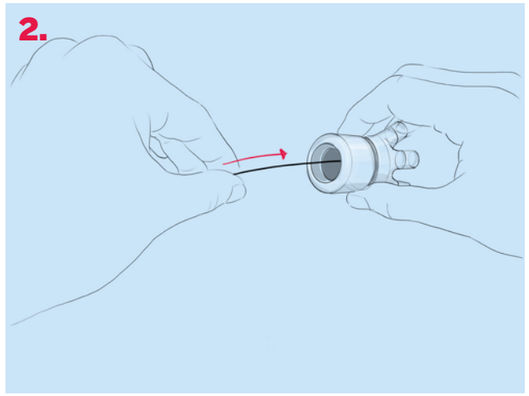
The connection's design can be adapted to fit other sheath hubs, such as the Check-Flo by Cook Medical, requiring just one part to change.



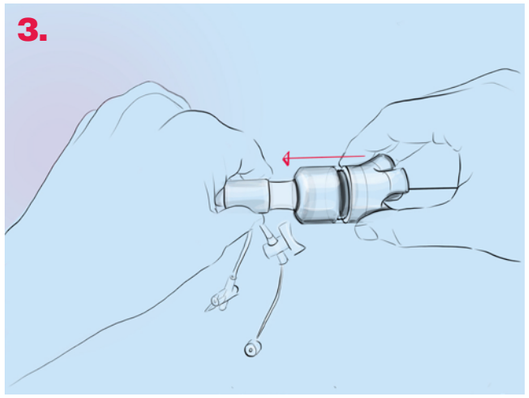
14. USE SCENARIO



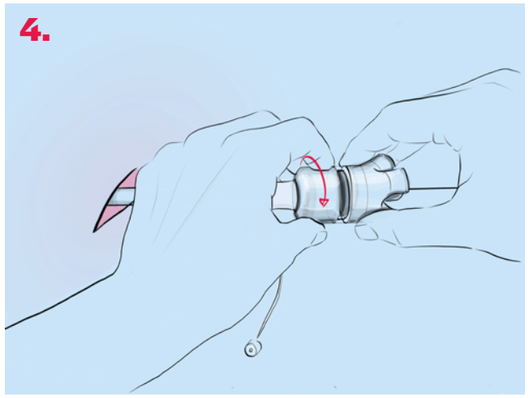
Scrub nurse flushes the add-on with saline solution.



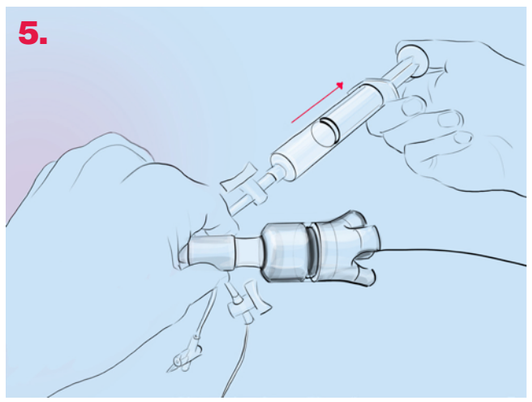
Scrub nurse inserts sheath's central guidewire and forwards the PENTAPLUG over the wire to the surgeon / IR.



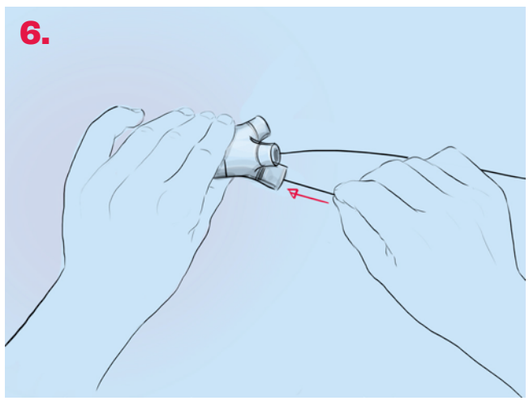
Surgeon / IR plugs the add-on onto the sheath's hub (with active valve).



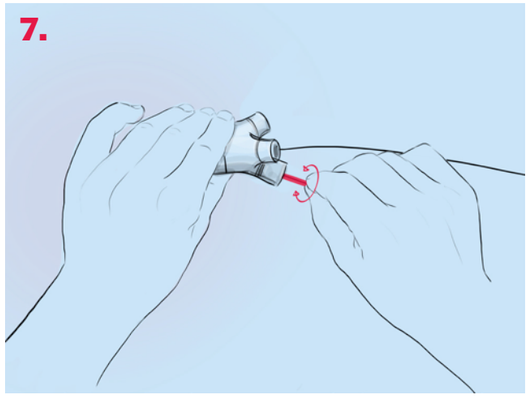
Surgeon / IR rotates (clockwise) the compression ring to secure the fixation to the sheath and make it leaktight.



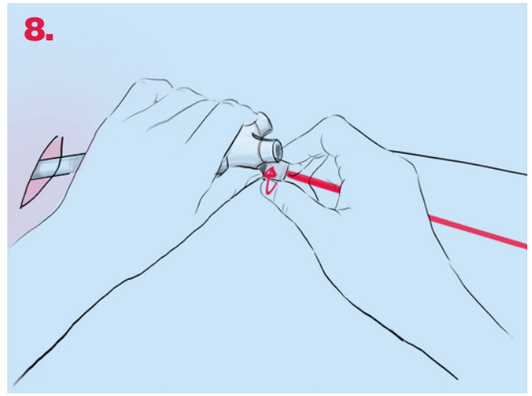
Surgeon / IR inactivates (deflates) the sheath's valve.



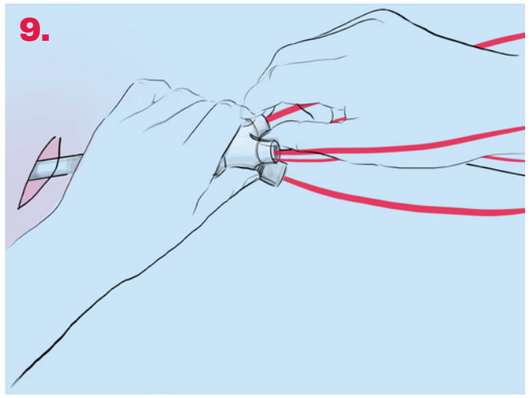
Surgeon / IR introduces the next wire, by positioning it in the screw cap's (tapered) entrance and guiding it forward.



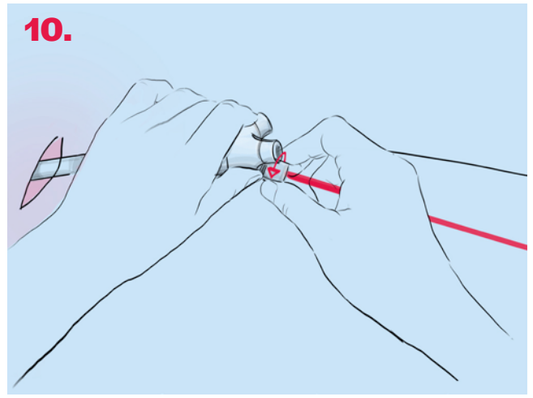
Surgeon / IR introduces the first catheter / sheath over the wire and manoeuvres it to catheterise a renal artery.



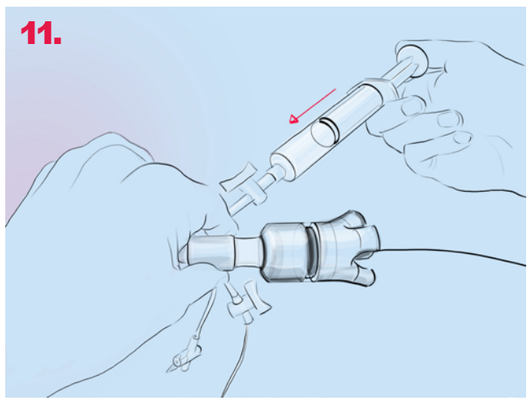
Surgeon / IR rotates the screw cap to lock the catheter / sheath in position.



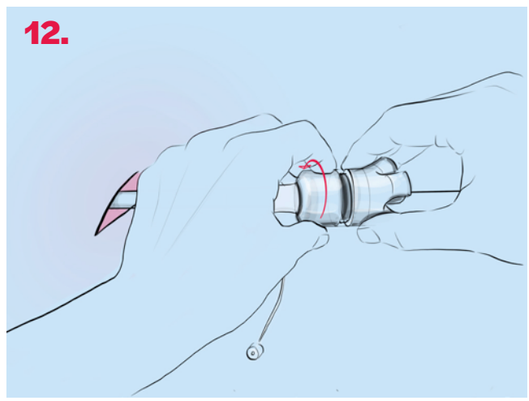
Surgeon / IR repeats steps 6-8 to catheterise all side-branching arteries and place the stents via the catheters.



Surgeon / IR unlocks and removes the catheters / sheaths and wires one-by-one.

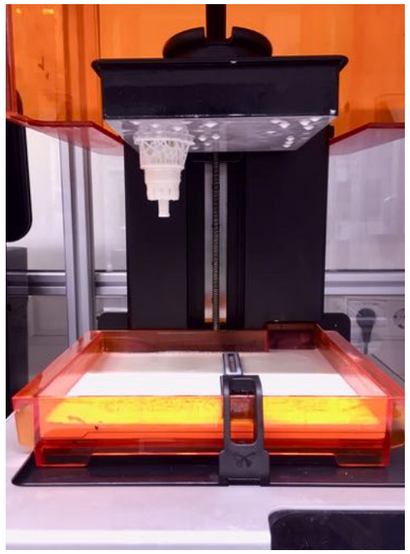


Surgeon / IR activates (inflates) the sheath's valve in preparation of removing the PENTAPLUG.



Surgeon / IR rotates (counter clockwise) the compression ring to loosen the connection and removes the add-on.

15. FINAL PROTOTYPE



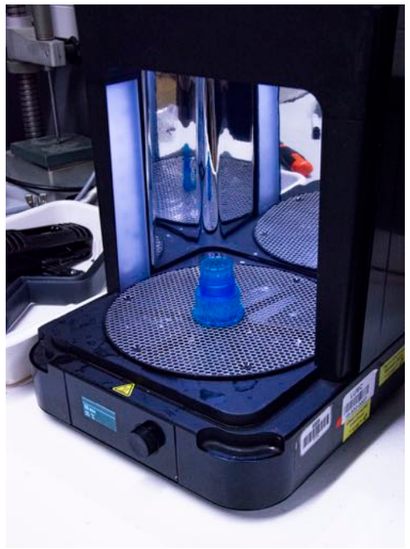


Figure 15.1 Top: SLA-printed main body part for aesthetic prototype
Figure 15.2 Bottom: UV-curing of the main body part for functional prototype
Figure 15.3 Right: various perspectives on the fully assembled functional prototype

Two final prototypes were made. The first was used for the final usability and functional validations within this project (Figure 15.3). The second is an aesthetic showcase of the final design. Respectively, they can be classified as an Alpha Prototype and an Appearance Prototype based on the iD Cards by Loughborough University (Loughborough Design School, 2014). Both consist of SLA 3D-printed parts and are printed on a Form 3 by Formlabs (Figure 15.1). Various resin types were used to mimic the materials chosen for the final design as much as possible. The resins Clear, Tough 2000, and Tough Blue were used. The last was applied for the main body part with the compression teeth, as it has good strength, while remaining flexible enough to let the teeth bend around the sheath hub without breaking (Figure 15.2).

The product-specific elastomeric parts were casted from Silicone with a Shore A 15 hardness, into FDM 3D-printed moulds (Ultimaker 2+, material PLA). Silicone was chosen instead of TPE, because it is more suitable for prototyping purposes. The valves in the functional prototype were obtained via the supplier MiniValve. The valves in the aesthetic prototype were manually punched from Silicone sheet material with a 1 mm thickness.

DESIRABILITY

PART 5

This chapter explains the added benefits of using the PENTAPLUG during FEVAR surgeries, for the patient, medical team, and hospital. Besides, the device’s safety, as well as the user’s interaction with and experience of the device are elaborated, containing ergonomics and aesthetics.

16. PROCEDURE IMPROVEMENTS

The use scenario explained in Chapter 14 does not stand on itself. It forms a new and changed part in the existing FEVAR procedure, described earlier (Paragraph 6.4).
The main pain points during this existing procedure that were identified, can be eliminated in the future by using the new add-on, creating improved surgery outcomes and user experiences. Multiple medical specialists expressed their enthusiasm about the device during usability evaluations (Paragraph 13.4.1).

The envisioned journey map (Figure 16.1) illustrates during which steps the improvements are implemented and these are further elaborated below. The light red emotion line follows the existing journey, and the bright red emotion line shows the improved version. It is focused on the stages that are relevant for the use of the add-on in specific. A differentiation between three types of steps is made: direct relation to the add-on's use; indirect relation to its use (happening outside of the perioperative stage); not related to its use but happening in between related steps. Especially, the first category is interesting, as the add-on design has the largest influence on these steps (14, 20-27, 29-33 in the journey map), thus these receive the focus. Illustrations of the Pentaport's implementation in practice can be found in Figure 16.2.

Figure 16.1 Envisioned Journey Map of the Pentaport's use

16.4.1 MAIN PAIN POINTS TACKLED

The use of the add-on starts with connection to the sheath. Here, the extra confirmation, given by screwing the compression ring tight, ensures the user that no leakage will occur around this part. De Jong (personal communication, April 6, 2021) emphasised this: "*it gives a good comforting feeling that you're sure that it is really fixed, then you can focus on other things*". This increases the trust in the new device and therewith the success of the whole procedure. He states: "*als je het vastzet, zit het vast!*", meaning "*if you fixate it, it stays fixed!*".

Next, introduction of the first wire and catheter or small sheath is already significantly improved from the original state, because

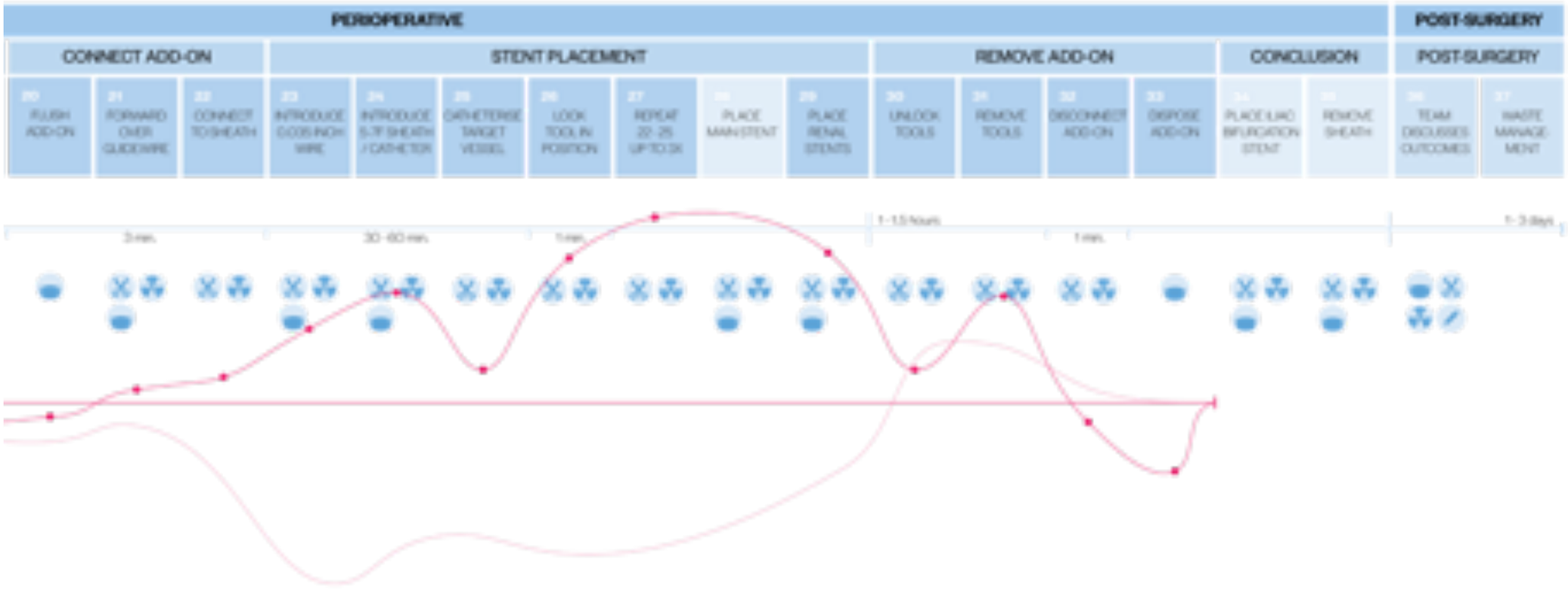
- The entrance is directed towards the user. Also, the valves can be thinner and more flexible than the Check-Flo's silicone 3-layer valve, because they only have to facilitate introduction of a single tool, creating less friction.
- The valve always remains closed, and does not require loosening to fit additional tools, because each tool has its own dedicated valve. This reduces the chance of leakage when inserting multiple tools in parallel.

- The valve is more proof to tearing and rupturing than existing sheath valves, because just one tool is inserted per valve, and no extra holes have to be pierced into the valve. Also, it is only exposed to the number of movements of a single tool, instead of the total of movements of all tools.
- Also, during BEVAR procedures, the super stiff wire can be pulled through one of the entrances, which are already positioned under an angle. In that way, the wire is still pulled straight through the valve, preventing that it is forced open.
- Next, the user does not need to hold a tight grip on all inserted tools constantly. Van Rijswijk (personal communication, March 31, 2021) expects that "*separate valves already cause much less unintended co-movement*". By additionally locking the individual tools, the user can be confident that they remain in position, even while moving other tools or forwarding the stents through the tools. This enables more freedom of movement of the user's hand to perform other actions and lets the user focus on the main operative tasks. Also, the risk that the tools dislocate unintendedly is eliminated, preventing harm to the patient's arteries and significant increase of the procedure's duration.

"separate valves already cause much less unintended co-movement"
- Van Rijswijk

"*The concept of locking is very nice, then you can make sure that the other catheters don't move when you're manoeuvring one.*" noticed Eefting (personal communication, April 6, 2021). Also Van der Vorst (personal communication, April 6, 2021) reinforced this: "*It is very nice that you can clamp the tools, then it does not matter what else happens, they stay fixed.*"

- Better tactility of tool movements, because the tools are not pressed together, creating friction in between. Besides, the chance that the tools get in each other's way, obstructing movement, is reduced, because the space in between them is larger. The funnel-shaped lumen guides the tools smoothly into the sheath's lumen.
- When removing the tools, they can again be unlocked on by one. Again, this eliminates the risk of unintentional tool movements. Besides, the valve shapes around the single tool, closing completely as soon as the tool exits, instead of requiring extra inflation to fill up the created cavity, as with the DrySeal.



“the combination of multiple valves and clamps, makes it interesting!”
- Van der Meer

“*By making such a part with four separate entrances, you prevent leakage from one large valve. If you get this working, it would really be practical. Besides, we have some devices with a single clamp, but the combination of multiple valves and clamps, makes it interesting!*” expressed Van der Meer (personal communication, March 31, 2021).

Possible confusion while (re-)ordering the add-on is prevented, because the add-on is not dependent on the sheath’s French size and can fit sheaths supplied by various brands. The hubs of the DrySeal and Check-Flo always have the same dimensions, disregarding the cannula’s French size. Therefore, only the sheath’s brand is relevant, which is mostly standardized for FEVAR procedures within a specific hospital, due to the specialists’ preference. Van Rijswijk (personal communication, March 31, 2021) stated: “*I think the interesting aspect is that you can make an add-on that fits on every sheath model.*”. This enables medical specialists to use their preferred sheath model and does not require them to switch to a completely new introducer sheath and train its use. “*Many people have good experience with the DrySeal, so it is a good idea to use that.*” explained De Jong (personal communication, April 6, 2021). Also, Nelissen (personal communication, March 15, 2021) underscored that an add-on is practical, because it is easier to use a tool that the medical specialist is used to working with: the surgeon can focus on the main task and the learning curve is smaller. He said that “*The most faults in medicine happen when a surgeon uses a new tool, and is not well trained.*”.

On the other side, three slightly negative moments can be seen. These are experienced during flushing, disconnecting, and disposing the add-on. The first two are new steps in the procedure, which can be experienced as extra efforts and time. However, medical staff view these in relation to the improved outcomes, as well as the saved efforts and time achieved for the whole procedure. The third, disposal, is critical, because waste and sustainability receive growing attention by hospitals and individuals. Thus, throwing away even more (single use) instruments is not desirable. Therefore, the device is designed for reusing and recycling opportunities in the future, which is further elaborated in Paragraph 23.4.3 & Chapter 26.

“*I think it is really cool what you made*” concluded De Jong (personal communication, April 6, 2021).

Figure 16.2 Possible implementation of the Pentaport in the procedure (right)

17. DEVICE SAFETY

As stated before, FEVAR surgeries are highly complex procedures, carrying many risks, sometimes with severe consequences. As such, use of the add-on in clinical practice brings about new risks to the procedures. These risks must be eliminated to ensure safe use of the device for the best possible outcomes. Design for Safety is aimed at identification and elimination of risks from the beginning product development, to design a product that is inherently safe to use, instead of relying on IFU's or labelling.

17.1 THE USABILITY ENGINEERING PROCESS

The device's usability, relating to safety, can be analysed, specified, developed, and evaluated through the process of usability (or human factors) engineering (ISO, 2015). This is a highly complex process of assessing and mitigating risks associated with correct use and use errors, that must follow various international standards. An example of the process can be found in Figure 17.1. The core of this process was sought, to ensure efficient integration of its key principles in this project, by interviewing two Human Factors Design Engineers: Chris Vincent (personal communication, April 9, 2021) and Cait McCarthy (personal communication, April 9, 2021). Both work for Design Consultancies specialised in Medical Devices, respectively PDD Innovation and Worrell Design.

McCarthy structured the process of design for safety and usability in three steps:
1. Task Analysis
2. Usability FMEA (Failure Modes and Effects Analysis)
3. Usability research and evaluation studies

These steps are not only essential for good product design. Their accurate execution and documentation are of great importance for the certification process as well.
Overall, *"there are two important standards that form your baseline during the Usability Engineering part of the design process, which are the IEC 62366 and the HE75*."* stated McCarthy. The first specifies usability requirements for the development of medical devices, where the latter contains information, design criteria, guidelines, and methodologies for the research & design of medical devices (Bramblett, n.d.).

The usability engineering process is applied in this project according to the three steps described by McCarthy.

*
EU MDR IEC 62366-1:2015, Medical devices — Part 1: Application of usability engineering to medical devices

ANSI/AAMI HE75:2009 (R2018), Human Factors Engineering - Design Of Medical Devices

17.1.1 TASK ANALYSIS

The task analysis forms the first step in the usability engineering process, to understand all key points in the device's use. For example, identifying who the stakeholders and users are, what tasks are performed with and by the device, and which tasks are the most critical (McCarthy).

In this project, the Journey Map (Figure 16.1) forms a conclusion of all tasks and their stakeholders that have been desired, based on literature, clinical observations, and expert interviews. Therefore, it its steps are used as basis for the FMEA.

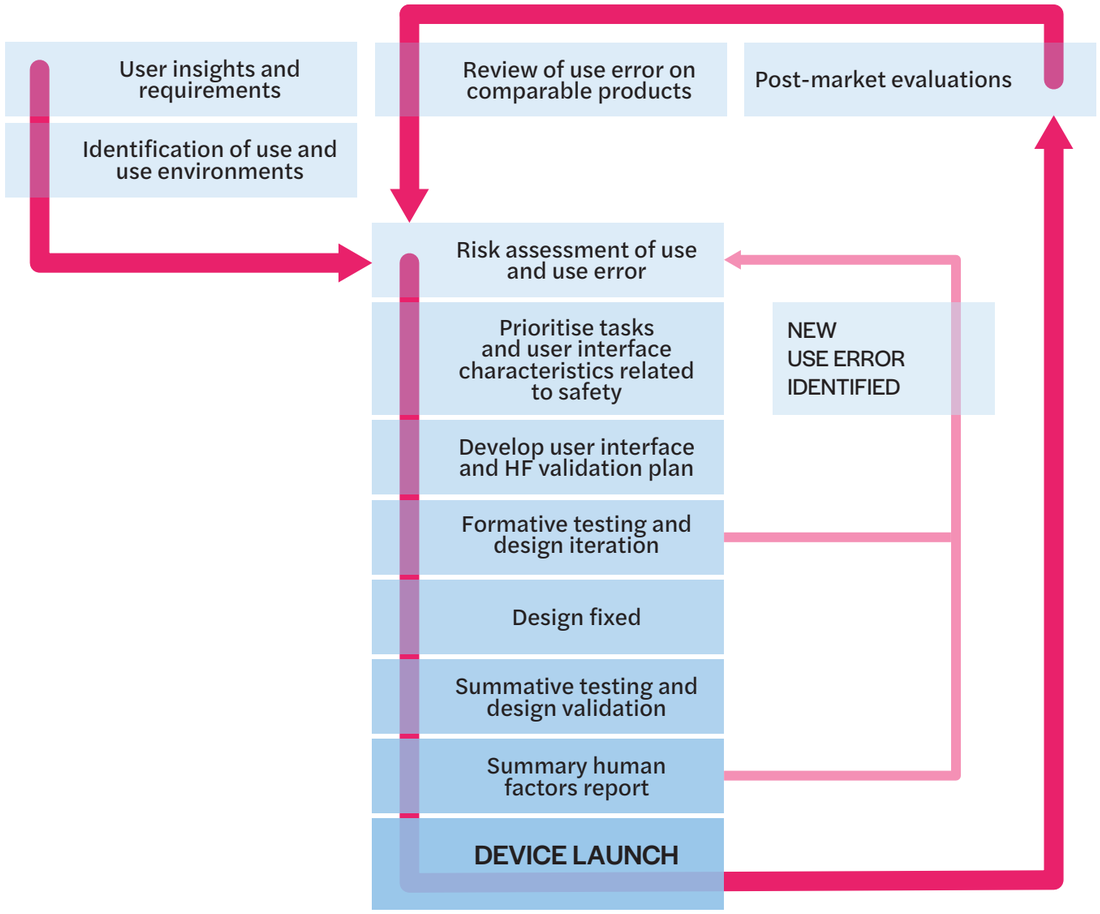


Figure 17.1 Example of the usability engineering process, based on the guiding document by the MHRA (2021)

" 'human factors' refers to how a person will interact with the systems surrounding them.

The science-based discipline of human factors uses knowledge from such diverse subjects as anatomy, psychology, engineering and physiology to help design products that suit the user, for more effective and safer use.

Human factors takes into account features of the intended user population, such as age, size, strength, cognitive ability and training. It also takes into account the intended environment of use."

– MHRA (2021)

Figure 17.2 Side view of the Pentaport, blood clotting could occur in the funnel-shaped cavity and connected lumina

17.1.2 USABILITY FMEA

Next, according to the steps in the Task Analysis, possible failure modes and their effects can be analysed. The severity of the effects, the expected occurrence frequency of these failure modes, and the chance of detection are numerically rated, resulting in the 'Risk Priority Number' (RPN). This number can be used to rank risks according to their criticality, the highest ones must be tested and evaluated, and the implementation of their risk mitigation actions must be prioritised (McCarthy). Risks identified earlier in the concept development process, for example in Paragraph 13.3, were also included.

For this project, a template by Bureau Tromp (2020) was adjusted to contain the essential parts for this product. The severity and occurrence scores, ranging from 1 to 10, were defined to be relevant for this use case. The FMEA can be found in Appendix Q.

The four highest RPN values related to the failure modes in the table on the right (Table 17.1). Mitigation actions were designed to decrease the RPN values to a tolerable level.

Not only the four main risks are eliminated with suitable mitigation actions. All other RPN's could be reduced to a value (most notably) below 36 as well. Examples of these design choices are:

- Add-on consists of one single unit and does not have small loose, separatable parts that can fall off. The only loose part is the compression ring. Ways were sought to make this part inseparable too, but this is not possible as the diameter needs to be smaller than the main body to enable compression.
- When connecting the add-on to the sheath, the user can visually and manually check whether the positioning and fastening is correct and the silicone seal in the compression connection compensates for small degrees of tilting.
- The add-on is designed to be as light as possible, to prevent bending the sheath down during use or even kinking of the sheath.
- The locking system still enables use of the wire insertion support tool for the valve.
- The add-on's main body is designed to be transparent to enable visual checks of the valves' closure and improve detectability of possible leakage.
- Locking mechanism tube is straight and close to entrance point, improving steerability through the mechanism and into the valve
- Add-on's length is kept to a minimum.
- Lumen designed for maximum size of 8F sheaths, forming an extra margin, because typically 7F is the maximum size that is used.
- The colour-coding is not artery related, giving the user flexibility in choosing the optimal entrance, instead of the entrance coded for a specific artery.
- Tube and valve materials with a high tearing resistance are used.
- Automatic stops are integrated in all thread designs, preventing the user from rotating the screw further and thereby stripping / breaking the thread.

NR.	FAILURE MODE	EFFECT	CAUSE	RPN	ACTION	NEW RPN
7	Blood getting caught in the lumina between the sheath and the add-on's valves	Blood coagulation	Ridges and cavities in the lumina (Figure 17.2)	315	• Lumen have a smooth and flush design, with minimal ridges at parting lines • The add-on is flushed before connection to the sheath and can be flushed up to its valves during the procedure, through the sheath's flushing port • The locking mechanism is placed behind the valve, so the valve prevents risk of coagulation around the locking mechanism • The add-on's body is transparent to improve visibility of valve functionality and detection of possible blood coagulation places • Anti-coagulation coating of the lumina's walls	50
12	Tearing of the clinician's gloves and harm to the clinician's skin	Risk of cross-infection for the patient and clinician	Sharp parts, edges or corners of the add-on	250	• Design has no sharp parts, edges or corners • Parting lines are reduced to a minimum on the add-on's outer surface, by using ultrasonic welding to connect parts • The connection between add-on and sheath is leak proof. Also, the locking mechanism catches possible leakage through the valve and guides it to the side of the add-on, thus the chance of blood entering the main body of the add-on is reduced • The design has a light outer surface, making blood stains well visible on the main body	42
30	Material of the locking mechanisms' silicone tubes tearing off	Particles enter the blood system and reduced locking functionality	A tool that gets stuck, bad material qualities, user forces tool through when mechanism is locked	216	• Tube material has high tearing resistance • Funnel-shaped entrance guides tools straight into locking mechanism, preventing tools from getting stuck • Locking mechanism is placed behind the valve, so valve blocks entrance of particles into blood system • Material supply and production and packaging facilities should be ISO 9001, ISO 13485, and ISO 14644 certified • Movement of tool through locking mechanism is enabled when a significant threshold force is applied, to prevent user from increasing force and creating damage	15
33	Unintended and unnoticed tool movements when the locking mechanism is left open accidentally	Harming the patient's arteries and increasing the procedure's duration, which is negative for the patient's condition	Unclarity of usecues or feedback for the user concerning the status of the locking mechanism, whether a tool is locked or not.	210	• Direct tactile feedback (increasing rotation force and rotation stop at maximum) of the screw confirms locking and unlocking • Continuous visual usecue (distance between screw cap and main body edges) displaying status of locking mechanism • Colour-coding screw caps • Separated lumina and valves decrease the chance of the tool moving along with movements of another tool	30

Table 17.1 FMEA summary of the four Failure Modes with the highest Risk Priority Number

As explained by McCarthy, risk mitigation should be proven by testing the design with users. Especially, the evaluation of the highest risks should be prioritised through usability research and evaluation studies. These are explained further in the next paragraph.

One serious concern, relating to Failure Mode Nr. 7 and expressed by medical specialists during usability studies (Paragraph 13.4.1), is that thromboses might be formed in the ridges of the connection between sheath hub and add-on. The occurrence of blood coagulation must be tested with real blood for realistic outcomes and depends on the prototype's fidelity. Therefore, it was not possible to test this concern and validate whether coagulation is a risk and how high the RPN is. This must be extensively tested in the future, ideally with real blood and a prototype fidelity (close to) representative of the final device.

17.1.3 USABILITY RESEARCH AND EVALUATION STUDIES

Usability studies can be categorised into four types, employed at different moments throughout the development process: generative, formative, summative, and post-market.

17.1.3.1 GENERATIVE STUDIES

Generative studies are aimed at gaining insight into the user's behaviours and needs, especially in the early stages of the process (Bramblett, n.d.). They are used to identify the key problems that should be solved by the new design.

During this project, generative studies were performed in the form of in-clinical observations and contextual inquiry with medical staff (surgeons, IR's, nurses, anaesthetists) during surgeries, as described in Chapter 6. Besides, semi-structured interviews were done with medical students and specialists in training.
Also, literature was reviewed, covering FEVAR procedures and use of the existing introducer sheath models.

17.1.3.2 FORMATIVE STUDIES

Bramblett explains formative studies as a means to "*test concept designs with targeted users to identify which concept is the best direction to pursue*". Also, refinement opportunities can be found.

Formative studies were applied during various phases of this project; testing and evaluating all human factors that impact user performance, comfort, safety, efficiency, and human error (Bramblett, n.d.).

First, co-creation sessions in the form of a cognitive walkthrough (MHRA, 2021, p. 15-18) were done with various experts for an early review of design directions and preliminary concepts (Appendix K). The interactions of the designs were 'walked through', reasoning about possible use errors and use benefits. The insights were used to choose the best directions to pursue, resulting in three concepts.

"In the end, it always comes down to safety" **- McCarthy**

Next, these concepts were evaluated in think-aloud usability tests, where end users (vascular surgeons and IR's) articulated their thoughts while interacting with the concept prototypes (Appendix N). The identified preferences and risks were taken along in the final concept choice. However, Vincent stated that "*if there is some fundamental risk in the design, you are not guaranteed to find it through formative usability studies with relatively small group of experts. It will always be opinion-based and slightly subjective, but there is also a lot of data for backing.*". Also according to McCarthy, "*In the end, it always come down to safety. Does it decrease the risk? Great. Does 75% of people prefer this? Even better.*". She states that the user's preferences should not be taken as a hard pull, because they often do not think about the underlying risks. Therefore, as suggested by Vincent and McCarthy, the usability test findings were backed with and/or weighed against more objective findings from expert interviews (for example, the interviews with Trauzettel, Anuba, Nelissen, Van de Stadt, and Berkhoudt described in Paragraphs 13.2 & 13.3), ergonomic research and data (Paragraph 18.1), as well as the FMEA (Appendix Q), when creating the final concept.

Lastly, the final concept is evaluated through a usability test as defined by the MHRA (2021, p. 15-18), the last evaluation within this project. Here, a high-fidelity alpha prototype is tested with a representative user (vascular surgeon) in a simulated use environment (a flow model simulating blood pressure and viscosity). The protocol is thoroughly informed by the Task Analysis and FMEA. In particular, the tasks identified as most critical are tested. The formative evaluation of the usability must include all critical safety-related "use-scenarios", says McCarthy. A summary of this evaluation can be found in Appendix N.

To achieve fundamental proof-of-concept, the final formative study should have 15 participants per user group (surgeons, IR's, scrub nurses), Vincent explained. In that way, patterns could be found of tasks that are done wrong, if multiple people make the same fault at the same step. If such patterns occur, they must be redesigned and tested again in a simulated set-up. However, due to limitations in time and availability of participants, it was not possible to complete such a study within this project. This would be one of the necessary first steps in further development of the device after the course of this project, further elaborated in the future roadmap in Chapter 30. Likewise, the summative studies and post-market evaluations are steps essential to future product development and market introduction.

17.1.3.3 SUMMATIVE STUDIES

After multiple sets of formative studies, the last type of studies is applied to validate a design with targeted end users along metrics established in formative research studies (Bramblett, n.d.). Realistic, high fidelity functional prototypes, packaging, and IFU's are tested. Summative studies are required to get certified clinical approval.

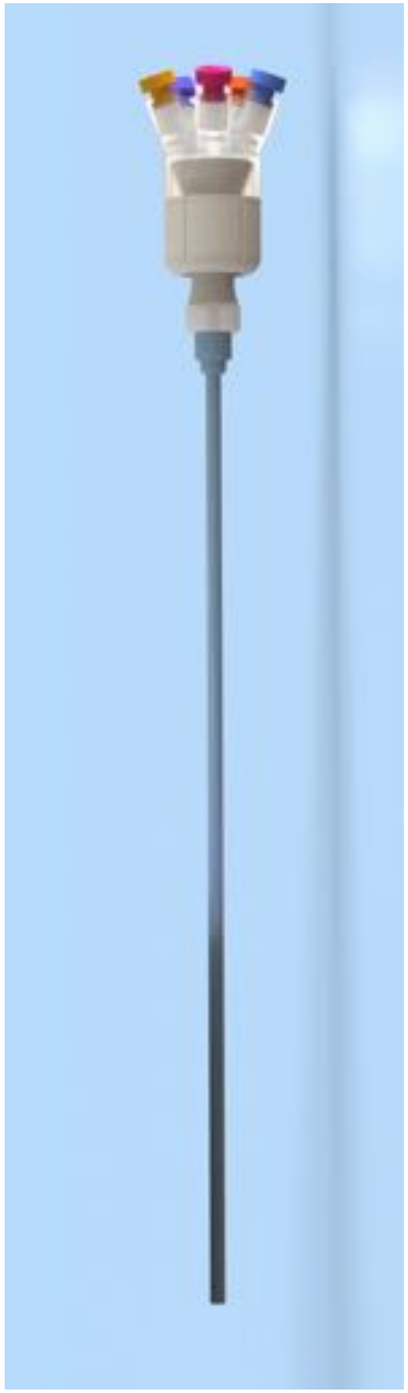


Figure 17.3 Side view of the Pentaport connected to a sheath

Within this project, only formative evaluations are performed, due to the current state of the device design. Summative evaluations are relevant as soon as the design is final. To reach that state, aspects such as design for production, as well as labelling, packaging, Instructions for Use (IFU), clinical tests, process description for post-market surveillance, etc. must be elaborated.

17.1.3.4 POST-MARKET EVALUATIONS

After market introduction, the usability engineering process is continued by doing a lot of post-market and in-clinical practice evaluations (McCarthy). This is an informative source for later product improvements and marketing purposes, making the product development circle round, because it is input for next generation models.

In essence, these evaluations were performed when analysing the use of the DrySeal in-clinical practice at the LUMC. In the future, these evaluations should be carried out for the new add-on design as well.

17.1.4 CERTIFICATION

Documentation of the summative studies and plans for post-market evaluations are key to achieve certification of the new product for clinical use.

According to Prof. Dr. Rob Nelissen (personal communication, March 15, 2021), the new MDR certification is based on the benefit / risk ratio for the patient, stated in Article 61 (EU MDR 2017/745). Clinical evidence must be achieved that the benefits significantly outweigh the risks.

The Johner Institut (2021) has developed a checklist for the MDR Usability Requirements (IEC 62366). Although it is too early in the process to check the new design for exact compliance with the MDR requirements, it was applied to prove completeness of the list of requirements (Chapter 10), introduce measures necessary to ensure patient safety (Appendix Q), and be ahead of possible problems during audits and authorisations.

The final design is a class Is device because it is intended to be used in combination with another device. As an accessory, it shall be classified in its "*own right separately from the device with which it is used*" (MDR, Annex VII, Rule 3.2). Meaning, it is classified independent of the class III introducer sheath, as a class I device used outside the body (Figure 17.3). This conclusion was confirmed by Aniba (personal communication, February 25, 2021). The device's sterility requirements are indicated by the 's'. Protocols to achieve these must be assessed by notified bodies. The future route to CE marking of the device can be found in Paragraph 27.9.2.

18. INTERACTION & EXPERIENCE

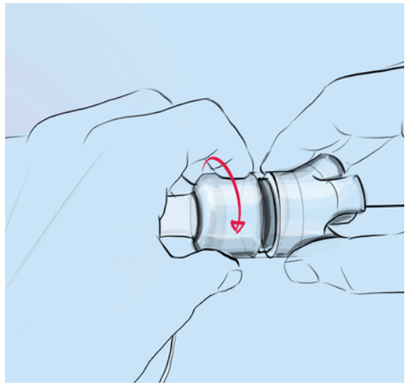


Figure 18.1 Tridigital subterminal opposition

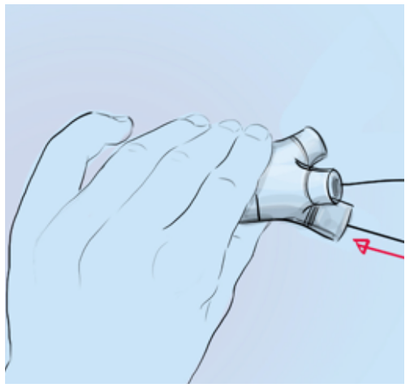


Figure 18.2 Pollici-tridigital subterminal opposition

FUNCTIONAL HAND GRASP (PINCH GRIP)			
	P5	P50	P95
True	21mm	43 mm	79 mm
Max.	108 mm	125 mm	150 mm

Table 18.1 Optimal dimensions for pinch grip, researched by Cornell University (n.d.)

In addition to offering a desirable functionality and safety, the product experience is designed to match the user's needs, desires, and context. Here, ergonomics and aesthetics come into play. Both directly influence each other, defining the user's interaction with the device and how that is experienced. For example, the device's symmetrical cylindrical shape is physically desired for optimal reach and colour coding contributes as usecue for better understanding.

18.1 ERGONOMICS

Ergonomics can be divided into physical and cognitive ergonomics. The first covers aspects such as suitable dimensions, as well as a good grip, tactility, and visibility. The latter concerns understanding of the device, for example through tactile and visual usecues.

No usecues relying on hearing or smelling senses are integrated, because they are found to be less functional for this use case. The soundscape present on the OR is already highly saturated by among others monitoring signals and communication between operating team members. Also, scents would not be recognized due to face masks and continuous air circulation.

18.1.1 MAIN BODY SHAPE & DIMENSIONS

Concept evaluations with medical specialists indicated a unanimous preference for a symmetric, cylindrical shaped main body: it should form a sleek, straight extension of the original sheath (Paragraph 13.4). This symmetrical shape enables use from all sides, no matter which side faces the user. Having a dedicated front and back side for the add-on, would require the user to position it on the sheath with a specific side facing forwards and comfortable use would depend on correct positioning. Also, the sheath could rotate during use, consequently rotating the add-on. Therefore, the design's circular symmetry eliminates the risk of a wrong-way-facing add-on. The same can be said for the design of the five entrances.

The optimal diameter of this cylindrical shape is defined based on the required types of gripping. As defined in the design drivers, the grip of the main body should feel comfortable and secure, even after multiple hours of use. Based on observations, user interviews and concept evaluations, the desired grip is formed by one, two or three fingers (index, middle and/or ring finger) on top of the device, supported by the thumb on the opposite side (Figures 18.1& 18.2). This can be classified as ((pollici-)tridigital) subterminal opposition, a type of precision grip, where the object is held between the pads of the digits, which spread around the object conforming to its shape (Palastanga et al., 1994). This precision grip enables optimal control and tactility during use.

The more fingers placed on top, the larger the force and surface of the grip are. Thus, the tighter, more balanced and secure the grip is. This pinching, precision grip is enabled by optimising the device's diameter to 34.6 mm, while maintaining enough internal space for the channels and sheath hub connection. This lies within 25.4 and 76.2 mm, the range for optimal functionality of this grip (Cornell University, n.d.), Table 18.1.

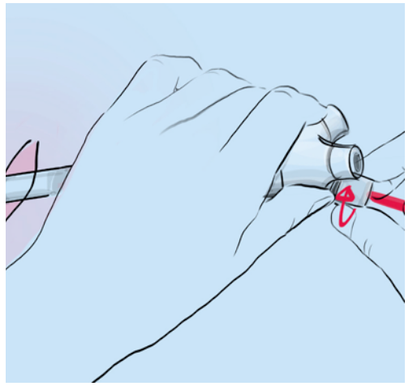


Figure 18.3 Cylindrical full palmar span

When a more forceful grip is required, the user can switch to a cylindrical (full) palmar span (Figure 18.3). For example, when overcoming a friction threshold while pushing a tool in. The adductor pollicis (the muscle located at the side of the palm where the fingers start) stabilises the device against the palm (Or et al., 2015). This enables the maximum force that can be developed by the hand, because it involves larger muscles compared to the precision grip, which can develop only about 25% of the maximum grip strength. Thus, the cylindrical span is classified as a power grip, functioning optimally when the cylinder size is between 25.4 and 50.8 mm in diameter (Cornell University, n.d.).

18.1.2 CONNECTING ADD-ON TO SHEATH

The first key action involving the add-on is the connection of the add-on to the sheath. The following design features of the add-on are intended to support the user during introduction of the main guidewire, correct positioning of the add-on, and safe fixation.

First, a taper helps directing the guidewire into the lumen (at its 'sheath' side), through the corresponding valve, and out of one of the tool entrances, without requiring the user to look into the opening. By placing the guidewire tip into the lumen and forwarding it, the user can be assured that it will find its way through the add-on automatically.

Next, the user must be sure that the add-on is positioned correctly onto the sheath's hub. Therefore, a visual check can be done to evaluate whether they are aligned or tilted.
If the user cannot see any part or edge of the sheath hub's hard plastic top edge, this means the hub's top part is inserted completely into the hollow space in the add-on. It is 'trapped' between the compression teeth and positioned straight against the silicone sealing layer. Otherwise, in case of tilted positioning, the edge of the hub's top part would stick out at one side.

Lastly, tactile and visual feedback is provided during fixation of the compression screw. When screwing the ring onto the add-on's main part, compressing the teeth, the user knows that the fixation is safe, as soon as the ring reaches the end of the thread and the cavity between the ring's and main part's edges is closed. Simultaneously, the user feels that the ring cannot be screwed on any tighter.
For extra confirmation, the user can even try to 'pull' the add-on from the sheath hub, which should not be possible and withstand considerable force.

18.1.3 TOOL MANOEUVRING

After connecting the add-on to the sheath, the user can start inserting tools, during which tactility and visibility are key. The design has diverging entrances to ensure more space in between the openings and other introduced tools, decreasing the chance of a blocked view, and facilitating improved visibility of the openings. This extra space also enables easier manoeuvring of the tools.

Again, funnel shaped openings at the tool entrances facilitate easier introduction, because tools are guided into the centre.

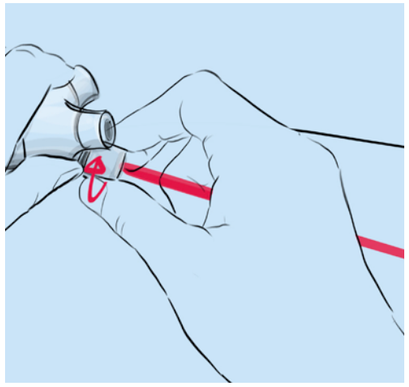


Figure 18.4 Terminal opposition grip

FINGER BREADTH (MM)			
	P5	P50	P95
Index	14	18	21
Thumb	20	23	26

Table 18.2 Finger breadth of Dutch adults 31-60, mixed, researched by Dirken et al. (2018)

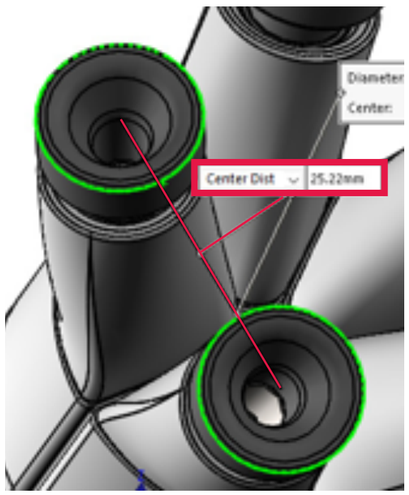


Figure 18.5 Minimal distance between screw caps (13 mm diameter) is 12.22 mm.

Next, tactility is essential while advancing and manoeuvring the tools through the sheath's cannula and into the patient's aorta. This means the friction due to valve and locking mechanisms' tubes should hinder the tactility as little as possible. Therefore, a flexible and smooth silicone type is chosen for the valve.
On the other hand, the locking tubes inner surface must create a relatively high friction to stop the tools from moving, this should not be reduced in the same way as for the valve. Thus, by adding a margin to the diameter of the tubes' central opening, even the largest possible tools are not completely enclosed by the tube, minimising the friction by the locking mechanism in its open state.

18.1.4 LOCKING TOOLS

The locking mechanism can be moved into its closed (and back to open) state by rotating the screw caps, placing the thumb's distal digit pad on the side of the screw cap and the index finger's distal digit tip on the upper edge of the screw cap (Figure 18.4). This also is a pinching precision grip, called terminal opposition, which is the most precise of all precision grips (Palastanga et al., 1994), ensuring optimal tactility while (un)locking.

The screw caps diverge from the add-on's centre. This angled position creates a larger distance between the screw caps' upper edges, and therewith more rotating space for the index finger. The distance between these upper edges is 12.22 mm (Figure 18.5), allowing enough room for the P95 index finger to comfortably control the screw, without being obstructed by the other screw caps, based on data provided by the DINED database (Dirken et al., 2018). As this database does not contain information on the breadth of the index finger's tip or distal digit, the index finger breadth (Table 18.2) is halved as approximation.

During rotating, the user feels the screw becoming tighter, because the increasing pressure on the compressed tube creates friction on the thread. This friction gives a continuous indication of the degree of fixation. The screw cap reaching the end of the thread, forms an automatic stop and therewith an indication of maximum fixation. However, both forms of tactile feedback are only experienced during the handling action. Therefore, visual usecues are added to communicate the status of the lock to the user, while performing other actions and not feeling the screw. The edge of the add-on's main body and the screw cap's lower edge are designed flush to each other, creating an obvious distance when moved apart. When these edges touch upon each other, the tool's position is locked. A clearly visible gap between the edges indicates that the tool is free to move.

Additionally, it is important for the users to know which of the tools are locked in place, and which tool lies in which entrance. If one of the team members accidentally moves the wrong tool, it can dislocate from its intended position, and repositioning can decrease efficiency. Therefore, colour coding is applied to the individual screw caps for easy distinguishing of the different entrances. Applying colours has the benefit of being visible from all sides and, therewith, all active team members positioned around the patient table. However, around 1 in 20 people are colour blind (Nichols, n.d.), presenting a chance that a team member might have difficulties differentiating between colours. Therefore, a colour-blind safe palette is used (Figure 18.6), offering distinguishable colours for the three colour blindness types protanopia, deuteranopia, or tritanopia (Figure 18.7). The chosen palette is based on the colour-blind safe palette developed by IBM.

CONCLUSION

Overall, the device's shape, dimensions, tactility, visibility, and understandability are designed for optimal physical and cognitive ergonomics. This ergonomic design strongly contributes to the product safety, preventing unintended use, as well as the user's experience. Consequently, the resulting design choices are taken forward in the aesthetic design, which is elaborated in the next Paragraph 18.2.

Figure 18.6 Colour-blind safe palette by IBM, retrieved from Nichols (n.d.)

Figure 18.7 Perception of the colour-blind safe palette by the different types of colour-blindness, retrieved from Nichols (n.d.)

18.2 AESTHETIC DESIGN

The role of aesthetics for this design is two-fold. Suitable aesthetic choices do not only create a safer and more pleasurable use as explained in the previous Paragraphs 17.1 and 18.1. They also influence the user's trust in the device. Through its appearance, the device can communicate its quality, functionality and professionality. Besides, research by Da Silva Cardozo (2016) has shown the benefit of efficiency in design: "people perceive beauty in a product when they perceive it to achieve 'the maximum effect' with 'the minimum means' ", called the principle of efficiency or MEMM.

The principle was applied in combination with the method "Nine Moments of Product Experiences" developed by Özcan (2016) to define the aesthetics, meaning and emotions required to achieve the desired product experience (Table 18.3). The resulting characteristics are sought in existing inspirational product designs and are turned into a moodboard (Figure 18.9), from which the device's final aesthetic features are translated and integrated in a design drawing exploration of the device embodiment's form aspects (Figures 18.8 & 18.10). Additionally, the form preferences identified during the usability evaluation are included (Paragraph 13.4.1).

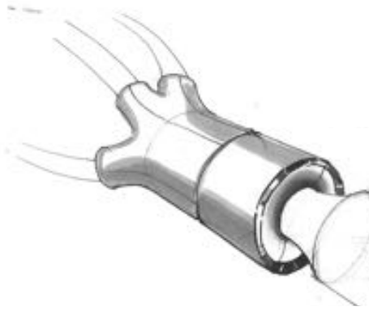
	MICRO	MACRO	META
AESTHETICS	Harmony (unified use of materials and colours & shape is extension of sheath) Clear indication of functional parts	Form unity with sheath Stability & precision (sensitivity)	Fit into the surgical OR context (sterile, professional, medical instrument)
MEANING	Safe to use (rounded shape, no sharp edges and corners and nothing to get caught, solid unity and no wiggling of parts)	Trustworthy & reliable (high quality, give confirmation of actions)	Improve patient safety (reduce risks of safety hazards)
EMOTION	Sensitivity of feedback (tactility of interactions & visual guidance) Visibility of leakage and dirt	Confidence & simplicity of use (straight forward, familiarity of actions & usecues, tight ergonomic manual grip)	Gain success: Increase efficiency of procedure (reduce workload and complications)*

Table 18.3 Nine moments of product experiences desired for the new design

18.2.1 MOODBOARD

Form language characteristics deducted from moodboard:

- Main body: geometric shapes with extremely soft, rounded outlines (edges and corners).
- Flat, “cut-off” surfaces for interaction or usecues.
- Colour, material, finish:
    - Matte & glossy white, light grey / blue / green plastic, colours used to highlight functional parts, grip parts mostly matte and possible with texture,
    - Some white translucent plastic parts, can be used to communicate information / light from inside.
    - Shiny silver metal details, often placed along parting lines.
    - Few black surfaces.
- Buttons: kept to minimum, placed central, same colour as surrounding surface, but visible by clear parting line or indented shape.



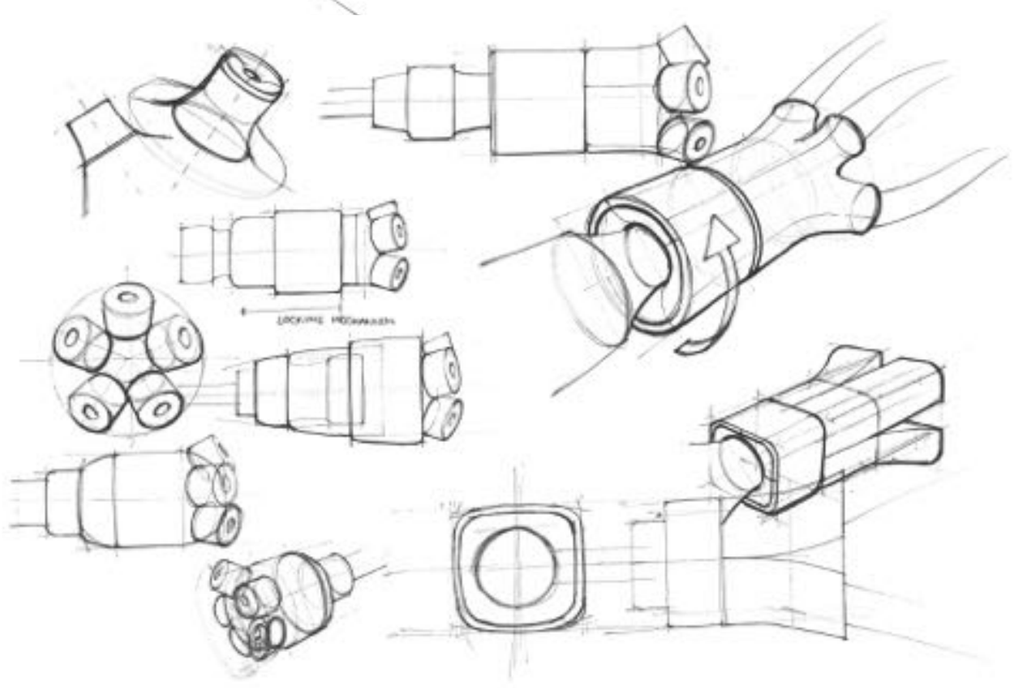


Figure 18.8 Below: explorative aesthetic design drawing
Figure 18.9 Right: moodboard for desired product experience and aesthetics

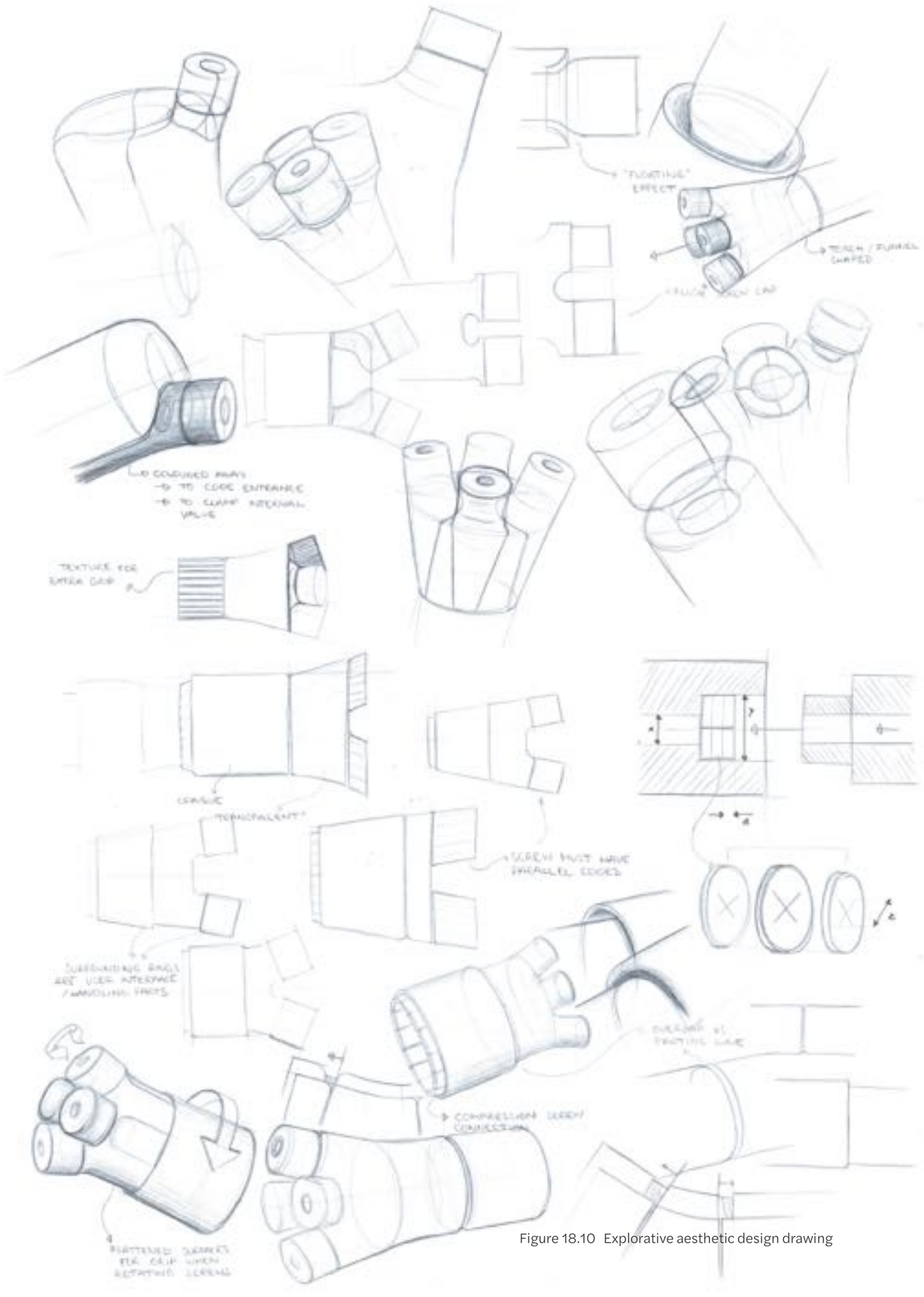


Figure 18.10 Explorative aesthetic design drawing

19. DESIRABILITY VALIDATION

In addition to the usability tests that were performed with the help of 7 Vascular Surgeons and 2 Interventional Radiologists (LUMC and Haga Ziekenhuis) during the concept development phase (Parapgraph 13.4.1), another evaluation and preliminary validation of the Pentaport's desirability was carried out. The goal of this validation test, like the feasibility and viability validations in the next chapters, was to prove the value of the design concept, at its current stage at the conclusion of this project. The identified value is categorised based on the design drivers. This preliminary type of validation should not be seen as or confused with the summative validation that is required for the product in its final form, ready for certification and production. Such an evaluation should be performed with a further developed prototype and more participants.

The Pentaport's final prototype, printed on a Form 3 (Formlabs), in combination with renders of the desired final product, were evaluated by two participants:

- Joost van der Vorst, Vascular Surgeon at LUMC (May 31, 2021).
- Carla van Rijswijk, Interventional Radiologist at LUMC (June 1, 2021).

19.2.1 MINIMISED BLOOD LOSS

First, Van der Vorst and Van Rijswijk expressed their enthusiasm for the Pentaport's main functionalities. Both mention the minimised blood loss as the most important benefit. Van Rijswijk: "*the reduced blood loss for the patient and consequential better procedure results, enable faster recovery and less chance of back ischemia*". Also, other post-operative complications, such as pneumonia, can be prevented according to Van der Vorst. Besides, he emphasises that less blood loss reduces surgery duration, time on the guarded hospital ward, and required blood products. He states that, all together, this "*translates into hard clinical outcome parameters*".

"I think it is a good prototype and am very curious how it will work in practice!" – Van Rijswijk

19.2.2 IMPROVED PRODUCT SAFETY

Second, both expect that the (feeling of) product safety during an operation will strengthen. They score this safety to improve from a 7/10 to a 9/10, if it works as intended, because high blood loss and unfixed tools influence the level of safety negatively. However, contradictory safety arguments were found regarding the transparency of the connector parts and dome. On the one hand, it can be experienced as distracting. As expressed by Van der Vorst: "*you become afraid that the blood might start clotting and if it [the valve] leaks, you see that anyway at the entrances*". On the other hand, the benefit is that "*you can see internal bubbles or clots*" (Van der Vorst). In practice, most sheaths and delivery devices have this transparency so you know that you should not flush it, if there is a big air bubble or clot inside. Some sheaths can even be opened for that reason. In this project, the practical safety of being able to act as soon as a bubble or clot is seen, was prioritised over the experienced safety by the user. Still, the need of transparent parts should be further researched and evaluated in the future.

Figure 19.1 Interventional radiologist introducing the second catheter

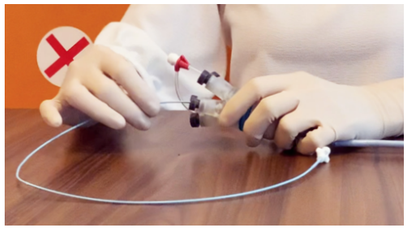


Figure 19.2 Manoeuvring the catheter

19.2.3 SMOOTH TOOL MANOEUVRING

Third, looking at tool manoeuvring, "it is a useful that you can fixate all tools in place if you have catheterized the target vessels" explains Van der Vorst (Figure 19.3). Also, Van Rijswijk states that "*it is clever that you can lock it [the tool]*". This is very practical for example, if the stent placement balloon is being pulled back after use, while all other tools are still introduced. The balloon can be frayed when deflated and pulls back the other tools.

Van Rijswijk addresses the need to test the risk of fluids and blood reducing the clamping functionality of the TPE tubes. Also, blood clots might get caught in between the threads, possibly jamming the screwing movement of the locking mechanism. This risk should be further examined in the future and evaluated by testing with real, heparinised blood. She suggests a bayonet-style lock as an alternative, for safer and faster control. However, this does not enable the variability in locking diameter that is offered by a threaded control, which is needed to make up for the broad range of diameters that must be lockable (from thin wires to 7F sheaths).

Besides, Van Rijswijk emphasises that the shorter the add-on is, the better, to prevent the need to switch to longer tools of 80 cm length, instead of 65 cm, or even 100 cm if 80 cm is not available. The longer the tools, the more difficult manoeuvring becomes. Van der Vorst does not expect an addition of around 5 cm to be problematic. Further testing should be done in a (close to) realistic setting with realistic tools to research the occurrence of tool manoeuvring complications and whether the need for longer tools comes up.

19.2.4 ERGONOMIC USE

Fourth, the diverging entrances improve the procedure's ergonomics compared to the original situation, because the user has more space to handle the tools. "*It is not as crowded around the sheath, there is more space between the tools*" explains Van der Vorst (Figure 19.4). Also, according to Van Rijswijk (Figure 19.1 & 19.2), it is "*practical that the entrances diverge, increasing control over the tools, and, that the wires have a different route on the table, instead of lying directly next to each other*".

Both confirmed that there is enough space between the entrances to rotate the screw caps. The use of locking mechanism is clear and intuitive to both participants. However, rotating the prototype's controls is quite stiff, due to jamming that can be related to over-dimensioned tolerances for 3D-printing. These movements should be smoother and require less force in the final device. Additionally, the rough texture intended for the injection moulded screw caps, would also improve the grip, because the prototype's screw caps surfaces are too slippery when covered with blood and wearing gloves. The screw caps are not too small, "*we are used to working with small parts*" says Van Rijswijk, "*and the total device is not too large, which makes it a very strong design, that it is not an enormous unit*".

Figure 19.3 Vascular surgeon rotating the screw cap to lock the catheter

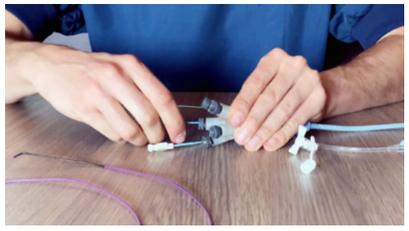


Figure 19.4 Introducing the catheter through the Pentaport and sheath

"It is not as crowded arond the sheath, there is more space between the tools"
- Van der Vorst

Holding the Pentaport was also found to be ergonomically comfortable, being not too large and enabling good fixation in the user's hand. The only concern is the lowest entrance. The user is inclined to bend the Pentaport up, to get a good view of the lowest entrance, possibly creating tension on the femur. This leads to the risk of kinking the sheath or harming the artery. However, the times that you need five entrances are very limited.

19.2.5 TOOL COMPATIBILITY

Fifth, both participants are enthusiastic about the add-on principle for existing sheaths. As described by Van der Vorst: "*Sheath suppliers made beautifully functioning sheaths for other procedures, which they are intended for. By making an add-on, you can use the qualities of these existing sheaths in the patient (e.g. their smoothness of introduction, advanced cannula materials composition) and combine that with the functionality of your system. That's the big advantage.*". The main competitor alternative by Lamed (Paragraph 7.2), is only compatible with their own sheath, which is too short for these complex procedures, explains Van Rijswijk. Therefore, the possibility of combination with various existing sheaths is seen as a practical way to make universal use of the Pentaport possible, as hospitals, also in other countries, work with different tools. But their different types of valves should be kept in mind when broadening the add-on range to other sheath models. Compared to earlier prototypes, Van Rijswijk sees the design's main improvement in the Pentaport's easy placement onto the sheath. "*Last time it was just one connection part, the fact that you can now easily slide it on and then screw it tight to fix it, really is an improvement. That is a unique feature.*"

19.2.6 EFFICIENCY

Other specialisations that could possibly be suitable for broadening the Pentaport's market, could be neuro (brain) interventional radiology, when they use multiple sheaths and catheters in parallel, and laparoscopy for abdominal surgery.

Overall, Van der Vorst sees this project as an example for future clinical challenges: "*this is a clinical problem originating from using a sheath, initially intended for other procedures, for these complex endovascular procedures too, because there simply is no other option. It is good to see that a solution is found now in the form of an add-on, that makes it possible to perform the surgery in a safer and better way. That really is a gain.*".

CONCLUSION

In conclusion, the desirability of the Pentaport's key functionalities is supported by the participating medical specialists. Also, multiple research and design recommendations are defined for further improvement of the usability of the device:

- The need of transparent parts should be further researched and evaluated in the future.
- The risk of reduced tool locking due to blood and other fluids should be further examined in the future and evaluated by testing with real, heparinised blood.
- Further testing should be done in a (close to) realistic setting with realistic tools to research the occurrence of tool manoeuvring complications and whether the need for longer tools comes up.
- For this project, five entrances were chosen, because this is the maximum that can be required. In the future, it could be interesting to explore the viability of offering possible variations with less entrances to improve reachability of all entrances.
- The Pentaport's compatibility should be broadened to other sheath models, with consideration of their differing valve types.

FEASIBILITY

PART 6

This chapter elaborates on the device’s feasibility, covering its functional working principles and their validation in a simulated environment, by testing with realistic pressures and viscosity; its materialisation; as well as its design for manufacturing and assembly.

20. WORKING PRINCIPLES

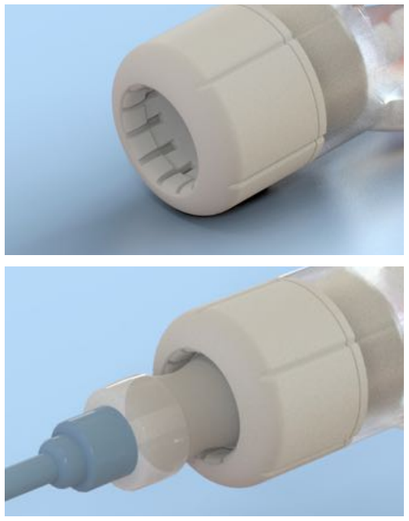
The device's functionality is facilitated by integration of various working principles. These are explained in more detail in the next paragraphs, organised into four functional systems, also defined and detailed in the new design's TRL (Chapter 28).

20.2.1 CONNECTION TO SHEATH HUB

The compression ring pushes the teeth inwards, clamping around the edge of the sheath hub's top, preventing it to move out, as the thickening part of the teeth pushes the sheath hub into the TPE seal (Figure 20.1). The TPE seal prevents fluid from exiting at the contact surface between the add-on and the sheath hub. The seal is 2K-injection moulded into the main body, forming a tight connection, and prohibiting blood to leak between the seal and the main body.

When rotating the screw, an automatic stop is implemented to protect the user from over-tightening the screw. This prevents stripping of the thread, too high force of the compression teeth on the sheath's hub damaging the hub, breaking of the compression teeth, or need of a too high force for unscrewing. This automatic stop is formed by the edge on the add-on's main body.

This compression connection was chosen over alternatives because it extremely strong once the compression ring is tightly screwed onto the main body, compressing the teeth. It is not possible to unintendedly loosen the connection, as could be the case with previous concepts (Paragraph 13.4, Concept 1 & 2), such as the flexible silicone sleeve or a bottle stop-like lever-arm clamp. With both concepts, the user could accidentally tilt the sleeve connection or get caught on the lever-arm, flipping it open, and causing leakage. Also, the compression connection provides the user with tactile and visual feedback of correct fastening, creating confidence and trust.



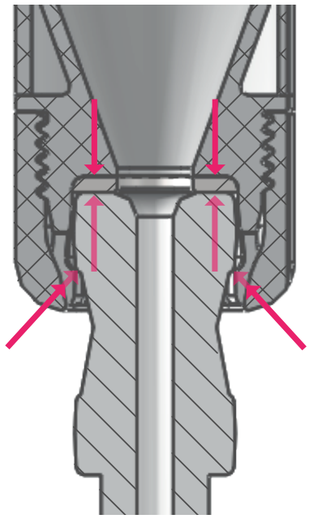


Figure 20.1 Detail of compression connection without (top) and with sheath (centre), schematic representation of clamping forces in compression connection (bottom)

20.2.2 TOOL CHANNELS

A single disc access valve, supplied by MiniValve, is used to close off blood flow through the channels and preventing anything besides the tools from entering. A possible alternative would be a combination with a 3-dimensional cross-slit valve, to reduce movements of the access valve, when it is in unfilled state, due to the pulsating blood pressure. However, this adds extra space and does not make a significant difference for the valve's degree of closure (Jan Willem Nijland, personal communication, April 23, 2021). Multiple disc access valves could also be layered for additional closure; however, this increases friction on the tool as well and enough closure is achieved with a single valve.

A snap-fit joint was chosen above gluing, because this creates a controlled pressure on the valve's edges and eliminates the risk of glue remains influencing the valve's functionality, it also enables easier disassembly. This snap-fit joint also connects the locking mechanism to the main body, serving an additional purpose. The benefit is that anything else can be 'snapped' to the main body as well, this provides interesting opportunities for future broadening

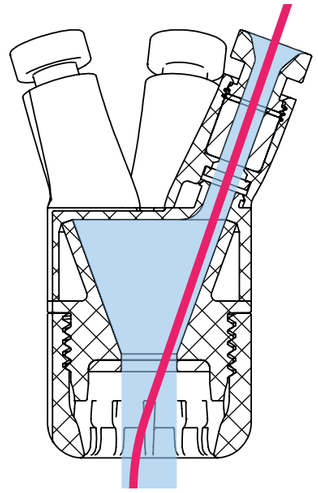


Figure 20.2 Schematic representation of tool channels guiding introduced tools

of the product's functionalities. For example, a clamp optimised to lock the strained super-stiff wire in place used during BEVAR surgeries.

The lumen's PC-PTFE material ensures that they are constantly lubricous and their funnel-shape directs the tools into the sheath's central lumen (Figure 20.2).

20.2.3 TOOL LOCK

The aim of the locking mechanism is to fixate the introduced tool in place. Rotating the screw cap, forces compression of the elastomeric tube (Figure 20.3). Consequently, the tube expands toward its only open side, its centre, reducing the diameter of its lumen and tightening around the tool. The bottom surface and outer wall are encapsuled by the connector, the top surface by the bearing. The lumen's surface has a textured finishing for increased friction and improved fluid resistance.
The bearing prevents translation of the screw cap's rotational movement to the tube, and thereby to the introduced tool. This is important because rotation is an important way of manoeuvring the tool, thus unintended rotation should be eliminated. Other methods, such as a rotating tube (Paragraph 13.3.1, Figure 13.12), were discarded for this reason.
The screw cap and bearing have a funnelled entrance, guiding the wire into its centre during introduction.

Like with the compression connection, a screwing lock is implemented in the screw caps, by snap-fitting them into the connector part instead of letting them move around the connector part's outside. This eliminates the contact surface between the TPE-tube and the screw cap, preventing transmission of the screw cap's rotational movement to the TPE-tube. In previous designs (Paragraph 13.4.1, Figure 13.27), the screw cap rotated around the connector's outside, creating a ridge between the connector, bearing and screw cap. Material of the tube could be compressed into that ridge as well, creating a contact surface with the screw cap, causing rotation, and causing a crooked connection. The final design ensures more equal and neater compression. Also, the thread is not exposed to the outside, protecting it from external influences, such as particles getting in between it and blocking it, tools moving against it accidentally and causing damage, or the user's glove getting caught in it, with the risk of tearing the glove. The screw cap's side walls move along the connector's edge, for additional straight guidance during rotation.

The compressible tube locking mechanism's main benefit lies in its flexibility. It is able to fit and clamp a broad range of tool diameters, from a thin 0.014 inch wire (0.3556 mm) up to an 8F sheath (approximately 3.2 mm). Besides, the large and soft contact surface divides the pressure over a relatively large surface on the tool. This ensures that point pressures are kept low, and no damage is done to the tools, contrary to alternative solutions such as clamping lever-arms with hinging or folding elements. These also have more fragile moving parts prone to breaking. In comparison, the thread is very sturdy.

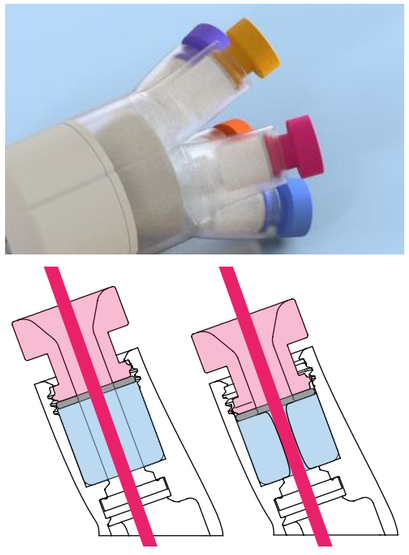


Figure 20.3 Detail of tool locks (top), schematic representation of tool locking mechanism in open (left) and closed (right) position

20.2.4 EMBODIMENT

The embodiment's goal is to create a uniform whole of the device, integrating and connecting all functionalities (Figure 20.4). Its weight and costs are kept to a minimum, by optimising the material use through reduction of wall-thicknesses and infill.

The outer walls are designed for optimal grip, providing an ergonomic diameter and enough space for two to three fingers next to each other on one side and the thumb on the other side. Five ridges were added for easy alignment and support when rotating. However, no dense ridged structure was added because this is less comfortable for the finger pads when holding the device up to multiple hours and it creates difficulties for resterilisation, since cleaning around small ridges is cumbersome.

The areas of the embodiment covering parts where leakage is critical (around the valves) are designed to have a 60% transparency. Full transparency would lead to a very detailed view of the internal parts, causing distraction. By applying a rougher, 'sandblasted' surface, the user sees the internal parts only blurred, but is still able to detect the red blood, in the exceptional case that leakage occurs at a valve. The 'grip' parts (outer surfaces of compression ring and screw caps) are opaque with a rougher surface finish, to prevent slipping. Also, the white matte compression ring and main body form a visual extension of the sheath's hub.

Figure 20.4 View of the device's embodiment

21. FUNCTIONAL VALIDATION

Similar to the desirability validation, the feasibility validation is aimed at proving the design concept's value, at its current stage at the conclusion of this project. Testing the device's degree of leakage and clamping functionality in practice. This test was performed successive to the previous functional evaluation performed with a pulsating, simulated flow model, described in Paragraph 13.4.2.

21.1 TEST SETUP

More reliable simulation and results were achieved by using a constant, closed flow model (Figure 21.1) with a pressure of 175 mmHg, forming an ample margin above a patient's realistic blood pressure (Figure 21.6). The fluid Voluven was used, because of its similar characteristics (viscosity and stickiness) to blood.

The prototype consisted of SLA 3D-printed parts, printed on a Form 3 by Formlabs, of the resins Clear, Tough 2000, and Tough Blue. The product-specific elastomeric parts were casted from Silicone with a Shore A 15 hardness, into FDM 3D-printed moulds (Ultimaker 2+, material PLA). The valves in the prototype were obtained via the supplier MiniValve.
The Pentaport was connected to a 22F-sheath. Four 5F catheters were introduced, and a 0.045 inch stiff-wire (Figures 21.2 - 21.5). During introduction, each tool was moved back and forth and was rotated, for 10 times, before introduction of the next tool. Subsequently, one locking mechanism was activated, and the other unlocked tools were manoeuvred repeatedly.

21.2 MINIMISED LEAKAGE

A minimal number of drops, estimated around 2 mL, started leaking from only one of the MiniValve valves, after repeated moving of the catheter. This leakage can be attributed to the fact that the manually casted tubes are not perfectly symmetrical. Therefore, the tubes' centre openings are not exactly parallel with the lumina's axes. Consequentially, the tool can be guided into the valve under a slight angle and not centred, resulting in reduced closure around the tool. The other valves remained leakproof throughout the test.

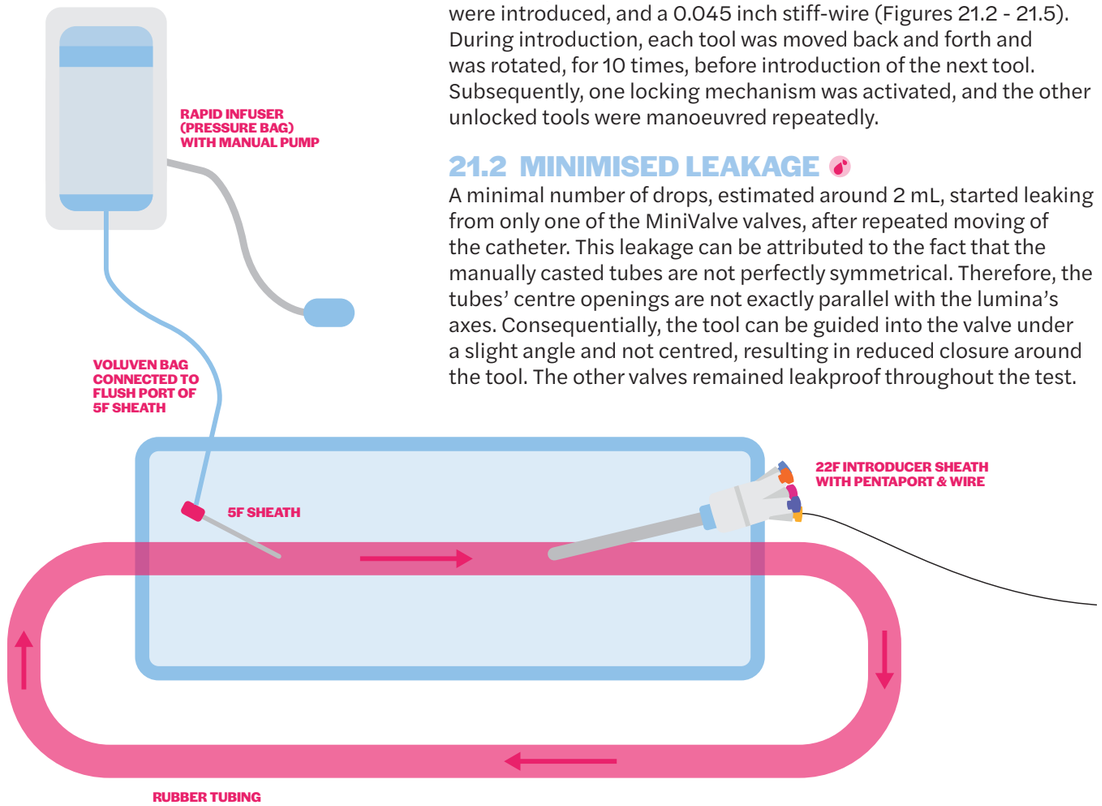


Figure 21.1 View of the device's embodiment

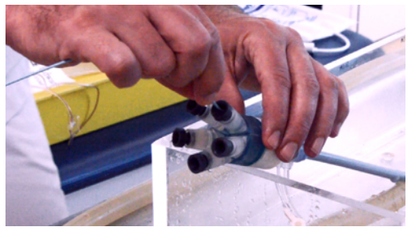


Figure 21.2 Introduction of first catheter

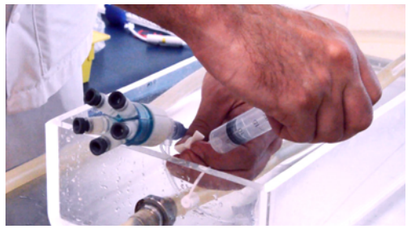


Figure 21.3 Deactivating the DrySeal's valve by drawing out fluid with syringe

21.3 SMOOTH TOOL MANOEUVRING

It was observed visually and sensed manually that the locked tool remained in position, even though some fluid had entered the locking mechanism and its elastomer tube. When pulling the tool with a relatively high manual force, slight movement of the tool was observed. This is not undesirable, as the force threshold is too high for unintended movement, but forms a fail-safe mechanism that enables removal of the tool even in locked position. It is expected that this locking functionality only improves when applying the intended TPE-material and surface texture.

The main challenge during the test was guidance of the tools, from the main body's funnel into the sheath's lumen, and especially through its original valve. This problem can be associated with the DrySeal's balloon valve, that collapses in deflated state, compromising the lumen's diameter. As the inserted catheters always search for the route with the least resistance (Van Schaik, personal communication, June 3, 2021), the collapsed valve walls in combination with the fluid pressure cause the catheter tip to buckle and move back in the opposite direction, into the main body's funnel. This makes introduction of the catheters more difficult and time consuming.

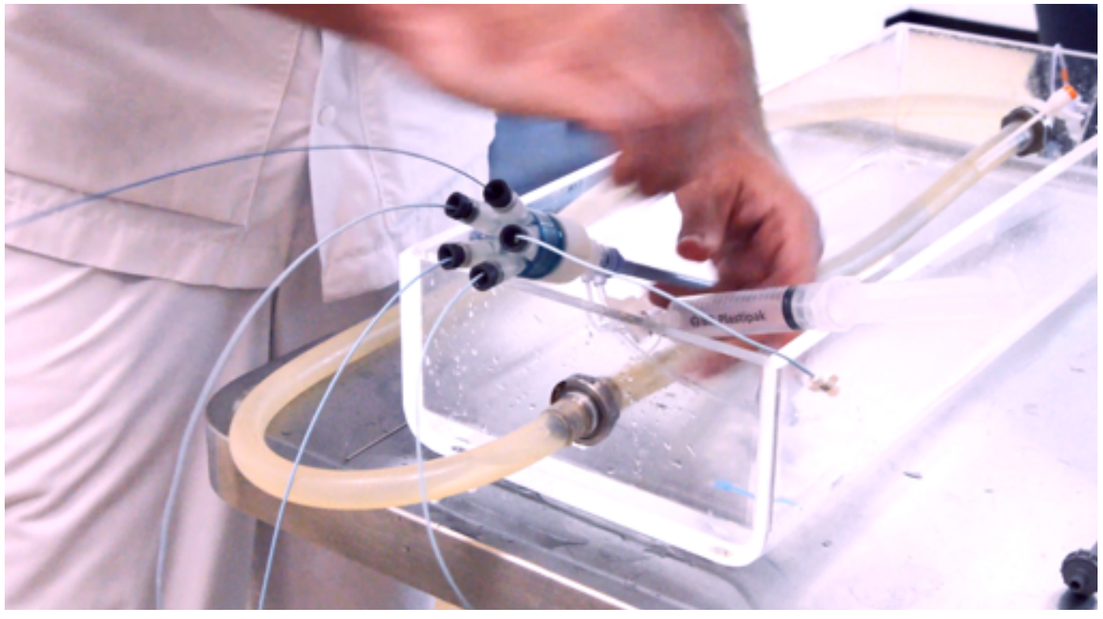


Figure 21.4 Test setup of 22F DrySeal sheath with Pentaport positioned in rubber tube, four 5F catheters and one stiff wire introduced through Pentaport into the DrySeal and rubber tube

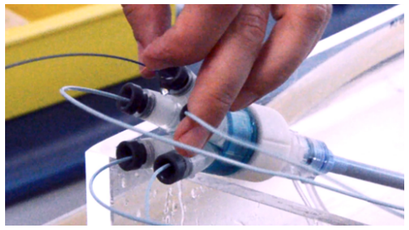


Figure 21.5 Manoeuvring of stiff wire, with visible leakage drop from valve

Figure 21.6 Manual pumping of pressure bag to build up 175 mmHg pressure

Figure 21.7 Recommended plug addition to prototype

21.4 RECOMMENDATIONS

As a possible solution, the main body's funnel could be extended into the sheath's lumen and valve. Such a funnel-shaped plug could push the DrySeal's collapsed balloon valve outwards to increase the lumen's diameter again and open the tools' way into the cannula (Figure 21.7 & 21.8). It could also eliminate the problem of the additional ridges between the sheath's hub and the add-on's TPE seal and PC main body. Such a central funnel-shaped part would also facilitate extra guidance while sliding the add-on onto the sheath and strengthen its positioning and fixation.

Such a plug was considered earlier in the process too, and the idea was turned down, because the plug's wall-thickness was expected to reduce the sheath hub lumen's diameter too much to fit all required tools. However, when reconsidering, this assumption was rejected, as the sheath hub's lumen (9 mm inner diameter) is wider than the sheath's maximum cannula size (26F = 8.7 mm inner diameter). The typically used maximum even is 24F (8.0 mm inner diameter). This leaves a small, but considerable, distance for the plug. Therefore, the frequency of use of 26F-sheaths for FEVAR surgeries should be researched to identify whether the Pentaport must be compatible with this largest size too. Besides, the design of the plug must be further detailed, as manufacturing from PC is unlikely to be possible, due to its 1.016 mm minimum injection moulding wall-thickness (Paragraph 23.3.3). Alternatively, the plug could be made similar to the cannula, for example from (reinforced) PEBAX and PTFE.

Another practical insight concerns the order of use steps. It is possible to pre-load the Pentaport with all required wires and sheaths, before connecting it to the sheath. In this way, the scrub nurse can perform the preloading step and the surgeon and IR can focus on the operative tasks as soon as the add-on is fixed to the sheath. A drawback could be reduction of the tool manoeuvring space because all tools are introduced from the start, and therewith create the chance of lying in the way. Contrary, the tools could be introduced through the sheath valve simultaneously, making introduction easier and faster. Such a change in steps, is difficult to implement, because it requires the medical team to change its procedure. Therefore, the added value must be researched extensively, to have a validated benefit and enough ground to stand on for implementation.

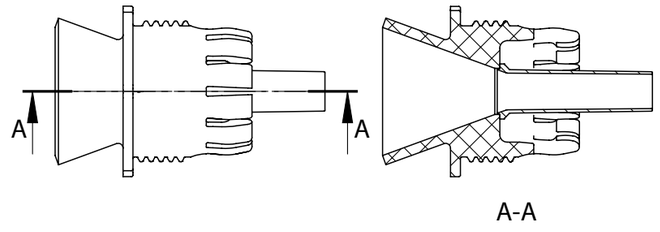


Figure 21.8 Technical drawing of recommended plug addition

22. MATERIALS

22.1 MATERIAL REQUIREMENTS

Before choosing the right materials for the device's components, the requirements for these materials must be well understood. These requirements are defined by the context of use, the type of sterilisation, the required material certification, and most importantly the part's functionality. The context of use contains aspects such as environmental temperature, experienced forces, and falling height. All requirements can be found in the List of Requirements (Chapter 10).

22.1.1 STERILISATION

As explained in Paragraph 8.5.4.2, two types of sterilisation are generally used with sheaths and comparable devices, Ethylene Oxide and Gamma Irradiation. The first is used most commonly. The advantage of both types is that they are performed at low temperatures, which is beneficial in use with most plastics typically used in (disposable) medical devices. Often, high temperatures, required for other sterilisation methods, affect the plastic's material qualities. Both sterilisation methods are performed at industrial facilities, in general, and not at hospitals, where methods such as autoclaving are more common. According to R. van der Meer, interventional radiologist at the LUMC (personal communication, March 31, 2021) "*It is not realistic to make it sterilisable in the hospital, with all the small parts and valves.*". Combination of the two suitable sterilisation types can lead to harmful interactions (AKI, 2009), therefore, one was chosen in specific.

22.1.1.1 ETHYLENE OXIDE

Ethylene Oxide (EO) has a high efficiency, destroying microorganisms and their resistant spores at a low temperature (between 25 – 55°C) and a large batch capacity (Finkiel, 2013). However, next to having an extremely long cycle (at least 14 hours), it is viewed more and more critical, because it is very dangerous to work with. It is carcinogenic, explosive and mutagenic. Finkiel: "*The use of poisonous gasses should remain limited to sterilizing products for which no alternative methods are available*". Also in The Netherlands, parties such as the RIVM declare a policy change towards a decrease in EO-sterilisation, forced by new ARBO and environmental requirements (Werkgroep Infectie Preventie, 2017).

22.1.1.2 GAMMA IRRADIATION

Gamma irradiation on the other hand, is considered significantly safer for the sterilisation workers. Currently, around 40-50% of all disposable medical products are sterilised by this method (Goronzy, 2018). It can be accurately controlled and even applied to packaged goods, ensuring that no infection occurs during packaging (Finkiel, 2016). It has no heat dependence and temperature increases are minimal during treatment (Goronzy, 2018). Besides, no end products requiring disposal are produced.

One of the main design drivers defined for this project is 'safety' that encompasses safety during use of the device, as well as safety during all other stages in the device's life cycle. Thus, with an eye on safety and future industry developments, Gamma Irradiation is chosen as the optimal sterilisation method. However, this method can damage materials that it is meant to sterilise. Therefore, the materials must be deliberately chosen for their suitability with this method (Table 22.1).

22.1.2 BIOCOMPATIBILITY

Lastly, the materials used for medical devices, like the add-on developed in this project, must be biologically evaluated and must meet the ISO 10993 biocompatibility standards (ISO 10993-1:2018 Biological evaluation of medical devices). This document applies to evaluation of materials and medical devices that are expected to have direct or indirect contact with the patient's body during intended use, based on the nature and duration of their contact with the body.

22.2 MATERIALS

All materials were chosen to meet the general requirements explained in the previous Paragraph. On top of that, the different parts ask for different material characteristics for optimal functionality. An overview of all parts with their specific requirements and chosen materials can be found in Figure 22.1.

The product has two categories of materials: thermoplastics for solid parts and elastomers for flexible parts. Relevant biocompatible materials were compared within both material categories (see Appendices R & S for a detailed comparison of (numerical) material qualities), based on data provided by CES Edupack 2019.

22.2.1 THERMOPLASTICS

22.2.1.1 ABS

ABS is a frequently used material in medical devices, because it is cheap and has good strength. Strength is especially important for the threaded parts, to ensure smooth screwing and prevent stripping of the thread. Besides, ABS can be easily injection moulded and is resistant to gamma irradiation. This is the main benefit over PP, a typical alternative, which has poor resistance to irradiation. Texture roughness can be easily added to the outer surfaces of parts requiring good manual grip, as ABS copies textures well that are pre-machined onto the injection mould's surface. Other mould surfaces can be pre-machined for a very smooth and glossy finish. This is suitable for the screw caps' inner surface, touching the bearing, which should be as smooth as possible for good rotation.

MAIN BODY

MATERIAL, PRODUCTION
PC reinforced with 20% PTFE, injection moulding

PROPERTIES
channels: high lubricity, no ridges
compression teeth: flexibility, high fracture strain, good strength
good adhesives bonding

COMPRESSION RING

MATERIAL, PRODUCTION
ABS, injection moulding

PROPERTIES
high strength, rougher texture on outer surface

DOME

MATERIAL, PRODUCTION
ABS, injection moulding

PROPERTIES
high strength, good lubricity of channels, good adhesives bonding

CONNECTOR

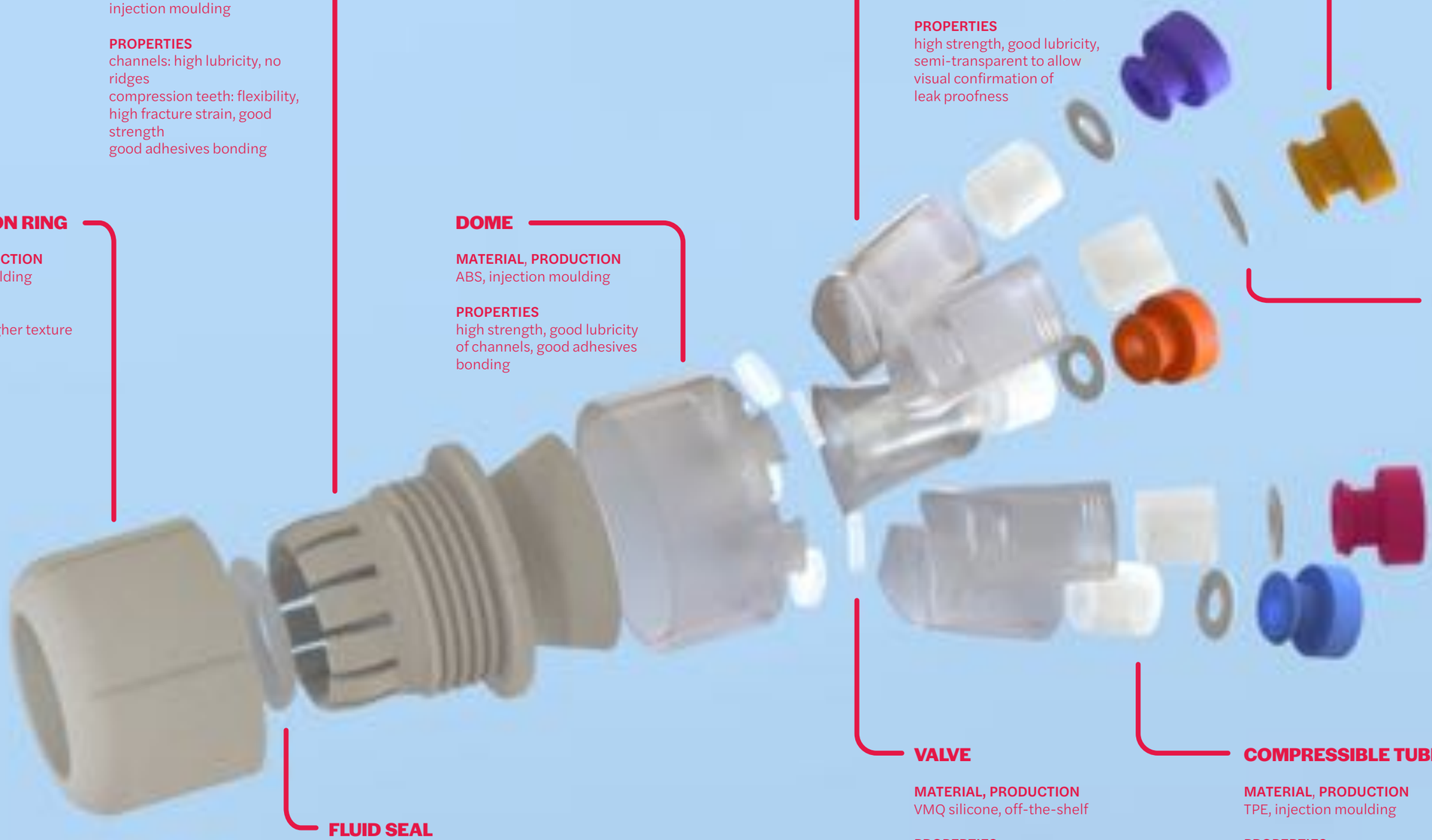
MATERIAL, PRODUCTION
ABS, injection moulding

PROPERTIES
high strength, good lubricity, semi-transparent to allow visual confirmation of leak proofness

SCREW CAP

MATERIAL, PRODUCTION
ABS, injection moulding

PROPERTIES
high strength, good lubricity, rougher texture on outer surface



BEARING

MATERIAL, PRODUCTION
Nylon, injection moulding

PROPERTIES
excellent lubricity, good surface and wear resistance

FLUID SEAL

MATERIAL, PRODUCTION
TPE, injection moulding

PROPERTIES
reasonable compression set, easy over moulding

VALVE

MATERIAL, PRODUCTION
VMQ silicone, off-the-shelf

PROPERTIES
high elasticity, high tear resistancy, high lubricity (low surface friction), good compression set (moving back into original shape after deformation)

COMPRESSIBLE TUBE

MATERIAL, PRODUCTION
TPE, injection moulding

PROPERTIES
high tear resistancy, high elasticity, high surface friction on inner lumen (when compressed), good compression set

Figure 22.1 Exploded view showing parts, materials, production methods, and specific properties

22.2.1.2 PA (NYLON)

The ring-shaped bearing should be as smooth as possible to ensure minimal friction and optimal lubricity during rotation. Therefore, Nylon is ideal for this application, as it provides a very smooth surface and good resistance to surface wear due to the rotational movement. Besides, it is relatively cheap and is suitable for injection moulding too. The only disadvantage is that biocompatible versions of Nylon are relatively costly. According to André Kramer, director at the injection moulding company Medanco (personal communication, May 4, 2021) these can rise up to €30 per kg. This is not a problem with the bearing, a very small part, but can lead to significantly higher costs when applied to larger parts.

22.2.1.3 PC (REINFORCED WITH PTFE)

The main body requires a material that is flexible, strong and lubricous. The compression teeth must be able to deform, outwards when snapping onto the sheath's hub and inwards when being compressed for fixation by the ring. Thus, they must have a high elasticity (Young's modulus) and withstand a relatively high compression before breaking. These qualities can be found in PA and PC, where the latter scores higher.
At the same time, the threaded part must be strong to prevent stripping, requiring a good Yield strength and enough hardness. Both PA and PC have a suitable Yield strength, however, PC has a higher hardness.
Lastly, the channels in the main body must have a lubricous surface, without any ridges, to ensure smooth tool movements and prevent blood coagulation. As explained above, Nylon is well applicable for such surfaces. However, PC can be reinforced with a 10-30% PTFE-percentage, to achieve a good lubricity. This is a more cost-effective way compared to applying relatively expensive medical-grade PA. Also, it eliminates the need for an additional PTFE-coating, as can be found on the surfaces of existing sheaths.
The choice for PC for this application and its suitability for the compression teeth was underlined by André Kramer, director at the injection moulding company Medanco (personal communication, May 4, 2021).

22.2.2 ELASTOMERS

22.2.2.1 VMQ (MEDICAL) SILICONE

The valve is designed to be a part provided by MiniValve, a Dutch valve manufacturer and one of the global market leaders. Their experience showed that VMQ Silicone is the most suitable material for valves in medical applications, such as catheters, as explained by Jan-Willem Nijland, Application Engineer at MiniValve (personal communication, April 23, 2021). These silicones pass ISO 10993 biocompatibility tests.
Main advantage is their low compression set (5-10% at room temperature), ensuring that the valve moves back well into its original position after deformation. Besides, Nijland emphasized that silicone is well suitable for gamma irradiation as well.

22.2.2.2 TPE (THERMOPLASTIC ELASTOMER)

TPEs (Thermoplastic Elastomers) are increasingly seen as alternatives for silicone, also in fluid seals of medical applications (Enplas Life Tech, 2020), as it is also available meeting the ISO 10993 standard. However, according to Nijland, for the valve it is not suitable, because the forces by the tool are too high, resulting in loss of strain and stretch.

On the other hand, a TPE such as SEBS could be suitable for the product-specific parts: the compressible tube in the locking mechanism and the fluid seal between the main body and the sheath's hub. The main advantage of TPE is that it can be injection moulded by simpler, automated methods and for smaller production volumes, in contrast to silicone (Enplas Life Tech, 2020). LSR (Liquid Silicone Rubber) moulding is only cost-effective for large production volumes. On top, the same moulds can be used for both TPE and hard thermoplastics, making 2K-injection moulding possible into the PC main body, explained Kramer. Additionally, the intended surface structure and texture, desired for the inner surface of the tube, can be achieved by applying these to the mould's surface.
Kramer also states that silicone moulding would lead to more post-production steps, such as de-skinning and post-curing.
Also, the material itself is less than half the price of medical silicones (CES Edupack, 2019).

An ideal hardness for the two applications would be a Shore A value between 60 and 70, which is typical for TPEs. Although it has a higher compression set than medical silicone, it is enough for these applications: the fluid seal does not require frequent spring-back, and the locking mechanism has less tight tolerances compared to the valve.

MATERIAL	STABILITY	INDICATION OF MAX. DOSE (KGY)	COMMENTS
Polyester TPE (thermoplastic elastomer)	+++		
Silicone rubber	++/+++	50 to 100	Usually polydimethylsiloxanes-methyl phenylsilicone more stable.
PC (polycarbonate)	+/++	1000	May become brittle at > 50 kGy. (Reversable) coloration possible.
ABS (acrylonitrile butadiene styrene)	+++	1000	Yellowing possible. Small increase tensile strength.
PA (polyamide) "Nylon 6"	+++		Hardens at high doses (1000 kGy). Much less stable as film (aircontact).

Table 22.1 Effect of gamma irradiation on chosen materials, provided by Steris (2021).

23. PRODUCTION

23.1 MANUFACTURING PROCESSES

Also during production of the device, maximum safety is a central theme. Often, products for the medical industry are produced in cleanroom facilities under normalised conditions (Promolding, 2018). Three ISO norms are relevant here: ISO 9001, ISO 13485, and ISO 14644. These define required quality management systems, specifically for medical devices, and cleanroom standards. When choosing manufacturing processes and facilities, it is of high importance that they meet these ISO norms. This forms a guarantee for safe production.

23.1.1 POSSIBLE PROCESSES

Three different manufacturing processes are interesting to consider for the production of the add-on: injection moulding, 3D-printing, and printed injection mould (PRIM). Their typical applications and batch size, based on the processes offered by Promolding (n.d.), can be found in Figure 23.1.

23.1.1.1 INJECTION MOULDING

Injection moulding is the process most commonly applied to produce single use medical products with strict requirements. In the book 'Manufacturing for Design', Tempelman et al. (2014) explain that this manufacturing process' high production speed, form freedom, potential for functional integration, and surface quality (eliminating the need for post-processing) make it ideal and frequently used for this application. The materials chosen for the device's main parts, ABS, PA and PC, are thermoplastic polymers and hence perfectly suited for injection moulding. sHowever, the process has a strong interdependence of function, cost, and quality, which depend on the product's size, complexity, the desired accuracy, as well as the number of units to be produced (Tempelman et al., 2014). According to Kramer (personal communication, May 4, 2021), injection moulding starts becoming viable at a minimum batch size of 5000 parts. As the total number of add-on units to be produced annually, especially in the beginning, is relatively low (Paragraph 24.5.1), the question arises whether a more cost-effective alternative exists.

23.1.1.2 3D-PRINTING

An upcoming process, gaining acceptance also in the medical industry, is 3D-printing (Thomassen, personal communication, April 30, 2021). Its main advantages are that it allows more complex shapes to be made and is especially viable for small series, as production cycles are relatively long, but set-up costs are low. However, starting with a 3D-printed design and switching to an injection moulded version to serve a larger market in the future, would require a significant change of design, consequentially requiring new medical certification of the product. Besides, parts require considerable finishing to smoothen surfaces, and material qualities are lower. For example, porosity is higher, reducing strength, structural quality, and material homogeneity.
The crux is, explains Thomassen, that you have to guarantee that the product is clean after printing, either sterility must be maintained during all process steps or once at the end by a sterilisation method. Oftentimes, 3D-printing resins are less resistant to sterilisation too.

23.1.1.3 PRIM (PRINTED INJECTION MOULD)

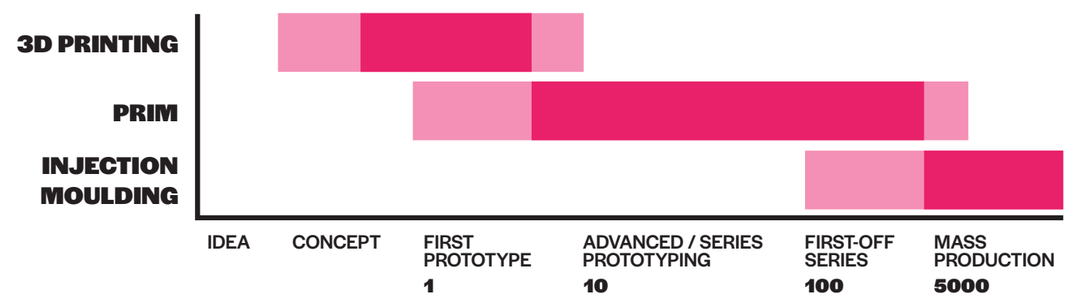
PRIM is found to be the ideal middle course. Besides forming a suitable method for high level validation of the design during further product development, it is also a serious manufacturing process for low-cost injection moulding of small series (Promolding, n.d.). It has a short lead-time compared with regular injection moulding, and still is compatible with the chosen materials. Even 2K-injection moulding with PC-TPE is possible. Lastly, future upscaling to regular injection moulding, is a logical step and does not require significant design alterations.

23.1.2 TOOLING INVESTMENTS AND PROCESS CHOICE

The different manufacturing methods are suitable for different series sizes and ask for different tooling investments. In the nearer future, during the phase of further design development, it is recommended to stick to PRIM. Its main benefits are the flexibility and low tooling investment costs it offers to optimise the design for production and perform relatively small production test runs. This method offers two types of moulds. Plastic moulds for first production tests, enabling manufacturing of a maximum of 100 parts before the mould is damaged, according to Gross, PRIM-expert at Promolding (personal communication, May 10, 2021). Whereas metal moulds enable a maximum series of 1000 to 1500 parts.

The main disadvantage of PRIM is that the economy of scale is minimal. He states that above a series of 200 parts, the price per part lies around €10 and does not sink anymore, because a relatively high degree of manual labor is required. Therefore, the switch to regular injection moulding should be made as soon as a medical market party is involved and can provide larger tooling investments. These medical market parties have global reach and certification experience, and they can sell the Pentaport in combination with their large-bore introducer sheaths. Thus, it is realistic to expect annual sales numbers to rise above 5000, the viable minimum of regular injection moulding (Promolding, n.d.), enabling part manufacturing costs to drop below €1. Besides, they already have ongoing collaborations with injection moulding facilities. Suitable moments and forms of collaboration with medical market parties is further elaborated in Paragraph 24.5 and Chapter 27.

Figure 23.1 Typical application & (minimum) batch size of relevant production methods, as defined by Promolding (n.d.)



23.1.3 DESIGN FOR PRIM INJECTION MOULDING

This Paragraph describes the design for manufacturing of the device's main parts. Form details that complicate manufacturing are connections such as the threaded parts and snap-fits, and cavities, such as the lumina. Their integration and optimisation for injection moulding are elaborated more extensively.

In general, the designs of all parts to be injection moulded adhere with the following design details, based on design for manufacturing tips by Protolabs (n.d.), 3D Systems (2021), and 3D Hubs (n.d.):

- Draft angles are 1 degree or greater to assure easy part ejection, the draft angle is increased by one degree for every 25 mm,
- Wall thicknesses are as consistent as possible,
- Wall thicknesses lie between:
    - 1.014 and 3.556 mm, the recommended range for ABS,
    - 0.726 and 2.921 mm, the recommended range for PA,
    - 1.016 and 3.810 mm, the recommended range for PC,
- Corners are rounded where possible,
- The number of mould parts and their design complexity are kept to a minimum.

Texture and finishing of the parts are important for a professional and trustworthy appearance, as well as functional reasons. For example, the screw caps should smoothly rotate over the bearings and the main part should have a higher surface roughness (Ra) to prevent slipping form the user's hand.
In general, texture and finishing of injection moulded parts is achieved through mould finishes, instead of post-processing (3D Hubs, n.d.). Especially, if mould ejection pins can be placed on not visible (inside) parts of the product. The desired surface finishes are:

- Glossy finish for the bearing and inner surface of the screw cap, for minimum friction during rotation, as a Ra (surface roughness) below 0.10 µm can be achieved (3D Hubs, n.d.).
- Textured finish for the 'grip' surfaces, being the outer surfaces of the compression ring, main body and screw caps. These parts have a 1-degree addition to their required draft angle for good ejection (3D Hubs, n.d.).
- All other parts have low appearance requirements, thus do not require a special mould finish.

23.1.3.1 THREADED PARTS

When designing threaded plastic parts, it is critical to carefully design the thread size and pitch, as wear or even 'breaking' occurs more easily than with metal threads, called stripping. Stripping causes severe impair of the thread's strength and can occur due to overtightening or rotating with little care, too fast, or angled (Boltcalc, n.d.). To prevent stripping, metal thread inserts are sometimes applied over plastic parts. However, this is not considered necessary for this application, because the forces working on the thread are relatively low compared to typical metal thread applications.

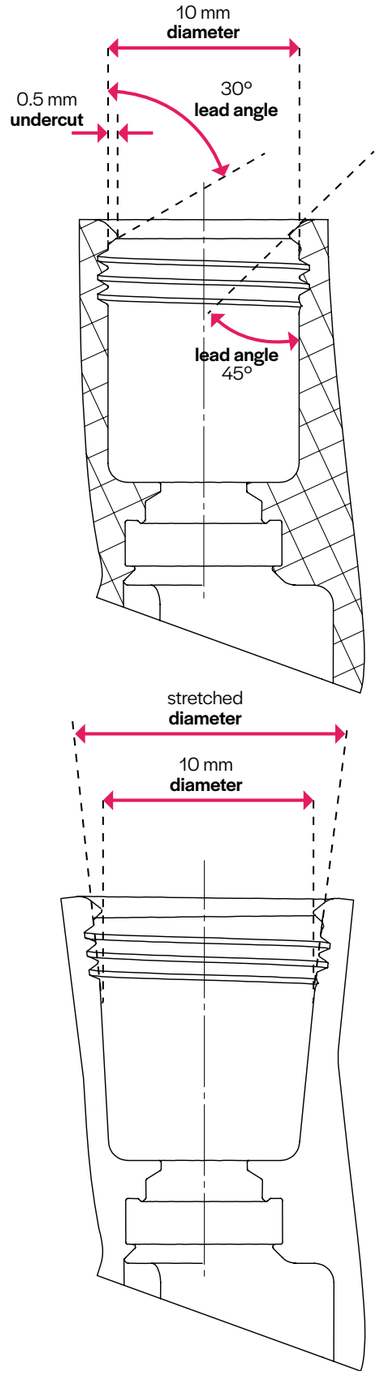


Figure 23.2 Schematic representation of connector in normal position (top) and during ejection (bottom)

A sufficient solution is to use optimal thread dimensions, instead of the standard (metal) 60-degree V-style thread. The diameter of an internal thread should be no smaller than 7.6 mm and use the coarsest pitch possible (Protolabs, n.d.). Thus, even the smallest internal thread, inside the locking mechanism's connector, has a diameter of 10 mm.

Threads on the injection moulded parts can be made by two methods, either machining them into the injection moulded part or directly moulding them with the part.
Other methods, such as self-tapping screws, are no suitable option, because repeated (un)screwing is required, and it creates the risk of crooked tapping.

The main advantage of machining over moulding the thread, is the use of simpler, thus cheaper moulds for the injection moulding process (Protolabs, n.d.). Also, the thread's design can be more easily adjusted later on, after creating the moulds. However, it does require an extra step in the manufacturing process, costing time and money. Still, on smaller quantities this can be the more cost-effective method.

In comparison, moulded threads are ubiquitous, think of plastic bottles. In the case of external threads, the mould's parting line is generally placed lengthwise down the centre of the thread, so the moulds can move outward after curing, away from the thread, without damaging it.
As the thread 'halves' are milled into each mould during mould production, the thread will have a minimal undercut of 10 degrees at both sides of the parting line, due to the way the mill moves into the cavity. These undercuts can be prevented by using side-actions (additional mould parts sliding in from the sides). But this drives up tool complexity and, therefore, tool costs. As the undercuts are hardly noticeable, especially on small threads, it is recommended to stick with a two-part mould for creating the threads.
This thread-moulding technique is applied for the threads in the compression fixation and the locking mechanism.

23.1.3.2 STRIPPING UNDERCUTS

Another feature requiring some additional thought, is the compression connection to the sheath hub, due to its individual, converging teeth. These can be made by use of stripping undercuts, also called bumpoffs. The teeth are designed to be flexible enough to bend outwards over the mould during ejection. This principle can also be used to manufacture the thread in the compression ring, as it is frequently applied for bottlecaps as well. Also, the snap-fitting connector with its internal thread (Figure 23.2), and the screw cap with the external thread, can be ejected as stripping undercuts.

The bumpoffs in the compression connection parts are designed, following the conditions defined by 3D Hubs (n.d.):
- The stripping undercuts are located at the outer ends of the part, away from corners, ribs, and other stiffening features.
- The undercuts have lead angles between 30° to 45° (see an example in Figure 23.2).
- The parts have space and are flexible enough to expand and deform around the internal mould part, after the removal of other parts.
- PC is a flexible plastic, and very suitable for this application. PC can tolerate undercuts of up to 5% of its diameter.

The triangular-shaped cavities, separating the compressible teeth, can be made with embossed shapes on the mould. When pulling the central mould part out, after removing the other mould parts, the teeth bend outwards, opening up the triangular cavities at the top, and making way for the embossed parts to move outwards with the mould. Thus, the same bumpoff principle is applied for creating these cavities.

Similar to the undercut features, the bearings are positioned in the screw caps by snap-fits, called built-in latching mechanisms (Bonenberger, 2005). Their main benefits are the ease of assembly, tolerance robustness to dimensional variation, and strength integrity (Altair University, 2013).
Both the screw caps and bearings are rotationally symmetric; therefore, annular snap-fits are the most suitable (Bayer MaterialScience, n.d.). This joint is designed to be difficult to disassemble (without the correct tools), to minimise risks of reduced functionality or unintended disassembly of the locking mechanism. This is determined by the chosen dimension of the undercut and its return angle.
It is not designed to be completely inseparable, because this requires more complex tooling (a split cavity mould) and eliminates the possibility to disassemble parts for reuse or recycling.

23.1.3.3 THE LUMINA

The highest production criticality arises with the lumina. The initial design incorporated curved lumina (Figure 23.3), intended to guide the tools straight into the sheath's main, central entrance. The curved wall would 'push' the tool into the direction that is co-linear with the sheath's lumen. This could prevent the tools from obstructing each other's way in the cannula.

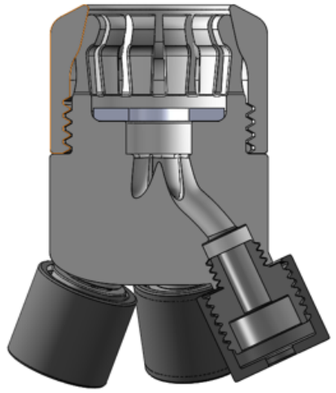


Figure 23.3 Initial design of curved lumina

While 3D-printing, which was used for prototyping and evaluating, is ideal to make such complex internal cavities, this is hardly possible by injection moulding. At least without making the moulds unnecessarily costly. Expensive moulds with cam-guided side-actions and collapsible cores could be applied, using separate moveable inserts to create the lumina cavities. Such complexity might be viable for high production numbers but exceeds the scope of this device. Therefore, the lumen-shape is simplified to a straight channel for easier injection moulding (Figure 23.8). The difference in ease of tool introduction between the curved and straight channel was tested and was found to be minimal (Paragraph 21.3), thus the simplified design does not lead to significant decrease of user-experience.

Other methods were considered too, such as gas-assist injection moulding, creating the cavities by inflating them with gas while the liquid plastic material is injected, and (CNC) milling of the lumen. However, the first is a relatively specialised technique, more applicable to straight, tube-like cavities and, therefore, not very suitable and too costly for this product. The latter adds machining, a lengthy post-processing step, to the manufacturing process, requires use of more material, and the typical milling depth to width ratio 6:1 forms a restriction for the lumen's shape too.

23.1.4 PRINTED INJECTION MOULDS

The design considerations explained in the previous Paragraphs were taken into account when creating a preliminary approximation of the mould designs. It should be noted that in general mould design is performed in tight collaboration with the manufacturing party, and mostly a bit later in the development process. However, it was decided to start thinking about mould design, because it confirms whether the product can actually be made, and it is a practical way to rethink the design. Experts were interviewed, and their practical experience was integrated to optimise the design for injection moulding:
- Erik Thomassen, expert on materials and manufacturing for design (April 30, 2021),
- André Kramer, Director at Medanco (May 4, 2021),
- Bastiaan Meulblok, Manager Operations at Promolding (May 5, 2021),
- Jeroen Gross, Business Unit Manager P3D (PRIM) at Promolding (May 10, 2021).

Visualisations of the mould design approximations can be seen in Figures 23.4 – 23.8, with the arrows indicating the mould release directions.

In general, wall-thicknesses of all parts are kept thin and hollow cavities are created to minimise infill, compared to the original 3D-printed prototypes. This reduces weight and material costs.

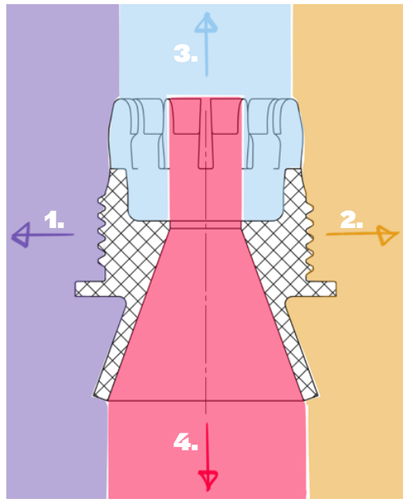


Figure 23.8 Schematic of possible mould for the main body

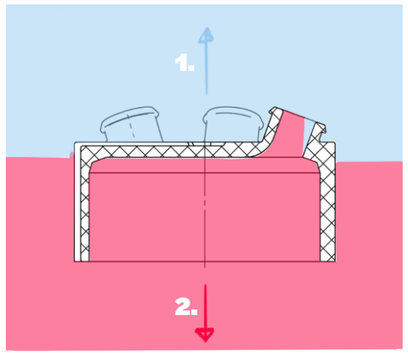


Figure 23.7 Schematic of possible mould for the dome

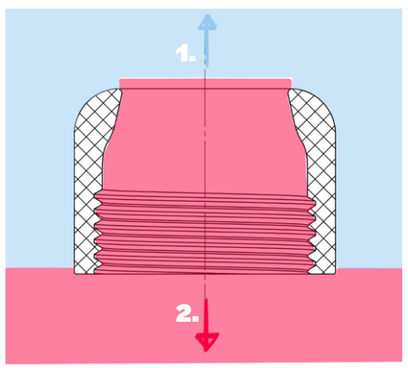


Figure 23.6 Schematic of possible mould for the compression ring

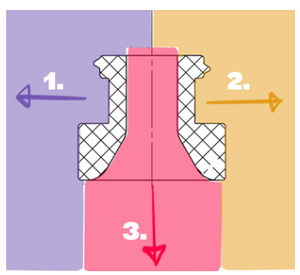


Figure 23.5 Schematic of possible mould for the screw cap

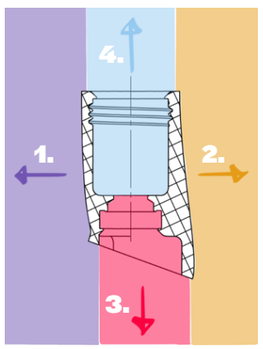


Figure 23.4 Schematic of possible mould for the connector

The main body part was the most problematic when optimising, due to the lumina, as explained in Paragraph 23.3.3.3. These were simplified to a funnel-shaped, central hollow cavity. However, the funnel's walls are positioned under a too large angle to enable ejection of a core mould and a collapsible core is expensive.

A different approach was chosen, to keep mould costs to a minimum. The core can be ejected to the other side if the funnel's wide, top side is open. Therefore, the main body is separated into the 'funnel shape' and 'dome shape'. The first is joined to create one part with the compression teeth component. This choice does lead to an extra surface to be joined (between the funnel and dome) and requires a fourth mould part. However, it simultaneously forms an opportunity for 2K-injection moulding of the TPE fluid seal directly into the PC part. This fourth, central mould part (Figure 23.8) can be left in place, so the TPE can be injected around it. Also, the separate TPE-tube for the locking mechanism, can be injection moulded with a simple two-part mould.

Finally, all mould approximations were validated with Gross (personal communication, May 10, 2021), the PRIM expert of Promolding P3D. Thus, it can be concluded that the device has a realistic, manufacturable design.

23.2 DESIGN FOR ASSEMBLY

The parts, manufactured with the processes and moulds detailed in the previous section, have to be assembled into a complete product next. An overview of the complete assembly process can be found Figure 23.9.

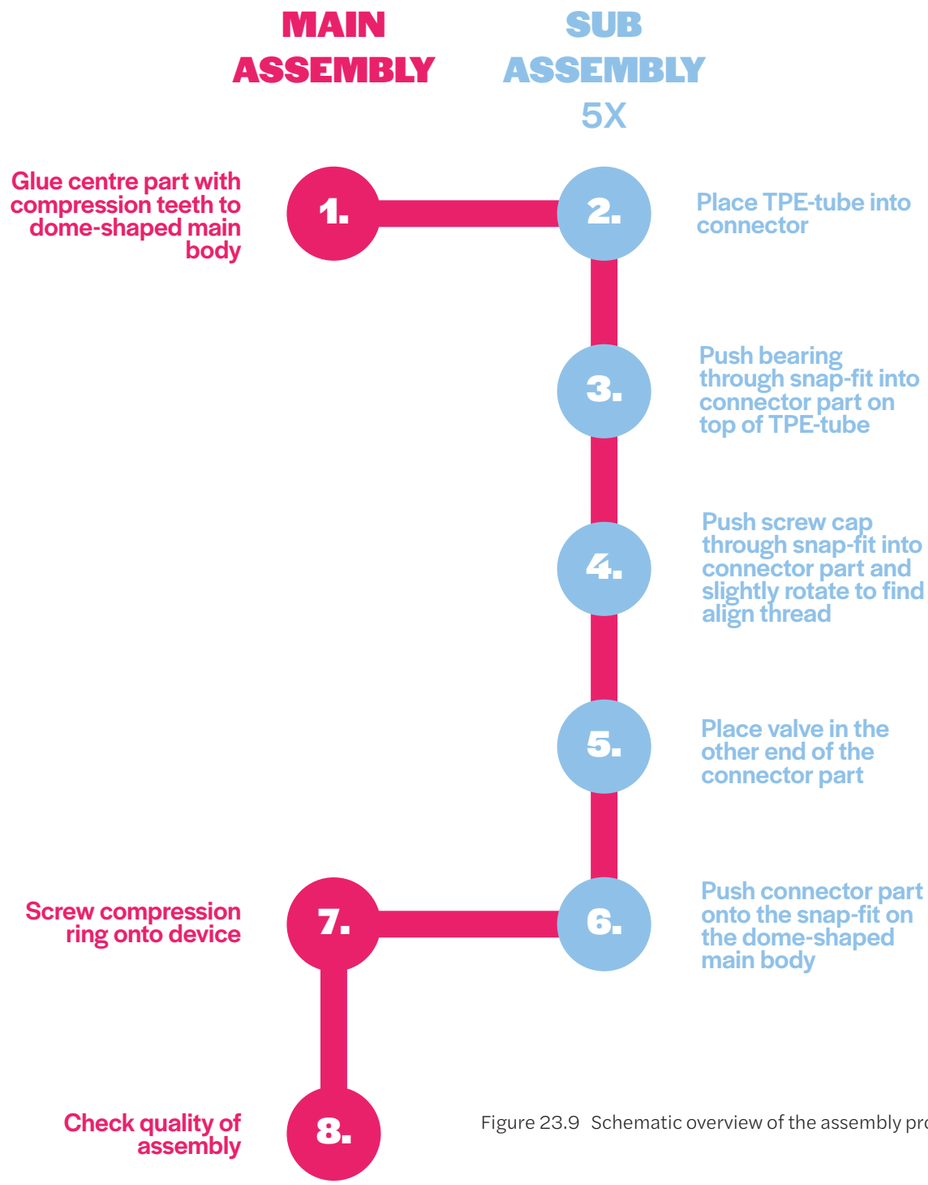


Figure 23.9 Schematic overview of the assembly process

23.2.1 MECHANICAL CONNECTIONS

A few connections are straight-forward, mechanical connections: the screw-connection of the compression ring to the central part, and the snap-fits joining the bearing and screw cap to the connector part and, subsequently, joining this whole unit to the dome. These mechanical connections are efficient during assembly and do not require any additional tools or adhesives. At the same time, these are used to hold the TPU-tubes in place and clamp the valves. Slight compression of the valves ensures that no leakage can occur around their edges. The right degree of compression is achieved, by applying the dimensions recommended by MiniValve for the cavity in which the valve is placed (Appendix T).

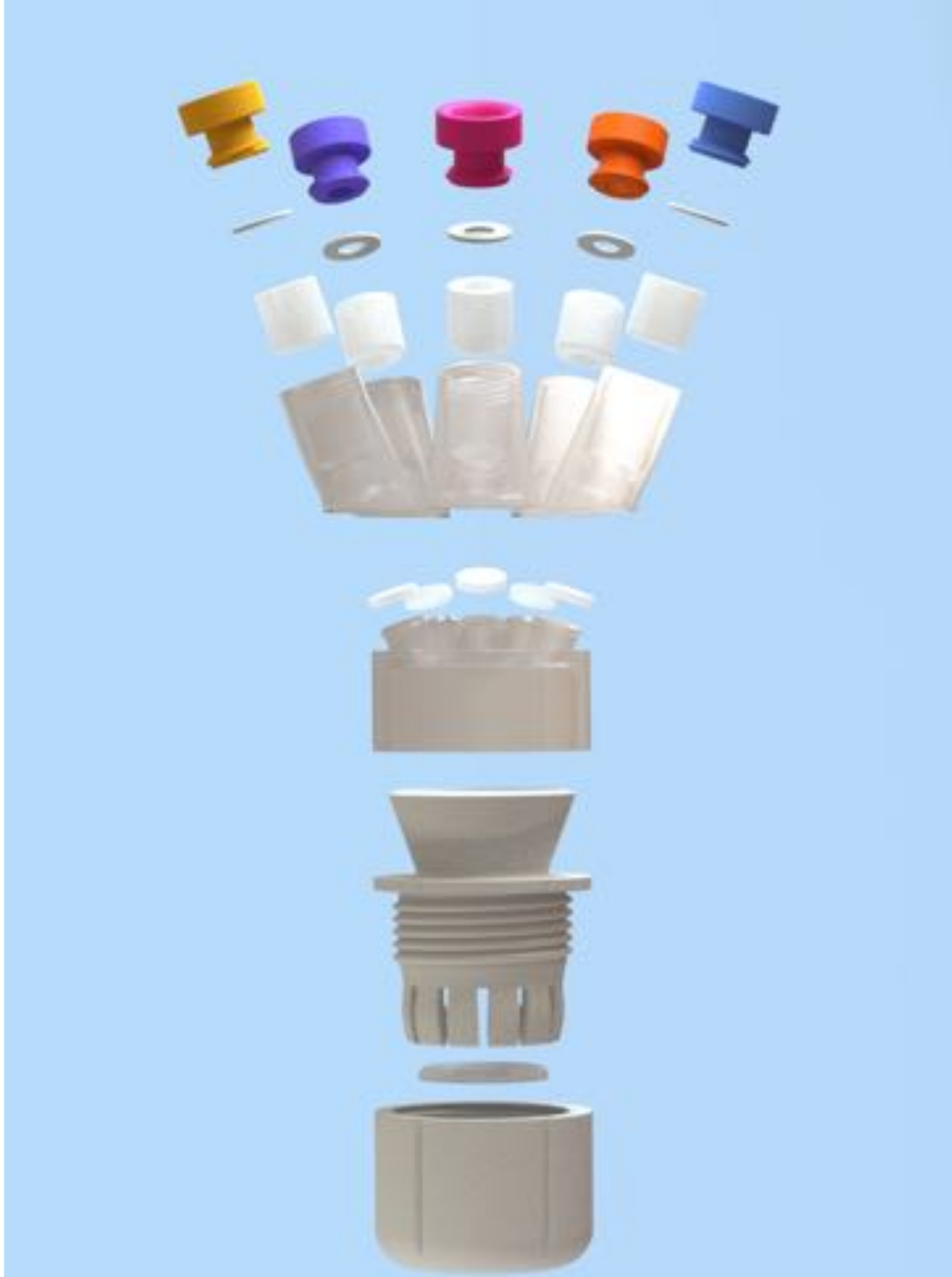
23.2.2 BONDING CONNECTIONS

A more complicated assembly method is needed for joining the centre compression teeth part and the main body's dome. Two suitable methods are considered: ultrasonic welding and gluing. Both are frequently found in comparable medical devices. Ultrasonic welding is a very neat and aesthetic method providing good material qualities around the joining line. On the other hand, it is mainly cost-effective for large series, because product specific tooling has to be made (Kramer, personal communication, May 4, 2021). In comparison, Kramer explains that gluing is the more realistic solution, as it is suitable for smaller series too and well applicable for PC. Again, the choice for PC above PP is validated here, as PP is more difficult to bond by adhesives. PC is especially well suited for solvent bonding, which is the least expensive joining method for permanent bonds and leads to aesthetical smooth, blemish free surfaces (CES Edupack, 2019). For example, many medical stopcocks are bonded this way.

23.2.3 DESIGN FOR DISASSEMBLY

Finally, the device is designed for disassembly as well. The snap-fits are designed to allow disconnection with appropriate tools by trained people (as explained in Paragraph 23.3.3.2). This makes the latter two methods of waste reduction possible, based on the 3R principle for sustainability: Reduce, Reuse, Recycle, as explained by Else de Ridder (personal communication, April 12, 2021). The positive impact on sustainability rises from right to left.
By enabling disassembly, solid thermoplastic parts can be separated into the different materials and reused, after resterilisation and inspection of material and structural quality. Reusing the elastomer parts (silicone and TPE) is not possible, due to significant material deterioration after repeated sterilisation. Especially, characteristics such as compression set decrease, which is undesired. However, as the valve and TPE-tube are separate parts, they can be easily replaced.

If refurbishing a part is not possible, because quality assurance is not met, the material itself can be recycled. Especially thermoplastics (thus ABS, PA, PC and TPE) are well suited for re-granulating, re-melting, and a second injection moulding cycle.



VIABILITY

PART 7

This chapter presents the add-on’s value proposition, encorporating the current market size and future growth, the product’s cost price, and its added value seen from a broader perspective.

24. QUADRUPLE AIM PROFITABILITY

The previous Chapters illustrated that the new product design would add value to its users and that it can be made to function as intended: it is desirable and feasible. Still, it must be viable to stay afloat in the difficult medical market. Viability can be explained as a profitable solution, with a sustainable business model for all stakeholders (Figure 24.1). This does not only mean that device sales should be financially profitable for the supplier, regarding current and future market size, the cost price and the marketable price of the device. Besides profits, sustainability incorporates the people and planet too.

The device should be viewed in its whole context and contribute to the complete Quadruple Aim, as explained in Paragraph 6.2. It should be a profitable, sustainable solution according to all four pillars and its main stakeholders. A more complete picture of the device's value can be viewed by zooming out from the device to the procedure, the hospital stay, the patient's life and society in general.

24.1 PATIENT

Patient satisfaction and improved clinical outcomes are relevant for the patient. Most importantly, the patient's post-surgery condition is improved by using the Pentaport. The decrease of blood loss during the procedure, eliminating the need for blood transfusion and/or cell saving, and the shortened procedure time, reduces the negative impact on the patient's body. Besides, prevention of unintended tool movements and additional recatheterisation efforts reduces the risk of harm to the patient's arteries. An improved patient condition requires a shorter stay on the costly Intensive Care and in the hospital overall. It can be assumed that the patient's recovery and rehabilitation period become shorter too, and the patient can return to 'daily' life faster. In this way, healthcare costs can be saved, as well as societal costs due to rehabilitation and sick leave. Although, the last will be relatively insignificant, as most patients are of higher age.

24.2 MEDICAL STAFF

The medical staff aims for the best possible clinical outcomes, thus the improved post-surgery patient condition. While achieving this, their experience, the 'provider satisfaction', is of importance too, as well as the operational efficiency in small extent.
The Pentaport improves the medical staff's experience by facilitating better handling and improved visibility, due to a less blood-covered workspace and fixation of the tools. The sterile team can remain more focused on the operating tasks, instead of being distracted by severe blood loss and unintendedly dislocating tools, resulting in better technical execution of the procedure. Also, when the vascular surgeon and IR switch roles and position at the operating table, the tools remain safely in their place.

The coded entrances improve communication within the medical team, as the colours are well visible, also for staff standing on a distance from the operating table, and the team can keep track of which tool is positioned in which artery.

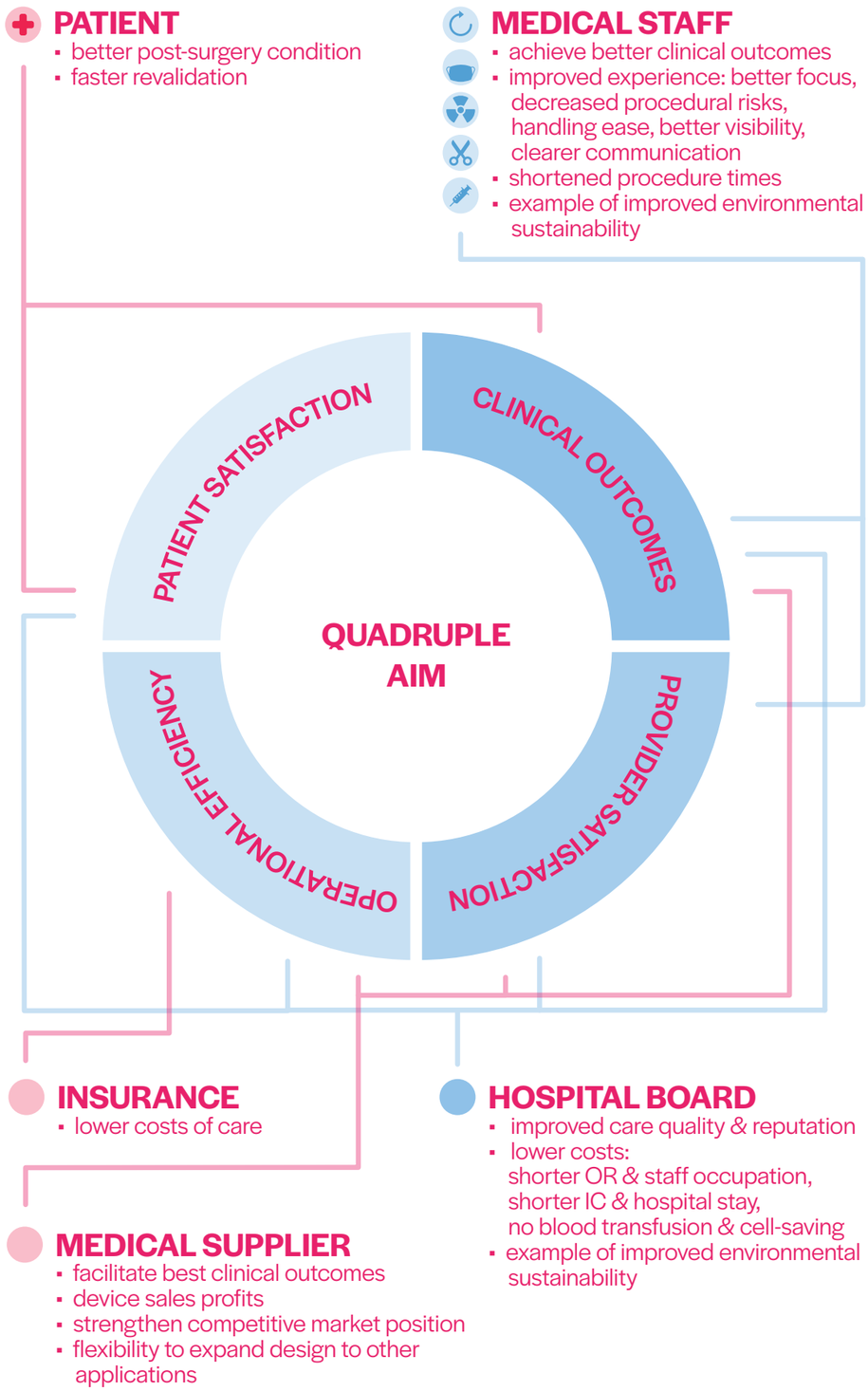


Figure 24.1 The gains per stakeholder based on the Quadruple Aim theory

By reducing the possibility of tool dislocation and consequential recatheterisation, also operating times can be decreased by minutes or even hours. Additionally, cleaning efforts and times are notably decreased when less blood is spilt, as blood remnants are sticky and can be difficult to remove from the floor and (ridges in) medical equipment. Even the chance of endoleaks (due to incorrect positioning or insufficient fastening of the stent graft) can decrease, due to better focus and communication of the team. These leaks can occur during and after surgery, requiring stent graft repositioning during the same or even a second procedure.

24.3 HOSPITAL BOARD

Forming the centre of care provision, all quadruple aim pillars come together in the hospital. By improving the clinical outcomes, the Pentaport strengthens the hospital's quality and reputation, as well as the patient's satisfaction about the procedure and shortened hospital stay. Besides the aspects explained in the previous Paragraph, environmental sustainability receives growing attention by hospital boards, as well as staff members. Next to moral and reputational incentives, this also contributes to patient and provider satisfaction, as it is a hot topic for society in general. The Pentaport has an improved life-cycle compared to existing sheaths and similar single-use, disposable devices, which is further elaborated in Chapter 26.

The hospital board, via the procurement department, has the final decision to invest in using the Pentaport. For the board, the main gain of this investment lies in the improved operational efficiency regarding time and costs. Table 24.1 presents an overview of the costs factors that can be reduced. All costs are based on current prices in Dutch academic medical centres. These are used to estimate the maximum possible financial savings per patient, besides the most important and unmeasurable improved health outcomes for the patient. It should be noted that the savings will differ per patient, depending among others on the reduction of blood lost during the surgery, compared to the situation without the Pentaport.

Table 24.1 Rough cost savings estimation based on Dutch national academic medical centre data

COST FACTOR	UNITS SAVED/ PATIENT	COSTS/ UNIT (€)	MEDIUM SAVINGS PER PATIENT (€)	MAX. SAVINGS PER PATIENT (€)	NOTE
Packed cell bag	1 - 7	410	1400	2800	Volume per bag is 300 mL
Thrombocyte concentrate	2	520	0	1040	Volume per bag is 300 mL
Cell saving disposables	1	150	150	150	Excluding equipment depreciation costs
OR occupation per hour	1	1000	500	1000	Excluding additional cleaning costs
Day on Intensive Care	2	2600	2600	5200	
Day on general ward	2	900	900	1800	
Total			**5,550**	**11,990**	

Most directly, the number of required packed cell bags depends on the volume of blood lost and savings can range from 1 to 7 bags, to compensate for a 2L blood loss. In few cases, roughly between every fifth and tenth patient (Van Schaik, personal communication, June 15, 2021), even thrombocyte concentrate bags are required. In other cases, cell-saving is needed, requiring numerous disposables leading to combined costs of €150 per patient. Thus, reducing or even eliminating the need for expensive blood transfusion and/ or cell saving equipment can save around €500 up to a maximum of €3990 per patient. Additionally, shortening occupation of the OR and the medical staff by up to 60 minutes per patient, results in savings of over €1000 per hour. Lastly, patients with a better post-surgery condition require shorter stays on the costly Intensive Care and in the hospital overall. Assuming that a maximum of two days can be prevented on both the IC and a general hospital ward, saves another €7000.

In conclusion, a maximum cost reduction of almost €12,000 can be achieved per patient for the hospital board by investing €300 in procurement of the Pentaport. In practice, it is expected that the savings will mostly lie below the maximum. Therefore, 'medium' savings per patient are calculated too, based on halved units per patient, and no need for thrombocyte concentration. As a result, around €5,550 can be saved per patient. However, the maximum reduction forms a relevant indication of the savings' possible scale.

24.4 INSURANCE

The main role of insurance companies is to finance the costs of care. Therefore, their profit results from the overall reduction of FEVAR treatment costs per patient. Looking at the total number of FEVAR procedures in the Netherlands, currently a maximum 150 per year, up to €180,000 of national healthcare costs can be saved annually, while investing €45,000 in Pentaport devices, resulting in a €135,000 reduction of healthcare costs. As FEVAR execution is growing, these savings will rise as well in the future. Besides, insurances benefit from lower post-surgery endoleak prevalence, and by that a lower number of follow-up procedures and corresponding costs.

24.5 MEDICAL SUPPLIER

At last, medical suppliers, such as W. L. Gore and Cook Medical Inc., aim to facilitate the best clinical outcomes with the devices they supply, while selling them with a profitable margin. Next to being a profitable product, integration of the Pentaport in the supplier's product portfolio can strengthen the company's competitive market position, because it improves the clinical outcomes of their current sheath models in FEVAR applications, setting them apart from other sheath suppliers. The Pentaport's modular design also enables design and production flexibility, making it possible to expand to other applications. For example, by creating a connector part specifically designed for super-stiff wires used for BEVAR procedures. Besides, the experienced satisfaction of their device users (the care providers) should not be underestimated, as their trust in and preference for a specific device is a determinant factor during procurement. As explained in Paragraph 24.2, the Pentaport improves the provider's satisfaction during FEVAR surgeries.

25. FINANCIAL PROFITABILITY

The device's financial profitability can be approached by estimating the market size (expected sales number) and profit margin per sold device, which is elaborated in more detail below.

25.5.1 FUTURE MARKET DEVELOPMENTS

Will there be a market need and how large will it be? This need depends on the number of FEVAR and BEVAR surgeries and whether this will grow.

As explained in Chapter 7, the prevalence of FEVAR and BEVAR surgeries is growing. Not only in The Netherlands, also in the US, which is the leading industry market, and in rapidly developing healthcare markets, for example in Africa and Asia. With these developments, the aortic stent graft market's worth is expected to have grown 6% within 6 years by 2024 (Research and Markets, 2019). In the same report, it is stated that vendors are focusing on and extensively investing in R&D activities to further develop FEVAR devices.

Efforts were done to find data regarding the number of these performed surgeries in Europe. Also, the US was included, as it accounted for the largest market share in 2018 (Grand View Research, 2019). However, due to a lack of exact data to be found, the market need is based on current prevalence in the Netherlands and growth predictions of EVAR procedures in general. Besides, the sales number of fenestrated and bifurcated stents by two large suppliers are included.

25.5.1.1 MARKET SIZE

In 2020 between 100 and 150 FEVAR and 40 BEVAR procedures were performed in The Netherlands, according to Dr. J. van Schaik (personal communication, January 20, 2021). This country has a population of almost 17.5 million inhabitants (Centraal Bureau voor de Statistiek, 2021). The population's percentage of patient's receiving FEVAR and BEVAR treatment can be calculated and is found to be a maximum of 0.00109%.
This percentage is translated to other European countries (Table 25.1), which are assumed to have similar demographics. It must be kept in mind, that healthcare systems differ per country, various European countries are not taken into account in the calculation, and that market expansion takes time. Still, this leads to a rough approximation of the possible market size, estimated at more than 4000 surgeries a year.

Extrapolating the Dutch percentage to the US, resulting in around 3600 surgeries, is assumed to have even lower accuracy. However, as the US has the largest market share, the number of surgeries is expected to be similar to Europe or higher.

Of course, these numbers should be taken with a grain of salt, as not all hospitals performing FEVAR and/or BEVAR procedures will buy the add-on. However, as an add-on, the product has the benefit of possible collaboration with current sheath suppliers. Instead of having to win their market share, it is possible to actually share it. Their sheath's functionality improves in combination with the add-on, making it a valuable addition for them. This was confirmed by experts of various backgrounds. Among others, A. Loeve (Biomedical Engineering), D. Eefting (Vascular Surgeon), C. van Rijswijk (Interventional Radiologist), R. Nelissen (MD and Member of Certification Body), and F. Aniba (Certification Consultant).

Currently, hardly any alternatives exist with a similar combination of functionalities. The only direct competitor, Lamed's sheath and multiple-access X-cath combination (Paragraph 7.2), does not have the advantage of being compatible with any other sheath and collaborating with any other sheath supplier. As a high percentage of surgery failures can be related to use of a new, unfamiliar tool (Nelissen, personal communication, March 15, 2021), this is a serious drawback. Nelissen explains that an add-on for existing, familiar sheaths, which the surgeon has experience with, is more desired, because the surgeon can focus on the main task. Also, it does not require the surgeons to gain trust in a completely new device, which makes this design more approachable.

Starting certification and sales in Europe, annual sales are estimated to range from 500 up to an absolute maximum of 4000 in the first years after market introduction. It is expected to be leaning rather to the lower side in the beginning, because skepticism must overcome and trust in the device's functionality must be won with the hospitals and users. This results in a relatively small market size. However, costs within this market are relatively high, which is elaborated in the next section.

Table 25.1 Rough estimation of number of FEVAR and BEVAR surgeries in Europe and the USA

COUNTRY	# INHABITANTS	# FEVAR SURGERIES	# BEVAR SURGERIES	TOTAL SURGERIES
Austria	9006398	77,19769714	20,58605257	97,78374971
Belgium	11589623	99,33962571	26,49056686	125,8301926
Denmark	5792202	49,64744571	13,23931886	62,88676457
France	65273511	559,4872371	149,1965966	708,6838337
Germany	83783942	718,1480743	191,5061531	909,6542274
Italy	60461826	518,2442229	138,1984594	656,4426823
Netherlands	17491854	150	40	190
Portugal	10196709	87,40036286	23,30676343	110,7071263
Spain	46754778	400,75524	106,868064	507,623304
Sweden	10099265	86,56512857	23,08403429	109,6491629
Switzerland	8654622	74,18247429	19,78199314	93,96446743
United Kingdom	68184563	584,4391114	155,8504297	740,2895411
Total	**397289293**	**3405,40662**	**908,108432**	**4313,515052**
USA	331002651	2837,16558	756,577488	3593,743068

25.5.1.2 PRICING IN THE MARKET

Costs of FEVAR procedures overall are high. Whereas in Europe, an EVAR procedure averagely costs between €12.090 and €13.956, a FEVAR procedure can cost €34.807 to €36.695. US-based research by Osman et al. (2015) presented the costs including hospitalization, being $57,000 (€47.518) for FEVAR and $91,000 (€75.863) for BEVAR, of which device-related costs accounted for 55%.

Two conclusions can be drawn from these numbers:
As overall procedure costs are significantly higher, the pricing of the device must be seen relative, thus a small difference in pricing of a 'cheap' device is relatively 'indecisive'.
By improving procedural outcomes and efficiency, a patient's condition will be better afterwards. Consequential reduction of hospitalization time and costs can save a significant amount of money spent on the procedure overall (Paragraph 24.3). Thus, pricing and viability are determined with a view broader than the device alone. Besides the device's cost price, prices of similar products are taken into account when defining a suitable selling price.

It is fairly difficult to get a hold of selling prices of similar products, as they are sold B2B (Business to Business), often through multiple-year contracts. Thus, the prices are communicated directly to the procurement department of these healthcare facilities. After inquiry with the suppliers, it was possible to receive information regarding the prices of the products most important to compare: the W.L.Gore DrySeal and Cook Medical Check-Flo introducer sheaths.

Table 25.2 Estimation of the production costs per part and batch, including raw material costs

PROCESS STEP		PRICE(€)/KG	PER PRODUCT (€)	1000 PRODUCTS (€)
Raw materials: Material, mass (g)	PC, 17.83	3	0.053	53.49
	PA, 0.05	6.50	0.0003	3.25
	ABS, 11.10	2.50	0.028	27.75
	TPE, 2.62	2.26	0.006	5.92
	Valve		0.05	50
Production	Manufacturing, finishing, assembly, packaging	Price per part: 10	60	60,000
Packaging & labelling	Plastic bag		0.75	754.40
	Cardboard box		0.51	510.20
	Label		0.15	150.90
Sterilisation validation	One time		4.60	4,600
Sterilisation	Per pallet	1000 products	0.75	750
Logistics			~	~
Certification	Per device design		6	6,000
Total			**72.91**	**72,905.91**

The Check-Flo, independent of French size, costs €315 in The Netherlands (Zijlstra, personal communication, January 28, 2021). The DrySeal costs around €330 (Schmitz, personal communication, January 6, 2021). As stated in the list of requirements, the new solution should not cost more than the original sheaths, or the higher price must be in proportion to significantly improved surgery outcomes.

25.5.2 COST PRICE & PROFIT MARGIN

An estimation of the cost price is made to validate whether it is realistic to set a selling price below the typical costs of an introducer sheath. Costs of the different steps in the process are included: raw materials, production (manufacturing, finishing, assembly, packaging, sterilisation), logistics. The calculation is performed based on the desired materials and production methods, mentioned in Chapters 22 and 23. Material prices are based on CES Edupack 2019, and production costs are according to Grosse, Business Unit Manager of P3D at Promolding (personal communication, May 10, 2021). Production costs strongly depend on the annual batch or series size. Costs of the next step, packaging and labelling, are based on prices provided by DaklaPack, a large supplier of medical device packaging. Comparable to sheaths, the Pentaport requires a sealed plastic bag and a cardboard box with sticker label.

Costs of sterilisation by Gamma Irradiation are based on information provided by Boon, Inside Sales Representative of STERIS (personal communication, May 31, 2021). Initial validation of the sterilisation procedure for the specific application costs approximately €4.600. Irradiation is performed per pallet of packaged devices. Estimating that one pallet (100 x 120 x 195 cm) fits around 1000 devices, and applying a minimum radiation dose of 25 kGy, which is required for sterile medical devices, sterilisation costs of a pallet lie around €750. Certification costs are based on research by Marešová et al. (2020). The later in the process, the more difficult and rougher the estimation is. Especially, because most of these steps still need to be defined, such as the location of production and the following logistics, and are strongly dependant on medical requirements and scale. An estimation of logistics would be guesswork. Therefore, the final cost price is rounded up to compensate for these missing costs, and these costs should be detailed in the future.

The total cost price per device, based on a production series of 1000, is estimated to be €72.91. A breakdown of the costs can be found in Table 25.2. When determining a selling price of €300, similar to a regular sheath, this results in a margin of 76%, and €227 profit per sold device (excluding logistics).

In conclusion, the device can be seen as a solution that is financially profitable for its supplier, the hospital, and insurance parties. The Pentaport is not only of value through direct profits, it can have an even larger indirect value for the whole healthcare cycle around FEVAR and BEVAR surgeries. Overall, it contributes to the full quadruple aim and is a sustainable solution for all main stakeholders.

26. THE SUSTAINABLE LIFE-CYCLE

Environmental sustainability is a factor of growing societal interest and growing importance for a product's future business model sustainability as well. Crudely, production and disposal of medical devices has a negative sustainability impact, indirectly harming people's health, due to emissions for example (Rijksinstituut voor Volksgezondheid en Milieu, n.d.). This impact should be minimised.

Initiatives such as the Green Deal, signed by hospitals nationally, green teams formed among medical staff members, and 'De Groene OK' (The Green OR) are widely emerging in The Netherlands. Also programmes outside the hospital, such as the circular instrument initiative by Van Straten Medical, aim to improve circularity of medical equipment. Similar developments can be seen in other European countries too. These initiatives demonstrate the intrinsic motivation of medical staff to improve environmental sustainability, as well as the growing moral and reputational urgency for hospitals and medical device suppliers to improve their Corporate Social Responsibility (CSR). For example, 'De Groene OK' focuses on stimulating circular use of surgical instruments and reduction of plastic waste from the OR.

To ensure that the Pentaport is future-proof, not only its physical design must be taken into account. Its whole life-cycle must be thought through, because the process of reusing and recycling comes with complex logistics that must be supported by a complete service system involving various stakeholders. A schematic of the recommended Product Service System (PSS) can be found in Figure 26.1. McCarthy (personal communication, April 9, 2021) supports that designing for the whole product life cycle is increasingly encouraged in the medical field.

26.1 RECOMMENDATIONS FOR THE PENTAPORT'S FUTURE LIFE-CYCLE

Starting, the devices must be directly separated from other waste, already in the OR. Here information and education are essential to ensure that medical staff members dispose of the correct items in the correct way. In this way, the devices can be separated from the hospital's costly infectious waste stream, reducing the waste management costs. Waste management of infected waste is 5 to 10 times more expensive than non-medical waste, and costs are even rising due to stricter regulations (Erasmus MC, 2014).

Next, it must be transported safely to facilities for disassembly, sterilisation, refurbishing and recycling. Importantly, these refurbished devices must pass certification, which can be tricky. However, it is not impossible according to McCarthy (personal communication, April 9, 2021). This is a reason to make the supplier responsible for centralised refurbishing and quality assurance, instead of performing these steps locally at the hospital. Also, sterilisation by gamma irradiation can only be done at industrial facilities. Sterilisation by gamma irradiation was chosen over EO, as it has a less negative impact on the environment and on the sterilisation staff's health (Paragraph 22.1.1). Recycling of pure materials could also be done by specific recycling facilities.

Finally, by reusing parts and recycling materials, the recommended PSS can improve the Pentaport's sustainability impact by reducing:
- the need for newly sourced materials,
- the number of parts to be produced,
- the materials that are incinerated.

Additionally, it can form an example for other medical suppliers by setting a new standard for a medical device life-cycle. Also, as soon as the PSS is in place, it can be used for other devices too.

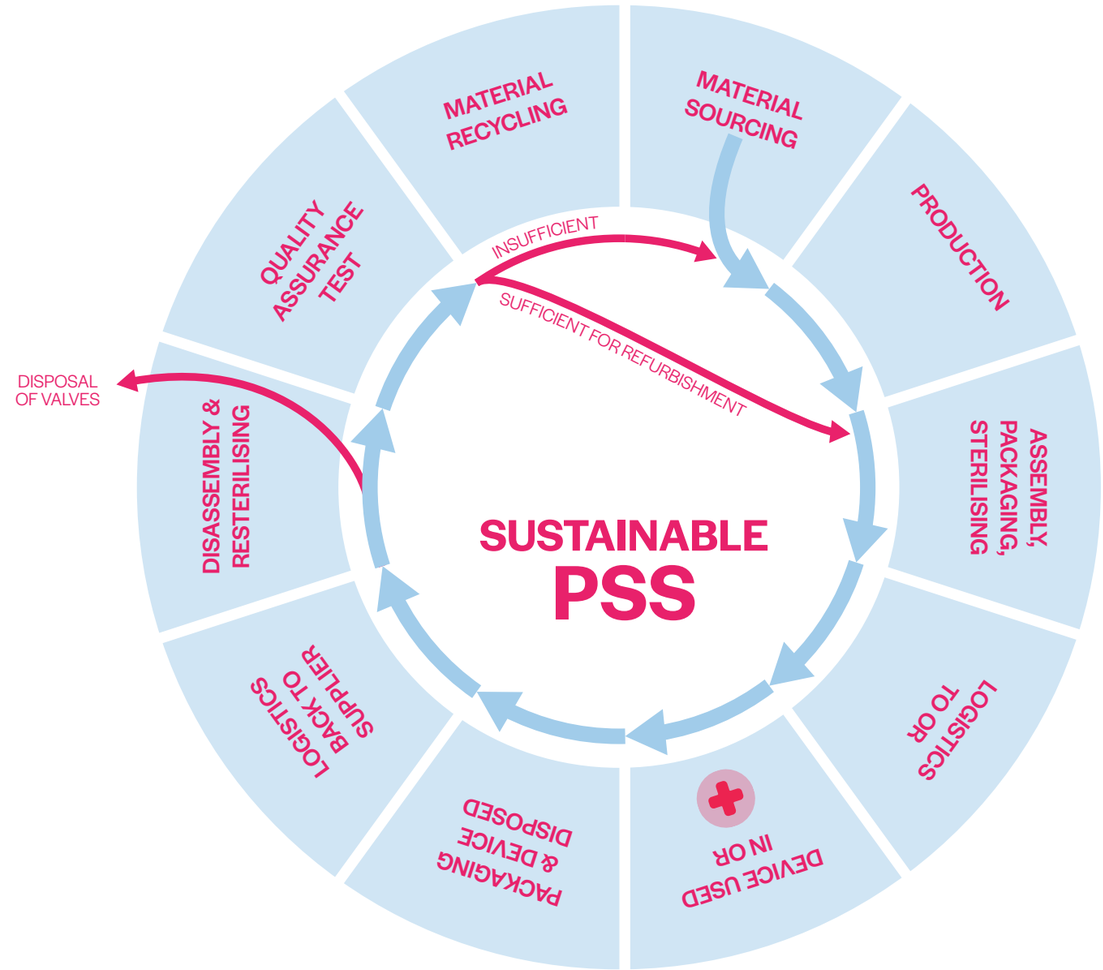


Figure 26.1 Schematic of the Pentaport's sustainable Product-Service-System

27. VIABILITY VALIDATION

“Why was this not invented before? I lose this type of inventions” **- Kok**

The Pentaport’s viability, as explained in previous Paragraphs, is validated by the expert opinion of Justin Kok, Innovation Scout & Business Developer at the TU Delft Valorisation Centre & Delft Enterprises (Figure 27.1). Kok has extensive experience with growing ideas, developed within the TU Delft’s academic context, to successful start-ups.

Kok (personal communication, May 20, 2021) exclaims as first reaction: “*Why was this not invented before? I love this type of inventions*”. He argues that he “*already believes in this idea*”, because the Pentaport is well ‘investable’, which means that it is an interesting solution for external investors. The main reason is that it is easily scalable. Therefore, he emphasises that now is the moment to start patenting the concept, because that makes it possible to start talking to market parties, next to the medical specialists already involved. The patenting process was started during the final weeks of this project in collaboration with LURIS, the Valorisation & Technology Transfer Office of the LUMC.
Kok envisions two different suitable methods to collaborate with market parties.

1. A good moment to initiate selling the patent and design would be before starting the certification process, as companies have the money to complete this process and commercialise the product. By involving these market parties in co-creation before certification, further development can lead to a device that meets their needs and interests too.
2. Collaboration can be initiated earlier in the process by providing licences to use the design. The advantage of licensing is that if one party buys the licences (for example W. L. Gore), other parties follow to keep their competitive position (for example Cook Medical Inc.). In that case, the first party can decide to acquire an exclusive license by paying a higher price. Similar to the first method, the external company is the party taking on the certification of the design for their own application. The main benefit for the company is that costly product development is outsourced to the start-up.

These methods are integrated in the innovation development route in the next Chapter. Based on Kok’s experience, it can be concluded that the Pentaport is a solution with market potential, that is interesting for investors and medical device companies.

Figure 27.1 Impression of activities of Delft Enterprises

FUTURE ROAD MAP

PART 8

Looking at the complete process of Medical Device Development, it can be concluded that this project only is the start of an extensive journey. This chapter explains possible steps for future design recommendations, based on the device's current TRL. Different routes to market device deployment are explored.

28. TECHNOLOGY READINESS LEVELS

Technology Readiness Levels (TRL) were initially used by NASA to assess the maturity level of a particular technology (Mai, 2017). Similarly, it can be valuable to evaluate the evolution of technical maturity of a product and its sub-systems, and to define the aspired level (and required actions) to be achieved in the future.

Figure 28.1 presents the add-on's TRL. The choice to develop a sheath add-on, instead of a completely new sheath, causes a clear difference between the systems defined in this TRL and the version presented during earlier stages of this project, which can be found in Appendix U.

The TRL developments are coupled to three moments in time: the project's midterm, the project's end, and future targets to reach market introduction (Figure 28.2).

MIDTERM | PROJECT END | FUTURE

Figure 28.1 Current and desired Technology Readiness Levels

At the project's midterm, most components were at the stage of a technology concept, formulated as a conceptual sketch. The critical functional sub-systems, such as the valve and screw mechanism, were already tested with early, low-fidelity prototypes (PLA 3D-print on Ultimaker 2+ printer). A small number of components, that were developed later as results of the concept choice, were only observed in other applications or not yet relevant at that time.

Between the midterm and this project's completion, the components have been tested in isolation or validated within their sub-system.

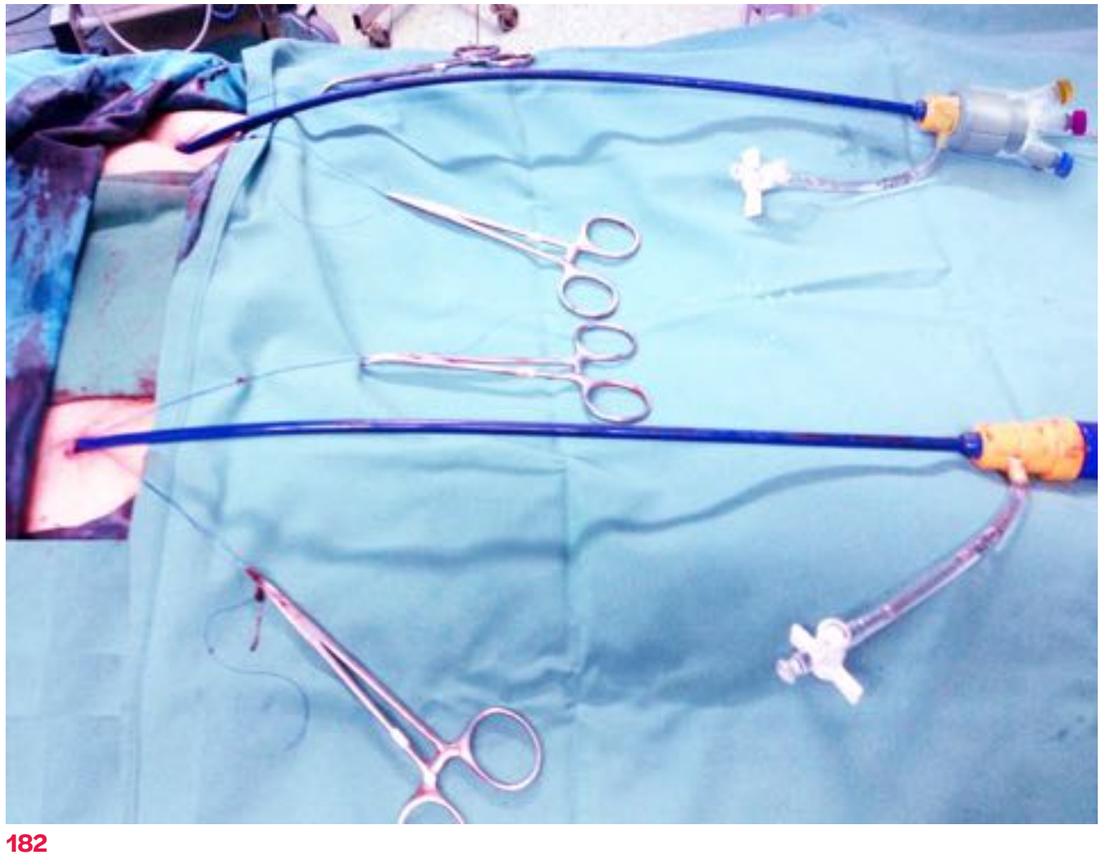
TRL 6 is reached at the project's end, the moment of writing this report. Finally, the components have also been demonstrated as a complete system. Both, their technical functionality and their usability have been tested and evaluated in a simulated environment. An Alpha Protoype (iD Cards (Loughborough Design School, 2014)) was used, bringing together key elements of appearance and functionality for the first time, simulating production materials. It was tested by applying a simulated blood flow and/or a simulated context of use, with realistic tools and manual actions.

PRODUCT	SHEATH ADD-ON																			
SYSTEM	CONNECTION TO SHEATH HUB					TOOL CHANNELS					TOOL LOCK							EMBODIMENT	
SUB-SYSTEM	COMPR. MAIN BODY			COMPRESSION RING		VALVE		LUMEN			CONNECTION	FRICTION	BEARING	SCREW MECHANISM				EMBODIMENT	
COMPONENT	TEETH	OUTER THREAD	SILICONE SEAL	INNER THREAD	COMPRESSING RIDGE	HEMOSTATIC VALVE	VALVE FIXATION	SEPARATE LUMINA	JOINED CENTRE LUMEN	CONNECTION TO LOCK & VALVE	SNAP-FIT CONNECTOR	SILICONE TUBE	BEARING RING	INNER TRHEAD	SCREW CAP	TOOL ENTRANCE	THREAD STOP	GRIP	HOUSING
9. System proven in operational environment																			
8. System complete and qualified																			
7. System prototype																			
6. Demonstrated in simulated environment	Operational model tested with users & flow pressure	Operational model tested with users & flow pressure	Operational model tested with users & flow pressure	Operational model tested with users & flow pressure	Operational model tested with users & flow pressure	Operational model tested with users & flow pressure	Operational model tested with users & flow pressure	Operational model tested with users & flow pressure	Operational model tested with users & flow pressure	Operational model tested with users & flow pressure	Operational model tested with users & flow pressure	Operational model tested with users & flow pressure		Operational model tested with users & flow pressure	Operational model tested with users & flow pressure	Operational model tested with users & flow pressure	Operational model tested with users & flow pressure		Operational model tested with users & flow pressure
5. Validation in simulated environment													Operational model tested with users & flow pressure, final design texture still requires testing.					Dimensions tested with users, but texture design still requires testing	
4. Validation in lab																			
3. Experimental proof of concept						Low-fidelity prototype tested	Low-fidelity prototype tested	Low-fidelity prototype tested						Low-fidelity prototype tested	Low-fidelity prototype tested				
2. Technology concept	Concept sketch	Concept sketch	Concept sketch	Concept sketch	Concept sketch				Concept sketch			Concept sketch							
1. Basic principles observed										Preliminary ideas	Preliminary ideas		Preliminary ideas			Preliminary ideas		Preliminary ideas	Preliminary ideas

All final validation tests have been done with operational models, made by SLA 3D-printing on a Formlabs Form 3B printer. The Formlabs resin “Tough” was used, mimicking the material properties of ABS. Therefore, the effect of the materials chosen for the final design must be validated next to achieve level 7: demonstration of a complete system prototype. Especially, functionality of the bearing and grip on the embodiment strongly depend on the material qualities and finish intended for the final design. A high-gloss Nylon bearing ensures better lubricity, and a roughly textured embodiment improves the user’s grip. Thus, their functionality is expected to improve significantly, and previous testing is not yet representative to classify as TRL 6.

Additional steps that must be taken to further develop the design into a marketable product, are described in the next paragraphs.

Figure 28.2 Illustration of the Pentaport in practice during a FEVAR procedure



29. DESIGN RECOMMENDATIONS

29.1 CONNECTION TO SHEATH

An add-on version should be created for the Check-Flo by Cook Medical. The same functional components can be used. However, dimensions of the main body and its compression teeth must be adjusted to fit the larger and differently shaped hub.

The precise form of the compression teeth should be optimized for the smoothest possible sliding movement onto the sheath hub. At the same time, the thickened part of the teeth, forming the discontinuous annular snap-fit, should be optimized to hook onto the hub as well as possible. Therefore, they should tightly enclose the hub and its edge, while having a smooth surface to prevent damage of the hub.

29.2 TOOL CHANNELS

Smooth guidance of the tools from the separate entrances into the central lumen should be further tested and optimised, concerning the channel’s walls and ridges. Also, lubricity of the lumina’s walls should be evaluated.

The main concern that was not possible to test during this project, is the chance of blood coagulation in the add-on’s lumina and between the add-on’s central lumen and the sheath’s lumen. This should be extensively tested in a realistic test setup with proper blood flow and actual surgery duration.

The current choice for transparent tool channels should be evaluated in a more realistic clinical setting with blood to identify whether it is a valuable addition to the device’s safety and user’s experience. Van der Vorst (personal communication, May 31, 2021) explains that most sheaths have such transparency, because it makes internal blood clots or air bubbles visible through the embodiment, which enables the user to act on them. However, he experiences the transparency and constant sight of the internal blood as a distraction too, as you can become concerned that the blood might start clotting. He states: *“If it leaks, you see that at the tool entrances anyway”*.

29.3 TOOL LOCK

29.3.1 BEARING

The bearing's nylon material should be tested, and if necessary, guiding pins should be added that are fixed in the connector part, to prevent any unintended rotation of the nylon bearing, and consequentially of the compressible tube and introduced tool.

29.3.2 TPE TUBE

The optimal shore A hardness of the TPE tube should be identified by testing both technical clamping functionality and the rotating force preferred by users to lock the tool. This depends on the tube's dimensions too, thus, they should be further optimised likewise. Consequently, the dimensions of the whole locking mechanism can be further optimised to reduce the add-on's length as far as possible. This would improve tactility of tool manoeuvring, however, according to Van der Vorst (personal communication, May 31, 2021) such an additional length of around 5 centimetres is not a concerning problem.

Also, the exact surface texture of the tube's inner lumen should be further refined and tested, to achieve optimal friction and minimal reduction of friction by fluids.

29.3.3 THREADS

The threads of the locking mechanism are relatively small, especially on the screw cap. Therefore, they should be tested for their strength and resistance to stripping and be optimised to prevent any signs of wear. The same should be done for the thread of the compression screw, however, this is expected to be less fragile as it is larger.

With the final prototype, jamming of the locking mechanism occurred, due to intended large dimensional tolerances between the threads of the screw cap and connector, required for 3D-printing. This should be prevented in future iterations, smoothening rotation, by increasing the number of revolutions of the thread on the screw cap (to more than one revolution) and applying tighter tolerances.

29.4 EMBODIMENT

The snap-fitted sub-assemblies, holding the valves and locking mechanisms, enable easy adaption of the device in the future. This facilitates using the device for other clinical applications. For example, the locking mechanism could be optimised for the super-stiff wire used during BEVAR procedures, or even an additional clamp could be added to enable fixation with high traction force.

These same snap-fits should also be further optimised for injection moulding. A straight ejection direction (along the part's centre line) can be enabled, by designing the snap-fits in the same direction, while keeping the lumen on the same position and under the current 25° angle. As a result, the snap-fit direction and lumen are not parallel anymore, requiring further optimisation of the valve's snap-fit clamping.

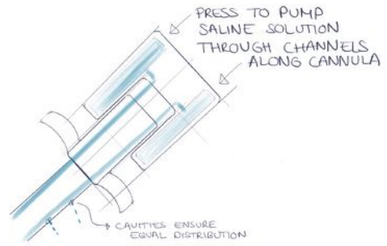


Figure 29.1 Sketch of possible future integrated flushing system

29.5 INTERACTION & EXPERIENCE

29.5.1 FLUSHING

Currently, the add-on can be flushed through the sheath's original flushing port. This choice was made because the distance between the add-on's valves and the sheath's flushing port is relatively short. Thus, it is assumed that the original way of flushing functions sufficiently. Also, surgeons indicated that this action is very familiar, requiring little attention and effort. Still, it was observed that the user needs to release and change the manual grip of the sheath hub, to engage the flushing syringe and port. These movements can be eliminated by removing the need for a syringe and integrating the flushing system into the add-on (Figure 29.1). In that way, the user does not need to release its grip of the sheath and less handlings actions are required.

29.6 PRODUCT LIFE CYCLE: PRODUCTION, ASSEMBLY, DISPOSAL

29.6.1 PROCUREMENT

Guidelines for the procurement and introduction of new medical devices into hospitals should be followed to improve the design according to their requirements, states Nelissen (personal communication, April 1, 2021). For example, the guideline "*Aanschaf en introductie van medische technologie in het ziekenhuis*" by the Rijksinstituut voor Volksgezondheid en Milieu (2012), and the "*Leidraad Verantwoordelijkheid medisch specialist bij aanschaf, ingebruikname en gebruik van medische apparatuur*" by the Nederlandse Vereniging voor Anesthesiologie and Orde van Medisch Specialisten (2014).

29.6.2 PACKAGING, LABELLING, AND IFU

Packaging, labelling, and the Instructions for Use were left out of scope during this project. These must be designed, also according to MDR requirements, to support the device's safety and usability as much as possible.

29.6.3 REUSE AND RECYCLE

As explained in Paragraph 23.2.3 and Chapter 26, a PSS should be built around the Pentaport to facilitate its improved environmental sustainability. Also, the device's materials are chosen for their recyclability. Their specific recycling characteristics should be further researched, to specify the exact material variant and composition for optimal recyclability. Likewise, the material's level of deterioration with every (re)use and (re)sterilisation cycle should be investigated to ensure safety and the maximum number of reuse cycles. A part tracking system should be added to enable monitoring the part's cycles.

29.7 DIVERGING INTO OTHER SPECIALISMS

Next to FEVAR and other EVAR procedures, these large-bore introducer sheaths are used for few other surgeries. As far as identified, these are percutaneous liver perfusion of hepatogenic metastatic carcinomas (Schaik, personal communication, January 04, 2021) and sometimes introduction of new cardiac valves in cardiovascular surgery (Schmitz, Field Sales Associate at W.L. GORE, personal communication, January 06, 2021). Van der Vorst (personal communication, May 31, 2021) imagines that radiology interventions of the brain and abdominal laparoscopy could be other suitable fields as well. Future exploration of similar needs in these and possibly other fields, providing opportunities to implement this solution as well, is interesting for further market growth and broadening.

30. INNOVATION DEVELOPMENT ROUTES

The design process completed during this project resembles the first two of six steps in the Medical Device Development process defined by Marešová et al. (2020): Initiation, Concept proposing, Design & development, Verification & validation, Production, and Market device deployment. Different innovation development routes that can be followed to achieve market deployment of this device are further illustrated in Figure 30.1 and the paragraph below, in order of the remaining four steps. Expert opinions by R. Nelissen (Chair European Expert Panel MDR), C. Vincent (Principal – Human Factors & Ergonomics at PDD Innovation), C. McCarthy (Senior Human Factors Engineer at Worrell Design), and M. Chmarra (Biomedical Engineering Researcher) were gathered and included in the proposed routes.

30.1 THE 'VALLEY OF DEATH'

It is important to be aware of the 'valley of death' explains Vincent (personal communication, April 9, 2021) during projects like this. This term describes a frequently observed phenomenon, where an innovation does not manage to bridge the gap, the 'valley', between research and commercialisation.

On the one hand, promising innovations are developed at academic or other research-based institutions, funded by research councils to solve fundamental problems. On the other hand, companies are mostly focused on selling products with incremental innovation steps.

"They [medical companies] might see your idea and might want to take it away"
- Vincent

Ideally, the first will transition into the latter. Starting off as fundamental problems to be solved, over time turning in to products for hospitals. However, that jump can be difficult. Vincent (personal communication, April 9, 2021) pinpoints how this jump can be enabled: "*often we have separate funding streams for those specific areas*". A good funding system should keep this in mind and make it easy to follow these different tracks or switch to the commercial track. According to him, it is important to have clear objectives and define whether the goal is publishing and informing people about the new method, or getting it into use in hospitals, because sometimes these sit at odds.

If the goal is publishing, three logical moments can be chosen in the process, as can be Figure 30.1 on the right, and confirmed by Chmarra (personal communication, March 16, 2021): after achieving proof-of-concept, IP marking, or clinical validation. The first, opens possibilities to quickly share the device's new surgical method through two approaches, a scientific paper or an open-source design. Both enable other parties to continue the development process, for example, other academic institutions and in-hospital device development departments. However, when publishing at this stage, IP marking is not possible anymore. The latter two moments enable informing others about the method, while it is already protected.

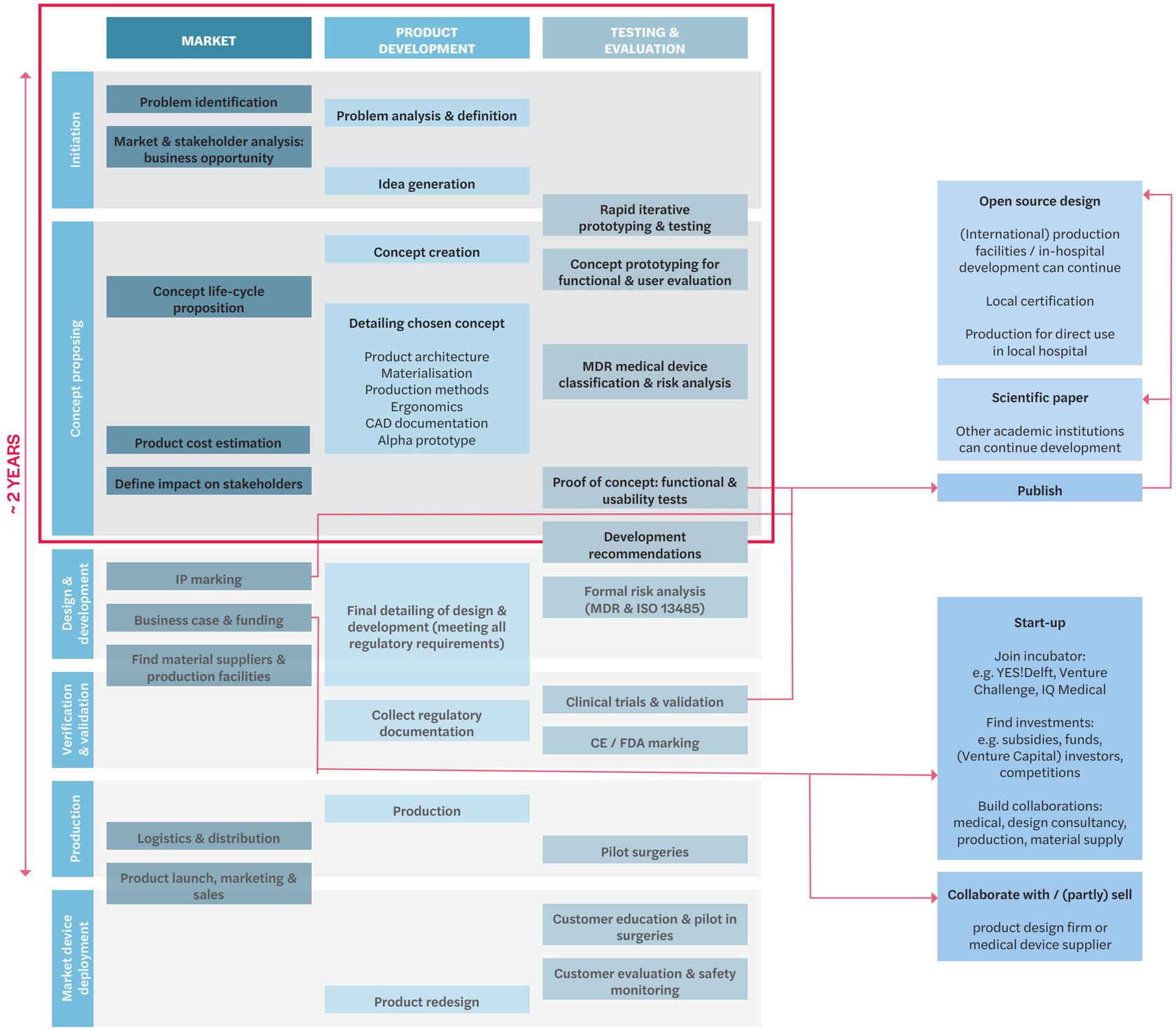


Figure 30.1 Medical Device Development process based on the six steps defined by Marešová et al. (2020): Initiation, Concept proposing, Design & development, Verification & validation, Production, Market device deployment. The tasks divided over the three columns Market, Product Development and Testing & Evaluation are formulated according to the sub-steps identified by Marešová and complemented with own experience of the design process.

Companies often do not have the same 'valley of death' problem; they are less ambitious with the problems they want to solve. This could be an argument to approach companies, if the goal is to get the device into use in hospitals, "*they might see your idea and might want to take it away*" explains Vincent (personal communication, April 9, 2021).

To make a device from scratch takes approximately 2 years of development according to Vincent (personal communication, April 9, 2021), and later device improvements can be performed in as short as 3 months, depending on the type of improvements. No time planning is added to the development roadmap, because duration of individual steps such as certification vary a lot, making predictions difficult and unreliable. Also, as illustrated in Figure 30.1, the steps described below cannot be seen individually, they happen in parallel and are dependent on each other.

30.2 STEPS IN THE PROCESS

30.2.1 DESIGN & DEVELOPMENT

1. Start with proof-of-concept of the Minimum Viable Product (MVP).

2. Get funding, for example EU and institutional funding, or competitions. Another option is through venture capital. Vincent (personal communication, April 9, 2021): "*for example, they can take the risk to provide the money to do CE marking".* This is not a one-time step, but continuous throughout the process.

3. In addition to the final prototypes, the complete task analysis, FMEA, and formatives studies should be completed. The backing by Van Schaik and the LUMC's vascular surgery department "*is of massive value*" says McCarthy (personal communication, April 9, 2021) to do an extensive task analysis and get more formative assessments done in simulated environments. These assessments are necessary to prove usability and conformity. All elements above should be documented in detail.

4. Get IP marking, ideally by applying for a method-based patent, because this automatically covers the final product too. This process is explained more elaborately in Appendix V.

5. When IP marking is achieved, the choice can be made to continue development in the form of a start-up or to (partly) hand over the design and accompanying development by selling it to another party, such as a medical device supplier. When continuing as a start-up, the selling step is also possible at later moments in the process. For example, after clinical validation, CE marking, or even after proving the device's functionality in pilot surgeries.

6. Establish the location for assessment, for example the EU or USA. "*Requirements depend a lot on the location where you are trying to get certification*", explains McCarthy (personal communication, April 9, 2021). Nelissen (personal communication, March 15, 2021) also emphasises this difference: "*The EU thinks more 'socially' about people, whereas the USA is more concerned about money making, but on either location, you must be accountable for your device as a supplier.*".

7. Get in touch with parties for collaboration, such as design consultancies and manufacturing companies. Mostly, they are well-established, thus also create confidence in the development process and trust in the new product design with external parties. "*The project sounds very good and on-topic. As a design consultancy we are currently working on similar devices, for liver and cardiac procedures.*" notes Vincent (personal communication, April 9, 2021), illustrating that design consultancies would be open to taking on further development of the design.

30.2.2 VERIFICATION & VALIDATION

8. Get conformity regarding design for manufacturing and final materials.

9. Get final production offers from manufacturing, packaging, sterilisation, labelling, and logistics companies.

10. Plan and perform clinical trials and summative usability studies.

11. Get final documentation complete, besides the previously mentioned documents, the following are required within the Quality Management System (QMS):
    a. Documentation: User Manual, Usability and Clinical evaluation, Functional test report, Task and risk analysis, FMEA, Labelling, Packaging (Marešová et al., 2020).
    b. Sterilisation protocol and validation of the sterilisation methods is essential here (Nelissen, personal communication, April 1, 2021), requiring material listing and their compatibility with the sterilisation method.
    c. Transport protocol and validation of transport safety, it should be proven that nothing breaks during transport and that all devices arriving at the hospital are safe to use (Nelissen, personal communication, April 1, 2021).
    d. Post-market surveillance and clinical follow-up plan, containing a system for tracking the distributed devices, mostly this is a national registration system (Nelissen, personal communication, April 1, 2021).

12. Start with EU MDR assessment for CE marking. Because the add-on can be certified as a separate class Is device, unrelated to the introducer sheath, only the sterilisation protocol must be reviewed by a notified body in the assessment process. The supplier is responsible to provide all other documentation, but this is only checked on a random basis. This strongly reduces the duration and costs of this step to averagely 360 days and €6000 in comparison to 480 days and €14,000 - €20,000 for a class II device (Marešová et al., 2020).

13. In the further future the FDA assessment can be done as well. However, this is a quite different process, as explained before, that must be approached as a separate application.

30.2.3 PRODUCTION

14. Full scale production: including material sourcing, parts manufacturing, assembly, sterilisation, packaging, and labelling.

15. Logistics: including storage, transport, and distribution.

16. Pilot surgeries: first (often collaborating) hospitals start using the device in practice, clinical outcomes are closely followed.

17. Market preparation: product launch, marketing, and sales, forming the bridge to the final step in the process.

30.2.4 MARKET DEVICE DEPLOYMENT

18. Costumer education: Nelissen (personal communication, March 15, 2021) encouraged making a workshop for end users as soon as the new device is market ready, to ensure correct training and future use of the device, as this often is the bottleneck with new device implementation.

19. Post-market surveillance and clinical follow-up plan is executed: evaluations are performed with users to find potential safety hazards and possibilities for future device improvement.

20. The outcomes of step 19 are used as input for product redesign, where the described process restarts again.

At the conclusion of this project, choices will be made regarding the desired development route, possibly resulting in a scientific paper or continuation of the development via the LUMC or an established medical device supplier.

PART 9

CLOSING

31. CONCLUSION

The Pentaport, the new add-on for large-bore introducer sheaths, is the solution to overcome the problem of sheath development falling behind with rapidly improving FEVAR stent technologies for the last 10 years.

Application of the add-on during FEVAR procedures can improve procedural outcomes by providing 5 separate tool entrances, each having its own valve and tool lock. This design reduces blood leakage to a minimum and fixates the individual tools in place, to prevent accidental dislocation, while allowing the use of multiple endovascular tools at the same time.

As a result, the add-on leads to a better patient condition during and after surgery, this can be attributed to three aspects. First, severe blood losses of 2L or more are avoided; second, the risk of arterial harm is brought back; and third, undesired recatheterisation efforts are eliminated, saving up to an hour of procedure time.

From a care provider's perspective, the Pentaport adds value during the surgery by increasing the surgeon's focus on the main operating task, because distracting factors are reduced, such as spilling blood and the need to constantly keep an eye out on the introduced tools' location. Besides, costs are saved by eliminating the need for expensive cell saving or blood transfusion and shortening procedure and cleaning times. The latter also increases availability of the medical team and OR. Overall, the new add-on frees up resources enabling the hospital to provide more care.

The Pentaport's functionality was validated with blood pressures over 180 mmHg and repeated introduction and manoeuvring of tools through the 5 entrances in parallel. Product usability and experience were evaluated with 9 medical specialists (vascular surgeons and interventional radiologists), and risks identified as critical were mitigated by design iterations. The product's financial value proposition was determined to be viable regarding direct profits, as well as indirect benefits for hospital and insurance parties.

It can be concluded from the summary above, that the final add-on design concept meets the project's six design drivers, as it minimises leakage, is designed for safety, enables smooth tool manoeuvring, facilitates an ergonomic use, ensures compatibility with tools required for FEVAR procedures, and stimulates time and cost efficiency.

32. DISCUSSION & REFLECTION

Looking back and learning from the project, it is important to reflect on the design, its full life-cycle and development, as well as on insights that might be relevant for people in the clinical and design fields too. For this reflection, both benefits and possible risks are included.

32.1 THE PENTAPORT

- First of all, consciously separating (critical) functionalities was found to be a suitable way to decrease a device's risks during use, as reduced capacity of one functionality does not directly influence the capacity of another. Therefore, the degree of criticality and quality of different parts can be distinguished and separately defined to match the part's requirements.
- Collaboration within team is strengthened on two levels:
    - Improved communication between the team members by coding the tool entrances of the add-on through coloured screw caps. The colour-coding is visible from all sides, for all team members. This method of (colour-) coding can be translated to other procedures as well.
    - An easier switch of position and tasks between the vascular surgeon and IR is facilitated by locking the tools in position. In that way, they can hand over the sheath hub two one another without the chance that the tools dislocate. This supports the teamwork and culture, emphasising the importance of helping each other without being 'afraid' of reputation loss, by stimulating better collaboration. This can form an example for other collaborative tasks within the team, as well as for other types of procedures. Overall, this links to the changing culture within surgical teams, from a previously hierarchic structure to a more team-focused atmosphere.
- The Pentaport's design is an example of widened compatibility with other tools, possibly by other suppliers too, by having a modular design that can be adapted. This prevents the need for prepacked sets of specific tools that only work with each other, eliminating the problem that half unused sets are disposed, only because they were opened.
- A drawback of the add-on might be reduced tactility of tool manoeuvring, if longer tools are required because of the length added to the sheath. This should be tested in practice. According to Van der Vorst (personal communication, May 31, 2021) this is not a concerning problem.
- A number of new ridges and material transitions are added to the route that the tool has to follow through the introducer sheath, such as the ridge between the sheath's hub and the add-on's TPE seal. These can reduce handling ease if the transition is not smooth enough and the tool gets caught on the ridge.
- Coagulation could occur in the lengthened lumina, among others along the additional ridges, as well as the funnel-shaped main lumen of the add-on. Besides, it is assumed that the add-on can be flushed through the sheath's flushing port, because the sheath's valve is inactive. However, it was not proven whether the add-on's flushing is sufficient to prevent blood clotting everywhere.

- As the add-on is functional in combination with a specific sheath model, it is problematic if the sheath and add-on model are not compatible. For example, if the introducer sheath falls during preparation, and an alternative model must be used. However, mostly one sheath model is preferred by the team and this model is used during all procedures. As the add-on is sheath-size independent, thus fits all sizes of a specific sheath model, it is expected that this risk is negligible.
- The possibility of human errors was minimised as much as possible by the design choices (see Appendix Q). Still, the add-on leaves room for human error on different levels. For example, the connection between the sheath hub and add-on can be tilted, the user can use a needle to insert a tool, or the user introduces a tool with a too large force, breaking the valve or TPE tube.
- A risk is that insufficient efforts are spend on educating medical staff in using and disposing the device. This could lead to new (preventable) errors and safety hazards during the procedure. Therefore, users should be trained and monitored for correct device use.

32.2 THE PENTAPORT'S LIFE-CYCLE

- The Pentaport contributes to the Quadruple Aim, an important topic of interest in healthcare, and forms valuable improvements for all stakeholders along the aim's four pillars (Chapter 24).
- The Pentaport's financial sustainability is ensured by a win-win value proposition: the medical supplier raises profits through sales and the hospital saves treatment costs, together providing more and better care for the same money.
- The Product-Service-System that should be designed to accompany the Pentaport's design for disassembly, reuse, and recycling, and to facilitate a circular life-cycle for the device, can act as a pioneer to improve the negative environmental impact of our healthcare system. It can form an example for suppliers of other single use, (plastic) disposables to also think about a product's full life-cycle, instead of solely its use. Additionally, once the PSS is in place, it can be used for other products as well.
- The PSS does bring difficulties as well, as it can be difficult to track a part's history, e.g. how often it has been resterilised or whether it has been dropped to the floor.
- It can be difficult to test and assure that material properties and functional integrity are not decreased when refurbishing a device. This also makes certification a lot more complicated.
- The PSS should be designed in a way that it is cost effective. There is a risk that the PSS is more expensive than simply disposing the add-on with the regular infectious waste stream and making a completely new product. Enabling a separate waste stream, resterilisation, quality assurance, refurbishing, and recycling can be costly.

32.3 THE PENTAPORT'S DEVELOPMENT

- The design's part modularity has various possibilities for the supplier: adaptability of the design for other sheath models and use cases, and disassembly for improved sustainability. Future adaption of the design can be achieved by changing the dome and/or connector parts for example, opening a larger or even new markets for the supplier.
- The FMEA created during this project forms a baseline for further development as well as certification. It can also be used as a communication tool explaining previously made design choices to people newly involved in product development.
- Having the goal to implement the Pentaport in FEVAR surgeries as soon as possible, to improve the procedure's outcomes, it is essential to reduce the certification process' duration where it is realistic. A large benefit of the Pentaport lies here, as it enables going around lengthy certification and assessment routes, by rethinking and being critical about what really is necessary. All advantages of existing sheaths are still used (e.g. introduction into the femoral artery and its advanced cannula materials composition), while only tackling their main problems. Therefore, it was possible to develop an add-on that remains outside the body and requires a less strict, lengthy and expensive certification process.
- The Pentaport's philosophy can function as an example for suppliers in the medical device market. Instead of focusing on competition and 'forcing' the user to use tools by the same supplier, because they are the only compatible tools, the Pentaport empowers collaboration between multiple suppliers. This collaboration is aimed at delivering the best possible healthcare and is achieved by making the design adaptable to sheath models by various suppliers.
- An add-on depends on the suppliers of compatible sheath models, which provides a risk factor. For example, if such a model is changed or taken off the market.
- During the development period, the risk exists that a (large) market competitor comes with a similar solution first. Especially in the period before patenting. This could eliminate the beneficial position of the Pentaport.
- It is possible that patenting turns out to be unapplicable for the Pentaport's design. In that case, little interest is expected from investors and medical device suppliers and copycats have a free course.
- When patented, the patent could be applied or even licensed to broader applications, such as other medical specialisations, as well as non-medical fields.

32.4 GENERAL INSIGHTS

32.4.1 FOR MEDICAL SPECIALISTS

- The analysis and synthesis of the medical procedure by an Industrial Designer can also give new insights to medical staff. According to Van Schaik (personal communication, March 3, 2021), it can create a new perspective on the procedure and structure it in a refreshing way. For example, the procedure's journey map that was developed and the pain points identified from the clinical observations and interviews, held up a mirror for the involved medical specialists as well. The fresh view can show ingrained patterns and habits that seem 'normal' to medical specialists, but that are notable to a designer that is not familiar with the specialised clinical context. These insights can be of help to the medical team to requestion such patterns.
- This project is an example of a medical specialist showing own initiative. It shows that a medical specialist can successfully take challenges, that are experienced during procedures, into own hands and by that improve the delivered care. This resonates with upcoming initiatives such as the 'Klinisch Leiderschap' (Clinical Leadership) programme offered by the Academie voor Medisch Specialisten (Beer, 2020). This programme calls on medical professionals to take the initiative to fundamentally change and improve healthcare.
- The Pentaport and the overarching PSS can also make medical specialists aware of the recycling need (if they are not yet), and especially show that recycling is possible in practice too. In that way, medical specialists can transfer this awareness and knowledge to other devices and encourage their recycling as well.

32.4.2 FOR INDUSTRIAL DESIGNERS

- One of the main learnings from the perspective of an Industrial Designer, is the importance of learning each other's language. This was achieved first by reading relevant literature and creating a glossary of clinical jargon, followed by clinical observations and conversations with nurses and specialists. The experience taught, that when being able to communicate with the correct clinical terms, the clinicians take you (as a designer) more serious and go more into depth in their answers, because they expect that you will understand.
- Just as for the medical specialist, it is insightful for the designer to identify the "obvious" and ingrained OR patterns. In general, medical specialists can be asked about these. But they might not be aware of all fully accustomed patterns, because it are their typical ways of working or characteristics, which are 'normal' to them. It helps, to hear about these patterns from other experts that have experience working with these medical specialists and know the traits you have to design for and with. For example, employees at the biomedical engineering faculty with an expertise in surgical instruments could tell me about 'unwritten' typical patterns and characteristics.
- Observations of surgical procedure & the context around it. It is insightful to notice that other factors, you might not relate to the specific product, can impact its use. For example, all prepared sheaths that fell down because someone rushed passed them, making them unsterile and unusable, requiring last minute replacement. Only another type of sheaths was available, thus the introducer sheath had to be compatible with those sheaths too. Also, the observations lead to finding the need of keeping the tools in position. The current way of working seemed obvious to the medical specialists, because they are used to it, but by putting a finger on it, they realised that there actually is a benefit in locking the tools.
- External factors can have a strong influence on the course of the operation and should be taken into account. For example, during this project, CoViD-19 lead to a shortage of available IC beds. Thus, sometimes there was no bed available for the patient to go after surgery, making postponing of the surgery date necessary. In that case, it was observed that medical specialists really engaged themselves to make sure their patients could be treated. If this was achieved, the surgery was started with a delay, causing time pressure, but a euphoric feeling could be seen with the medical team.
- A problem-solving mindset, similar to an Industrial Designer's, was recognised with the vascular surgeons, for example during unexpected events in the procedure. In such a situation, the best possible solution must be found, with the available equipment. Therefore, it can be valuable if a device design gives the specialist the flexibility to use this mindset in situations where it is necessary. It is important here though, that the chance of human errors is still minimised.

- As in most projects, prototyping (even rapid models) helps users that are inexperienced with design methods and process, to quickly provide insightful and relevant feedback. For example, it makes it possible to hold and feel the prototypes, understand the design's dimensional scale and experience the level of control over certain interactions. During this project, the early start of prototyping made fast, but well-supported decision making possible, freeing up time for more in-depth detailing and analysis in the project's latter phases. In this way, both a broader and more thorough overview of the device's use, functionality, and market could be achieved.
- Fast evaluation & iteration with the medical specialists was extremely valuable. However, it is important to keep in mind that medical specialists have little time mostly, so the designer should be aware of ways to use it as efficiently as possible. For example, during this project user evaluations were practiced in a pilot with other people first, before testing the device with medical specialists.
- Early awareness of the MDR classification and consequential requirements is beneficial to ensure their integral implementation in the design. However, this should not limit the creative design process. Thus, it can be used as a tool to prioritise ideas for example.
- An FMEA should be started as soon as possible, as it is a strong tool to ensure that the design is safe and all steps in the task analysis are thought through and risk free. Again, it can be a tough and detailed analysis to fill, but it is important especially to document and communicate design choices later in the process.
- Simplicity is key, even if the clinical procedure and solution seems to be complex, the tool should remain as simple as possible for users to use it safely and intuitively.
- During this elaborate, individual project, I once again experienced the importance of a detailed planning. It formed an extra push to be efficient and get things done, as well as round off specific parts by making decisions in time and putting results on paper. Besides, it helps to plan meetings and sessions with other people timely in advance. However, such events depending on various (external) factors, still formed bottlenecks sometimes. For example, usability evaluations where the completion of prototypes (depending on availability and functioning of 3D-printing facilities), the calendar of medical specialists, and the timing of milestone (concept) decision moments came together, lead to (preventable) planning problems or postponing of personal deadlines.
- The Quadruple Aim receives attention by various parties active in healthcare innovation currently and can form a central guideline for new device development. It was experienced as a practical tool to ensure that a new design meets all four pillars and is a positive contribution for all main stakeholders.

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