

Design of a Biopsy Storage System for a Core Biopsy Needle

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1. Introduction

1.1 Biopsy in Current Practice

Diagnostics and Medical Tests

If there is a suspicion a person might suffer from a particular disease, such as cancer, a medical test may be performed to confirm or determine the presence of the disease. Such medical tests are called diagnostic tests. Usually, a diagnostic test is ordered based on symptoms reported by either the patient or observed by the physician. A diagnostic test can also be ordered based on results of other medical tests. Examples of these diagnostic tests are: taking blood samples to check for bacterial infection; biopsying liver tissue to check for cancer; using nuclear medicine techniques to check for tumors; monitoring electrocardiogram readings to check for any heart irregularities. The focus of this research project is on a diagnostic test called biopsying, as can be seen in Figure 1.2b.

Biopsies Assist Imaging Studies

In order to minimize the invasiveness of the operation, a biopsy in general is not the go-to diagnostic tool. Very commonly, imaging tests are performed to assist in determining whether the tissue is non-cancerous (benign) or cancerous (malignant). When imaging studies are not conclusive, a biopsy may be issued. A biopsy can also assist in identifying other conditions, such as infections and autoimmune disorders, as well as aid in matching organ tissue before transplants.

Advantages of Core Biopsy versus Excisional Biopsy

Many of the aforementioned biopsy sites can also be biopsied surgically, but needle biopsies offer a number of advantages over surgical biopsies. The needle biopsies provide a reliable method to help detect or diagnose whether tissue is cancerous. These biopsies are less invasive than open or even minimally invasive surgeries, both of which involve a larger incision than a needle biopsy device. This leads to brief recovery times for patients and shorter hospital stays. Furthermore, in general, the results of a needle biopsy are as accurate as when a tissue sample is removed surgi-

Biopsy Sites in the Body

Virtually any organ in the body can be biopsied. Some of these biopsies are superficial in the body, such as some biopsies in the breasts, the skin, or the testicles. These sites are generally easier to reach than sites deeper deeper in the body. Examples of other, harder to reach biopsy sites, are: abdominal, including stomach biopsies (Figure 1.1b), bone and bone marrow biopsies as well as kidney (Figure 1.1a), and liver and lung biopsies (Figure 1.1c). For most of these biopsies, the number one reason to perform them is to check for cancer. Needle biopsies are performed with the help of image guidance, for example: in bone and bone marrow biopsies, in breast biopsies (Figure 1.2c), in kidney, lung and liver biopsies, in muscles and skin biopsies, as well as thyroid biopsies (Figure 1.2b).

Three Types of Biopsy

A biopsy is a medical test, which consists of extracting sample tissue for examination to determine the presence, cause, or extent of a disease. Most commonly, biopsies are used to investigate possible cancerous and inflammatory conditions. There are roughly three categories of biopsies, depicted in Figure 1.2, ranging from more to less invasive. In excisional biopsies (Figure 1.2a), an entire lump or area of tissue is removed. In incisional or core biopsies (Figure 1.2b), only a sample of tissue is removed, preserving micro anatomy of the removed tissue. In needle aspiration biopsies (Figure 1.2c), sample tissue or sample fluid is removed in a way that the micro anatomy of the tissue is usually not preserved. Out of these three categories, core biopsies are most prevalent in case of cancerous or inflammatory conditions.

cally [7]. Also, the chance of an infection when using needle biopsies, since the skin is punctured, appears to be less than 1 in 1.000 [8].

1.2 State of the Art

Overview of Core Biopsy Devices

There are many core biopsy device available on the market, as can be seen in Figure 1.3. Despite many different features for ergonomics, loading, reloading and activating the biopsy mechanism, there are roughly only two different types of core biopsy devices with regards to soft tissue biopsies. These two

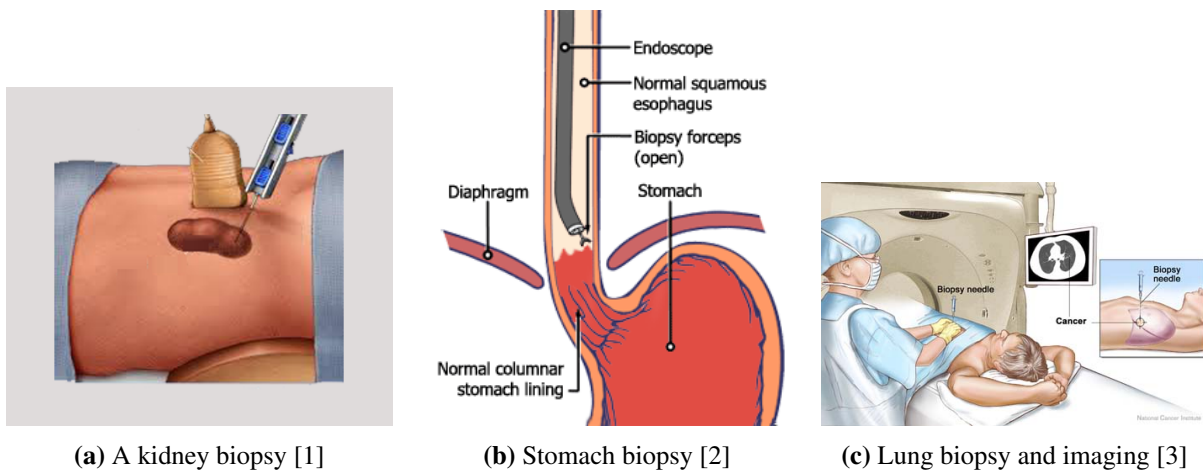


Figure 1.1: Different sites in the body that can be biopsied. Figure 1.1b shows a ‘long’ route to the stomach.

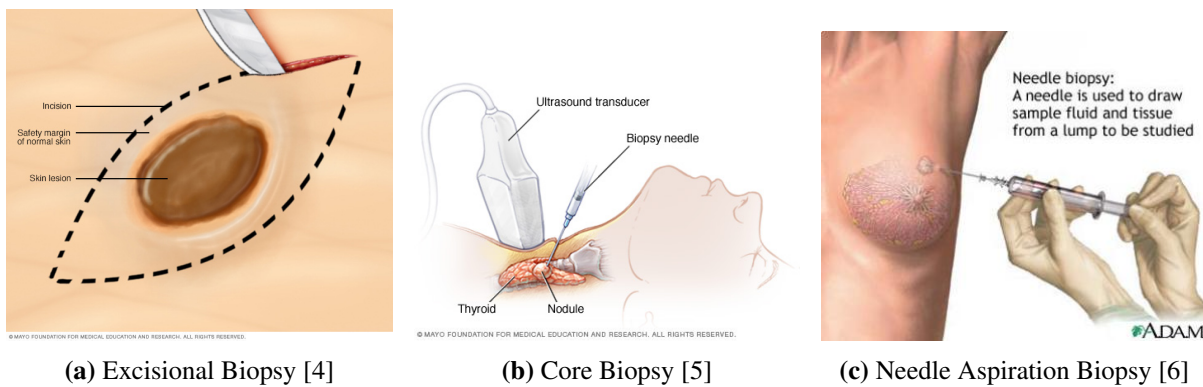


Figure 1.2: Overview of three types of biopsies.

types of devices are divided based on the location of the notch in which the tissue forms before it is cut off. The first type of needle is a side notch needle, because of the notch in the side of the needle. The second type cuts from the tip and is branded as the ‘BioPince’ needle.

1.2.1 Working Principle of a Core Biopsy Device

In this section, the workings of the two types of core biopsy needles are investigated in more detail. In general, the working principle of a core biopsy device is based on a needle and some sort of cutting actuation. Very commonly, the cutting actuation is handled by an axial, spring-loaded mechanism.

BioPince Needle Working Principle

The BioPince needle working principle is roughly the same as that of a side notch needle. The biggest difference is that the BioPince needle does not contain a side notch. Instead, the device cuts from the the tip of the device, see Figure 1.4b. The BioPince consists of three needles. There is the stylet (most inner

Side Notch Needle Working Principle

Side notch needles consist of two coaxial needles, see Figure 1.4a. The inner needle contains a 15-20 mm notch on the side of the needle. The outer needle acts as a knife. When this type of needle is inserted, the inner needle is protruded and the tissue of interest forms into the notch. Through a spring charge, the outer needle is then released and cuts off the tissue of interest from the rest of the body. The outer needle acts as a protection and keeps the biopsied tissue inside the needle, after a biopsy is taken. The entire needle can then be retracted from the body and the biopsied tissue can be examined by pulling back the outer needle and extracting the tissue.

needle), the inner coring cannula (middle needle) and the outer cannula (the outer needle). These three needles are inserted as depicted Figure 1.4b. The middle needle is actuated through a spring charge and advances forward through the tissue. This needle cuts straight forward at the tip, very similar to an apple core puncher. To cut off the piece of tissue at the end

of the middle needle, the outer needle is slid over. This needle contains a pincer and cuts off the last part of tissue that is connected to the body. The device is then retracted with the inner needle retracted, and both the middle and outer needle protracted. Once removed from the body, the inner needle can be pushed forward and the biopsy is removed from the needle.

1.2.2 Core Biopsy Device Challenges

Core needle biopsies do not only provide advantages. There are several challenges that exist for these type of devices and procedures. Challenges that are faced when biopsying, using core needle biopsy, can be divided in at least these categories:

- **Maneuverability:** a lot of biopsy sites are either hard to reach or are relatively more invasive if a ‘shorter’ route is chosen. An example of a maneuverability challenge: going through the duodenum (first part of the small intestine), to perform a gastrointestinal biopsy. An example of the latter is going through the stomach for a gastrointestinal biopsy. An other view of the ‘long’ route in a stomach biopsy can be seen in Figure 1.1b.
- **Precision:** several imaging techniques are used to guide a biopsy, such as ultrasound (Figure 1.2b and Figure 1.1a), x-ray, computed tomography (CT scanning) and magnetic resonance imaging (MRI) (Figure 1.1c). Finding both the location to biopsy and tracking the location of the biopsy device is challenging. Furthermore, because of the heterogeneity of cancerous tissue, a core biopsy device might miss the tissue of interest while performing a biopsy, resulting in a false negative [13].
- **Health Risks:** challenges from the above two categories can lead to unnecessary damage to the body. Furthermore, since only single biopsies can be taken per needle, there are two options: 1) first the biopsy has to be analyzed and diagnosed before a potential follow-up biopsy

has to be performed. This would increase the risk of the disease spreading over time, as well as a second hospital trip for the patient. 2) Increase the number of biopsies taken in a single operation. This can lead to unnecessary damage due to multiple needle insertions, as well as increased patient discomfort.

- **Procedural:** In traditional devices, a singly biopsy per device can be taken. To obtain a sufficient volume of tissue, multiple needles are inserted. The biopsy process takes up more time because of the consequent insertions, especially since precision is a big challenge. Furthermore, if a biopsy device has to be completely removed from the body, reaching the same site, or near the same site for a second biopsy can be a challenge, for example in milk ducts in the breast. Furthermore, during analysis, biopsy volume can be limiting for a pathologist to perform a sufficient number of tests. This poses a challenge on the volume of biopsied tissue to acquire.

1.3 An Ideal Core Biopsy Device

One of the aspects of an ideal core biopsy device would be to collect higher volume of biopsied tissue during a single needle insertion. The goal of collecting more tissue is to always provide a pathologist with sufficient tissue to perform tests. The goal of a single needle insertion is to improve the speed of the procedure, as well as patient comfort and recovery speed, compared to multiple needle insertions.

1.4 Goal of this Study

The goal of this project is to design and prototype a core needle biopsy device that is capable of taking and storing multiple biopsies in a single device. Such a device requires less needle insertions than a traditional core biopsy device and is able to take biopsies

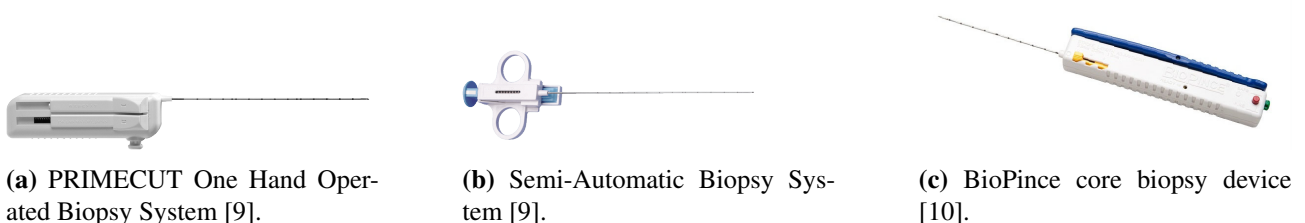
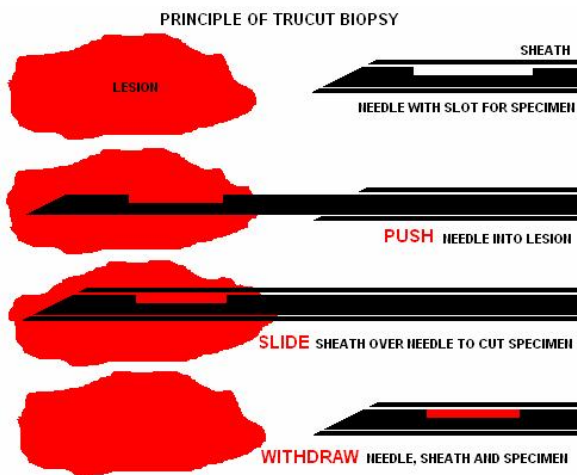
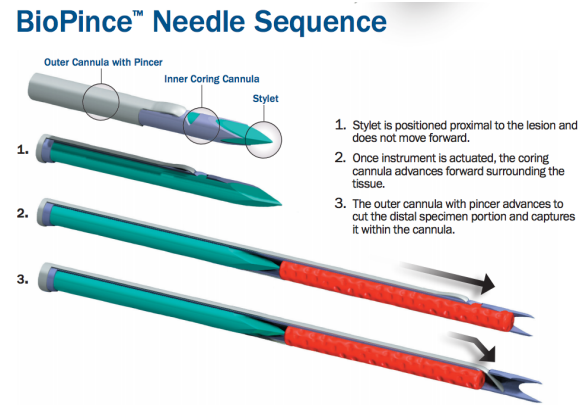


Figure 1.3: Overview of different core biopsy devices.



(a) Side notch device working principle [11]



(b) BioPince device working principle [12]

Figure 1.4: Illustrations of the working principles of the side notch needle and the BioPince needle.

from the same location in the body. This could lead to a lower number of false negatives during diagnosis.

1.5 Layout of this Study

This report describes the design of a biopsy storage system for a core biopsy needle throughout the following chapters:

In Chapter 2: Biopsy Needle Development, the design process of a core biopsy needle with a storage system is described. Firstly, an area of interest is chosen. Then, the functionality of such a core biopsy needle is determined. Together with the area of interest, design requirements are set for the device. A critical function to solve is selected and concepts are created, categorized and selected. The chosen concept is further developed into a final geometry.

In Chapter 3: Prototypes, the design of a biopsy storage system is prototyped. This happens in two steps. Firstly, a first proof-of-principle prototype is created, based on the final geometry design. The performance of this first proof-of-principle prototype is then used for the design of the final prototype. The design, production and assembly of the final prototype are described in this chapter as well.

In Chapter 4: Experiment, the testing of a core biopsy needle with a biopsy storage system is described. The final prototype is used to test the biopsy mechanism, as well as the workings of the transport and storage system.

2. Biopsy Needle Development

In this chapter, the design process of a core biopsy device with a biopsy storage system is described. Firstly, an area of interest is chosen. Then, the functionality of such a core biopsy needle is determined. From these functions, together with the area of interest, design requirements are determined for the device. A critical function to solve is selected and concepts are created, categorized and selected. The chosen concept is further developed into a final geometry.

2.1 Area of Interest: Breast Biopsy

Introduction, Prevalence & Mortality The field of breast biopsies was chosen as an area of interest. In the Netherlands, 1 in 7 women get breast cancer [14]. In 2016, there were at least 17.315 cases of breast cancer. 5 years after diagnosis, 86% of the female patients was still alive, and 77% after 10 years. Every year, over 3.000 people die of breast cancer. Over the last years, the survival rate of breast cancer has risen with 1% each year. In the US, approximately 1.6 million breast biopsies are performed annually. Around 20% of the biopsies are diagnosed with breast cancer [15]. The most common risks associated with a breast biopsy are bruising and swelling of the breast, bleeding and a small chance of infection at the biopsy site [16]. In a study of Boba *et al.*, a false negative (undetected cancer) happened in 2.2% of 988 cases, and generally ranges from 0-6%, when using core biopsy devices [13]. The main causes were 1) biopsying at the incorrect site (the lesion was not penetrated), and: 2) histopathological non-homogeneity of cancer infiltration, meaning the cancer is not spread out homogeneously, and therefore sometimes not caught in the small volume of a biopsy. A false negative result can lead to a delay in diagnosis and treatment of breast cancer.

Biopsy Analysis

Once the biopsied tissue is obtained, the tissue is preserved in a material such as formalin or formaldehyde to preserve histopathological information of the tissue and to prevent microbial infestation [17].

The biopsy is then processed by freezing it into a block of wax. This block of wax is sliced into microscopically thin slices to perform tests on. Since this slicing can be done manually, a pathologist would

like to be provided with a high biopsy volume in case of a skewed slice of tissue. Once the pathologist runs out of tissue, no further tests can be done. Therefore, it is extremely important to provide a pathologist with an adequate volume of tissue to perform tests on.

2.2 Functions of a Core Biopsy Device with Storage System

The functions of a core biopsy needle with a biopsy storage system are broken down in this paragraph to better understand the workings of such a device. The order of these functions is based on envisioning a biopsy procedure wherein multiple biopsies can be taken and stored within a single needle. A graphical representation of this process can be found in Figure 2.1.

- **Reach:** The device shall to be able to reach the site where the biopsy will be taken. The device shall introduce as little damage to the body as possible en route to the biopsy site.
- **Biopsy:** The device shall be able to biopsy the tissue of interest.
 - **Cut:** The device shall be able to cut through the tissue of interest.
 - * **Actuate:** The cutting movement of the device must be actuated.
 - * **Stop:** The cutting movement of the device must be stopped at a predetermined location.
 - **Disconnect biopsy from body:** The device shall be able to separate / disconnect the cut tissue from the body
- **Store:** The device shall be able to store the biopsy. The biopsy shall be separated from the body, i.e. not be in contact with the body after the biopsy is taken.
- **Transport:** The device shall be able to transport a biopsy inside the device to create space for a new biopsy.
- **Separate:** The device shall be able to separate biopsies.
- **Retract:** The device shall be able to retract from the body, causing as little damage to the body as possible.
- **Remove:** It shall be possible to safely remove the biopsies from the device.

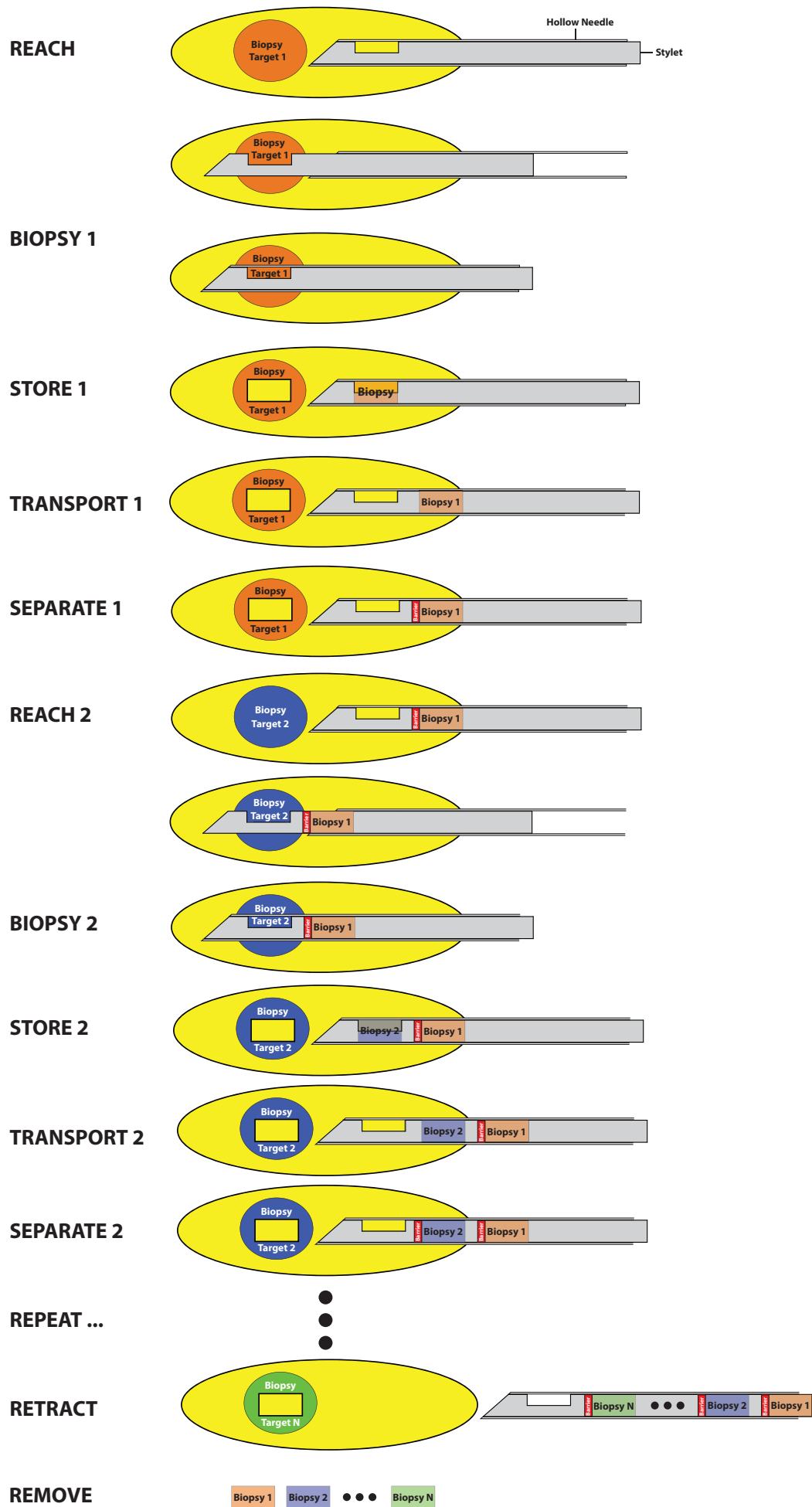


Figure 2.1: Overview of the steps in a core biopsy procedure.

2.3 Design Requirements

From the biopsy analysis paragraph and existing core biopsy devices, design requirements for a biopsy device can be investigated.

Needle Outer Diameter

Core needle biopsy is used to remove a small amount of tissue and is usually aided by imaging equipment such as ultrasound. The needles for this type of biopsy are around 1.27-2.18 mm (18-14 gauge) in (outer) diameter [12, 18]. The design requirement for the outer diameter of the device is set to 2 mm.

Needle Length

Typical biopsy needles for breast biopsies range from 100-200 mm [18]. The breasts are external body parts and therefore relatively easy to biopsy compared to internal body parts. The length of the needle is dependent on breast size and therefore ranges between 100 and 200 mm [18]. Therefore, 150 mm is chosen as a design specification for the needle length.

Number of Biopsies

The number of biopsies taken in a procedure depends, among other things, on the imaging technique used. For example, when stereo tactic guidance is used, the recommended number of biopsies to take is 5. When using ultrasound guidance, that number is 4 [19]. Ultimately, the number of biopsies required is based on the required biopsy volume for a pathologist to perform meaningful and sufficient diagnostic tests and the level of confidence that the correct tissue (the tissue of interest) was indeed biopsied. The number of biopsies to be taken by a single needle is set to 5.

Biopsy Volume & Length

The number of biopsies and volume acquired is related to the biopsy length (and diameter) per sample. The BioPince needle has options to set throw distance to increase or decrease the biopsy length. One of the reasons for having this option is to reduce unnecessary damage to the body during a biopsy. The biopsy

lengths range from 9 mm to 29 mm of biopsy length. Most side notch needles have a notch length of 15-20 mm [12, 18]. As a design specification, a 20 mm notch is chosen. At an inner diameter of 1.4 mm, this results, at 100% fill rate of the side notch, in approximately 150 mm³ of biopsy volume if 5 biopsies are taken.

2.4 Critical Function to Solve: Biopsy Transport

This paragraph describes the selection of the function for which concepts were designed. In the next sections, these concepts are categorized and evaluated. After this evaluation, a suitable concept was selected and further developed.

One of the issues for a core biopsy needle with a biopsy storage system is the accumulation of biopsied tissue inside the device, at the point where the device cuts away the tissue. When a core biopsy device has one spot to cut away tissue from the body, that spot has to be cleared after a biopsy to make way for another. Therefore, the 'transport' function was chosen as one of the critical functions to design concepts for in order to realize a core biopsy needle with a biopsy storage system. Other functions, such as separating, storing or cutting are solved in later stages after a suitable concept for transport is chosen. During the development of the concepts, the spring actuated cutting function of a core biopsy device was omitted. This function adds complexity to the design, but does not aid in the goal of designing a biopsy storage system for a core biopsy device.

2.5 Multi Biopsy Concept Categorization

Designing concepts can lead to a huge number of different ideas. In order to make sure that no category of solutions is overlooked, categories are introduced according to the MECE-principle (Mutually Exclusive, Collectively Exhaustive). Using this principle, any possible concept can always be aptly categorized.

Table 2.1: Overview of the design requirements for a core biopsy device with a biopsy storage system.

Needle outer diameter	2 mm
Needle length	150 mm
Biopsy length	20 mm
Biopsy volume	150 mm ³
Number of biopsies	5

All concepts are categorized based on their biopsy transport direction. There are three categories of biopsy transport direction. Inside a tube, a piece of tissue can move in three ways: axially, radially and tangentially. The concepts are categorized on how the biopsied tissue moves away from the spot where the biopsy was taken. A graphical representation can be found in Figure 2.2 .

2.6 Multi Biopsy Concept Generation

The basis for concept generation is the TruCut core biopsy needle. One reason is the prevalence of this type of needle in the industry. Secondly, the movement of the outer needle in this device can be evolved to include a mechanism to allow biopsies to be transported inside of the device. Thirdly, since this needle uses a side notch, it's possible to take multiple biopsies from the same site in the body.

The concepts were generated by means of a brainstorm. Over time, after some analysis and discussion of the concepts, additional ideas and concepts were added. The full number of concepts, as well as a more elaborate description of the concepts, can be found in Appendix A. A selection of the concepts can be found in Figure 2.3. These concepts are divided and categorized in the biopsy transport directions. More specifically, under the Axial Transport direction, concepts have been subdivided in 'push', 'slide' or 'pull' categories based on how the biopsied tissue is transported through the device.

Alternatives

One alternative to using the TruCut needle is to devise a new core biopsy needle that can cut at different sites, and store biopsies at different places inside the device, omitting the transport function. One such device could have multiple side notches at different locations for example.

Another alternative would be to base the design on a BioPince needle. This device could also be evolved

into a device that could cut multiple biopsies. A problem, however, is that this device cuts at the head, and would cut further and further through the body. One major reason not to use the BioPince is that biopsied tissue will be exposed to the body again when the outer canula would be drawn backwards for a consecutive biopsy. A second reason is that the BioPince cannot reposition using the stylet after a biopsy, since the biopsied tissue is in front of the stylet, and the stylet has no way to pass.

2.7 Multi Biopsy Concept Choice

Selection and Elimination Criteria

Different methods for concept selection exist. Due to the small scale nature of this device, elimination criteria were set up to filter unfeasible or unwanted solutions.

In order to choose a suitable concept for the design of a biopsy storage system for a core biopsy needle, concepts are eliminated based on the following categories of criteria: 1) biopsy transport direction 2) scalability for multiple biopsies 3) wishes and demands from the designers

Biopsy Transport Direction

Two out of three transport directions can be directly eliminated. In the concepts that use radial or tangential biopsy transport, the biopsy volume is reduced by at least a factor 2. Since pathologists require biopsy volume to be as high as possible, these concepts would still require multiple needle insertions to acquire sufficient biopsy material. Concepts (16) and (17) would accumulate virtually the same volume of biopsied tissue as a traditional side notch needle would, but then in smaller pieces. The alternative is to combine a radial or tangential transport direction with an axial transport direction. This solves the low biopsy volume problem, but this would require multiple cutting actuations to obtain the same biopsy volume, and the forceful cutting actuation (and stopping) causes patient discomfort.

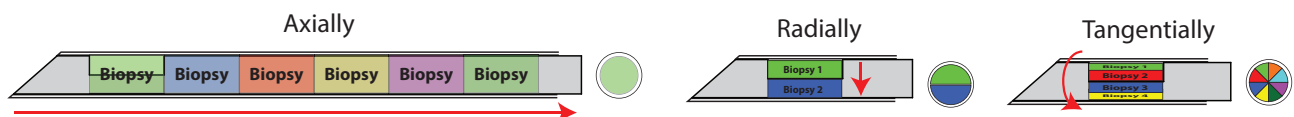


Figure 2.2: Options for biopsy transport directions to categorize biopsy transportation concepts.

BIOPSY TRANSPORT DIRECTION

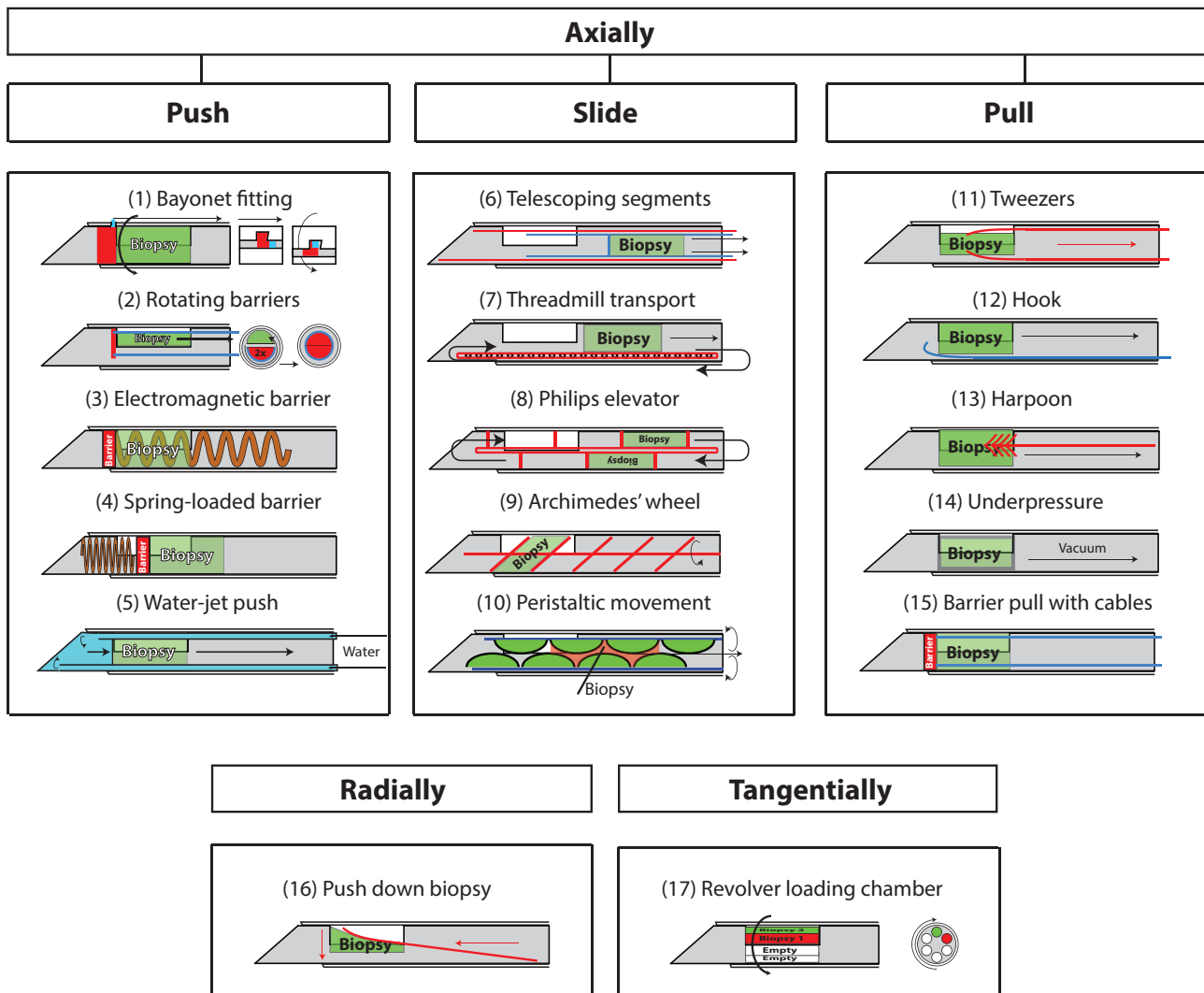


Figure 2.3: Overview of a selection of generated concepts categorized by biopsy transport direction.

Scalability for Multiple Biopsies

In order to acquire the required amount of biopsied tissue volume, a few concepts were eliminated. These concepts were deemed unable to scale up to allow not just a single biopsy to be transported, but multiple. In other words, these concepts can be considered as single-use transport mechanisms. An example is concept (5), where the water would have to be sealed off from the body somehow, but still allow a second biopsy to be taken and moved. Concept (15) is another concept that is eliminated on this basis. Once the barrier is pulled with cables, it cannot be put back into place by pushing on the same cables. Instead, it would require some sort of rod. This leads to the next (sub)category of elimination criteria.

Radially Scaling Mechanisms

Any mechanism that would scale radially in the needle of the device, in order to allow multiple biopsies

to be taken, can be eliminated. Such a mechanism would reduce the total biopsy volume. Concept (15) is one of these mechanisms. If the barrier were to be put back into place after pulling away a barrier, something like a rod must be used to push the barrier into place. This interferes with the space available for biopsies. Alternatively, multiple barriers could be introduced, with each barrier their own set of cables. But regardless, such a concept would scale radially at some point, thus reducing available space for biopsy volume. Likewise, Concept (6) 'telescoping segments' would conflict directly with the internal space of the needle of the device. The more biopsies need to be moved independently, the more segments are required. Each addition of telescoping segments would mean more radial space is used and less space is available for the biopsy. Likewise, this is true for Concepts (2), (11), (12) and (13).

Small Scale Radial Mechanisms

A general design rule for small scale, high aspect ratio (medical) devices, such as needles, is that radial mechanisms are practically impossible to manufacture on a micro scale. Any concept that relies on the use of a radial mechanism is therefore eliminated. This includes any type of gears, thread mills and (compliant) hinges inside the needle. Based on this feasibility criterion, concepts such as (7), (8), (9) and (10) were deemed unfeasible. Save Concept (7), the other three concepts also reduced biopsy volume per biopsy which is undesirable. Mechanisms that are based on tangential and axial movements however (rotating and sliding parts), are possible. This includes Concepts (1), (3), (4), (5) and (14) for example.

Wishlist of the Designer

The wishlist consists of a number of criteria which the device should follow. This idea behind these criteria is to avoid an overly complex system. The criteria are: 1) no cartridge system, 2) no external power input such as electricity, fluids such as water, no vacuum, no pressurized air. Due to these extra limitations, concepts such as (3), (5), (14) and to a certain extent (4), are eliminated. Concept (4), 'spring-loaded barrier' would require the spring to be reloaded for a consecutive biopsy transport. This reload action would introduce a rod or extra tube to enable the reloading, which, in turn, will reduce biopsy volume.

Concept Choice

A detailed overview of the complete concept selection can be found in Appendix A. In order to get

a 'feel' for the concepts, some cardboard prototypes were made to gain insights and to translate the concepts from 2D drawings to 3D mechanisms. Through the selection and elimination criteria, assisted by the cardboard prototypes, the bayonet concept was the only viable concept left and was selected to further design a biopsy storage system for a core biopsy needle. The bayonet concept is promising for a multitude of reasons. This concept does not interfere with the internal volume of the needle and biopsy volume is not lowered. The concept works axially and tangentially, which are the only two ways small scale devices can work. Furthermore, this concept would scale axially when designed for multiple biopsies, leaving more internal volume for biopsied tissue. The design of this concept is featured in the following sections.

2.8 Final Biopsy Needle Geometry

In this chapter, the chosen concept of a bayonet mechanism will be further developed into a core biopsy device, such that the device will be able to take and store multiple biopsies within a single needle. Throughout these sections, the design of the biopsy container system will be explained by going through the designs and functionalities of different parts of the device. In Figure 2.4, an overview of the entire device can be seen. The device consists of ten parts: the tip, four barriers, the inner needle, the bayonet needle, the outer needle, the rotation handle and the grip. Additionally, there are magnets inside the tip and inside the barriers.

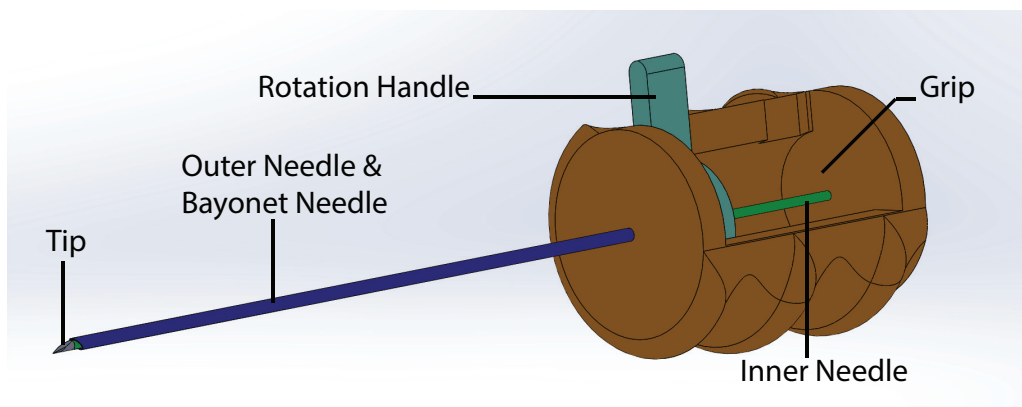


Figure 2.4: An overview of the device.

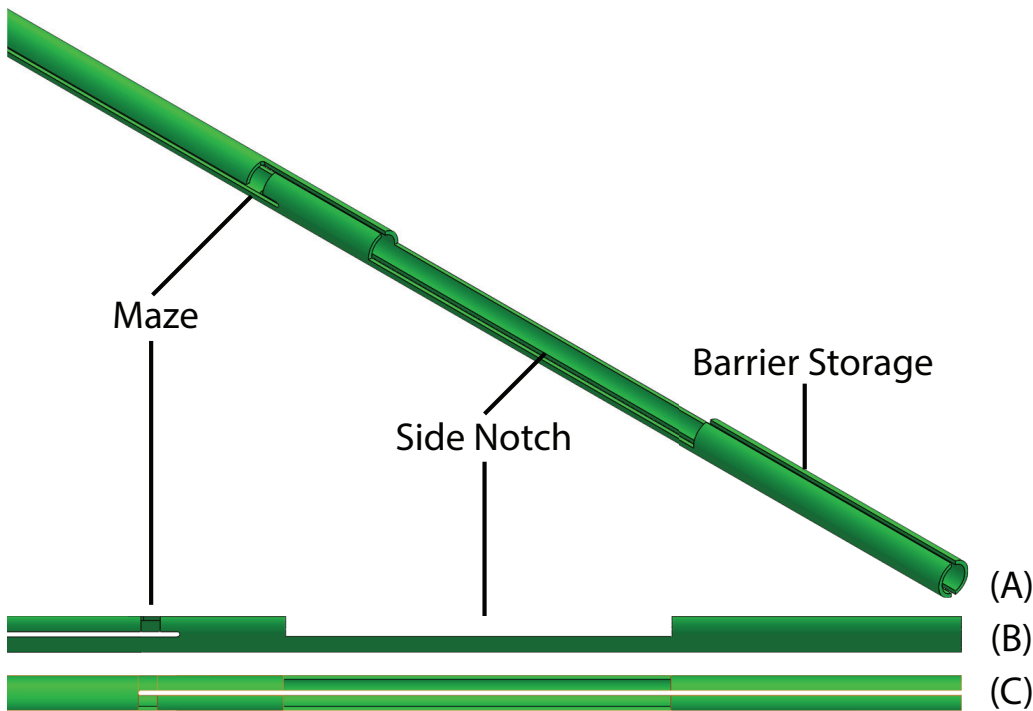


Figure 2.5: The inner needle part. Shown are three views: (A) is an isometric view of the tip of the inner needle. (B) is a side view of the tip of the inner needle. (C) is a top view of the tip of the inner needle. Visible are the side notch, the barrier storage and the start of the maze.

2.8.1 Inner Needle

The inner needle forms the basis of the device and can be seen in Figure 2.5. This part has to house the barriers, the biopsy and provide a strong and stiff enough structure for the biopsy mechanism.

Side Notch

The very first component about this part is the side notch, as can be seen in Figure 2.5. Without this side notch, there is no biopsy functionality. The notch is designed 20 mm in length. The height (or depth) of the notch is one radius of the inner needle's diameter. Making the notch smaller (less than one radius in height) results in less area for the biopsy to enter the device. Making the notch bigger (more than one radius) results in a less stiff inner needle. Additionally, at a height of one radius (or less), assembly of the device is also simplified as will be described later.

Tip: Barrier Storage

The tip of a normal side notch needle contains the sharp ended tip, and is relatively short. In a device with a biopsy storage system, the tip contains a number of barriers that are able to transport and separate the biopsies. Therefore, the tip is relatively long,

when compared to a traditional side notch needle. The increase in the length of the tip is proportional to the number of barriers that are stored in the tip.

Barrier Pin Slots

Along the length of the inner needle, there are two slots that guide the pins of the barriers. These slots are designed to be 180° apart, because the manufacturing process on a small scale for the prototype will be done using wire EDM. The slots have 90° turns in them in order to turn away the barriers and lock them in place, such that the barriers do not move back up towards the tip if a consecutive biopsy is taken.

2.8.2 Barriers

The barriers, which are stored in the tip of the inner needle, have the function to be grabbed by the bayonet needle through two external pins on the barrier. The barriers can be viewed in Figure 2.6. These pins are then guided through the slots of the inner needle, by moving the bayonet needle backwards and by rotating the bayonet needle. By doing so, the biopsy that was in the notch is transported backwards, because the barrier is clearing the notch space much like a piston in the cylinder of a combustion engine.

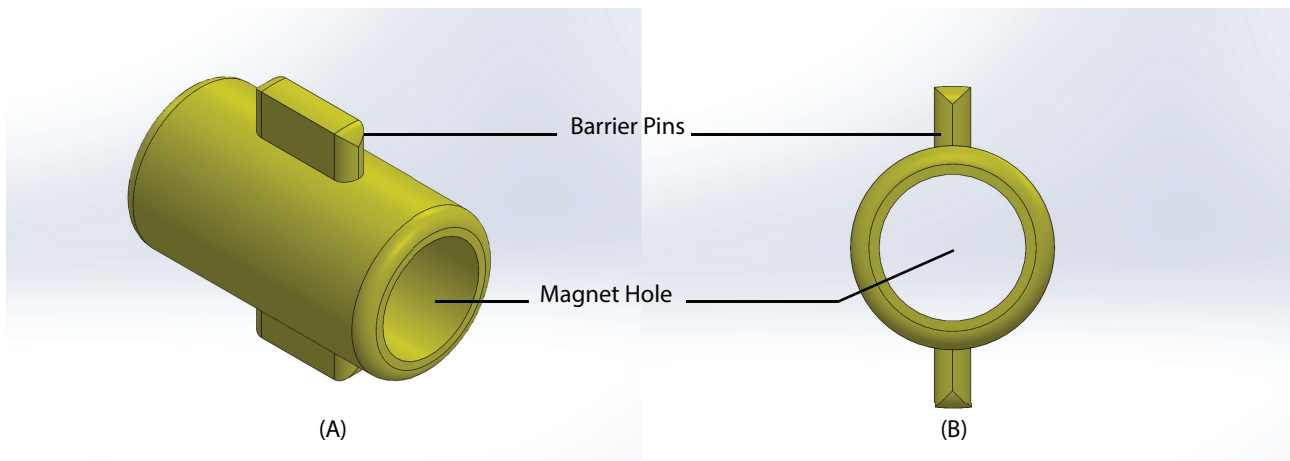


Figure 2.6: The barrier part. (A) shows the barrier part in isometric view. (B) is a front view of the barriers. Visible are the barrier pins used in the bayonet mechanism, as well as the holes to house magnets.

The barriers are cylindrically shaped and contain two pins for the bayonet needle to catch on to, and house magnets to stay connected to each other. These barriers pose a problem, or risk, in the sense that they can fall out of the needle through the notch. This can be solved in multiple ways. One way is to decrease the height of the notch to below one radius of the inner needle. This way, the barriers are always locked in the inner needle. This would also increase inner needle stiffness. However, it would also likely compromise biopsying mechanism quality. Because of assembly and biopsy functionality reasons, the notch is one radius and so this remains a problem to be solved, or a risk to be accepted. An other solution is to make barriers with three pins instead of two, which could shape lock the barrier inside the inner needle. However, making three slots is not feasible with wire EDM. The process also poses a problem with material removal around the notch, as it would significantly reduce the stiffness of the inner needle.

An other issue of the barriers is the ‘drawer effect’. If the barriers are too short relative to their diameter (i.e. aspect ratio), they can rotate and get stuck inside the inner needle. Luckily, this problem can be solved in conjunction with the barrier pins. the barrier pins cannot span the length of the entire barrier. The bayonet needle needs to be able to reach behind a pin, like in a bayonet fitting, or how a comb needs to be able to catch hairs, in order to pull it away. This results in pins that are less than the span of a full barrier. Since the pins can not be infinitely small, a sensible solution is to increase the length of the barriers slightly, which also alleviates the ‘drawer effect’.

The barriers are held in place in the tip of the inner needle by magnets. The concept is that there are always more magnetic force in the tip, holding the barriers in place, than there is magnetic force inside

a single barrier. This way, not more than a single barrier will be detached from the storage of barriers. Otherwise, the first barrier will be grabbed, and the entire stack of barriers would move along with the first one.

2.8.3 Bayonet Needle

The main function of the bayonet needle is to cut away the biopsied tissue from the body. The bayonet needle can be seen in Figure 2.7.

If this device is to be used for only one biopsy, the bayonet needle needs a cut-out for the pins of the barriers in the tip of the inner needle. Once the bayonet needle has moved forwards, it needs to be able to grip one of the barriers. Therefore, two more cut-outs have been made. The first one is a slot for the barrier pin to slide into. The second cut-out is made in such a way that the bayonet needle does not hit any other barrier pins. This set-up ensures that only the first barrier can be grabbed, because the bayonet needle is not able to rotate around any other barrier.

After this 90° turn in the slot, there is a small notch. This small notch is made to hook the barrier pin in, and for the bayonet needle to be able to pull the barrier backwards. Because of the small notch, the barrier will not move laterally inside the bayonet needle and can be pulled straight back, together with the biopsied tissue.

Now an issue arises for multiple biopsies. The slots are continued throughout the entire bayonet needle, just like in the inner needle. But the tangential slots need to be bigger in size to account for the fact that the barriers are not grabbed from the same location in the tip. This is more easily understood in the section on the biopsying sequence. An alternative would have been to design a mechanism in the tip that

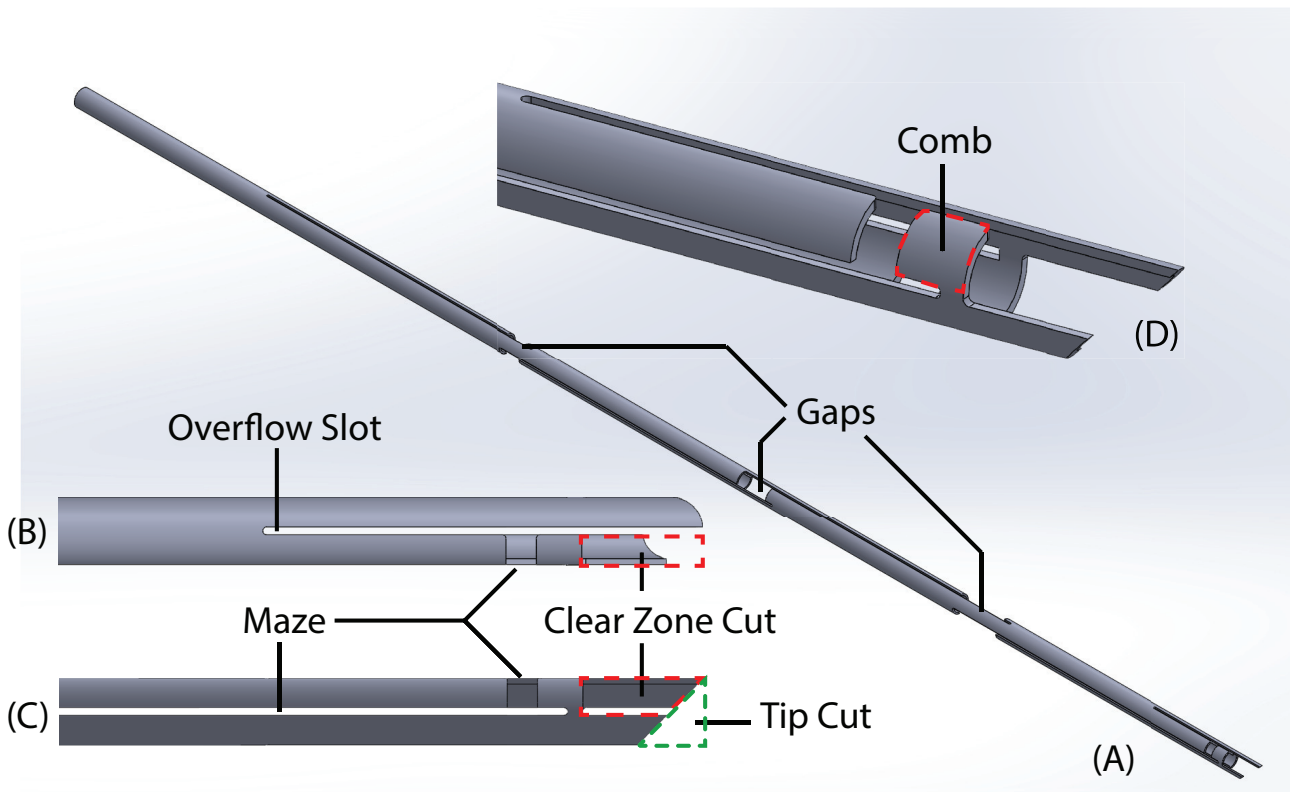


Figure 2.7: The bayonet needle part. (A) shows the bayonet needle part in isometric view. (B) is a top view of the bayonet needle. (C) shows a side view of the bayonet needle. (D) is a dimetric view of the tip. Visible are the overflow slot, the maze, the cuts for the ‘clear zone’ and the tip, as well as the gaps in the maze and the comb in the tip.

ensures the barriers are always positioned in the same spot. However, this would likely require some sort of radial mechanism which is hardly feasible on such a small scale.

2.8.4 Outer Needle

The function of this part is simple. It is to cover up the slots of the outer needle and to create a complete cutting profile for the outer needle. The outer needle can be seen in figure 2.10.

2.8.5 Tip

The tip of the device is a separate part, unlike in a traditional side notch needle. The main function of the tip is to pierce through the skin and tissue. Additional functions in this device is to house magnets and to reconnect the tip of the inner needle.

The shape of the tip in this design is taken from an existing side notch needle, since the focus is on the biopsy storage system. The tip can be glued in place to connect with the inner needle.

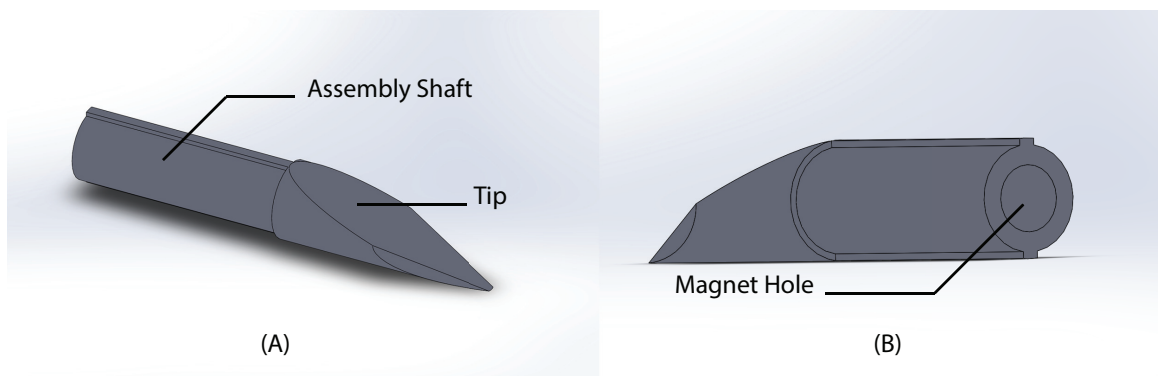


Figure 2.8: The tip part. (A) shows the tip part in dimetric view. (B) is a panned back view of the tip. Visible are the tip, the assembly shaft to connect to the inner needle, and the hole to mount magnets.

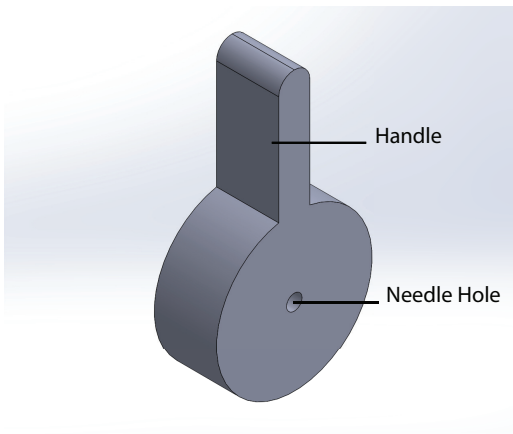


Figure 2.9: Handle part. Visible is the handle and the hole for the needle assembly.

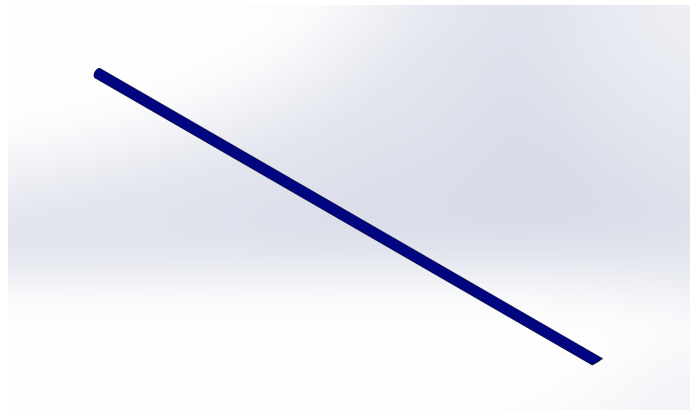


Figure 2.10: The outer needle of the device.

2.8.6 Handle and Grip

The function of the handle is to be able to operate the device. The handle also protects the internal mechanism of the barriers and pins. The materials are relatively weak and force feedback is small. Inside the body, there is no visual feedback of the location of the barriers and outer needle. That is why the handle has to take care of these functions. The inner needle is connected to the handle. This connection limits movement of the inner needle axially, radially and tangentially. The outer needle needs to be able to move axially and tangentially over the inner needle and can be actuated using a handle. The device cannot rotate more than 90° and does not have a throw distance of more than a single biopsy.

Exploded View

All parts can be seen in the exploded view in Figure 2.12 and the parts in the tip can be seen in more detail

in Figure 2.13. Compared to a traditional side notch needle, this device has one extra tube (bayonet needle), a few barriers and a hollow inner needle, rather than a solid shaft.

2.9 Final Biopsy Needle Functionality

2.9.1 Biopsy Taking Sequence

The biopsy sequence can be seen in Figure 2.14. In the figure, the first barrier is already moved backwards. Shown is how the bayonet needle has a clear-out in the maze to allow the bayonet needle to turn 90° without clashing with the barrier pins. Once the bayonet needle has moved forward, it can rotate the 90° **only** when the second barrier is grabbed. Then the bayonet needle can move backwards and independently transport the first and second barrier backwards, including biopsied tissue.

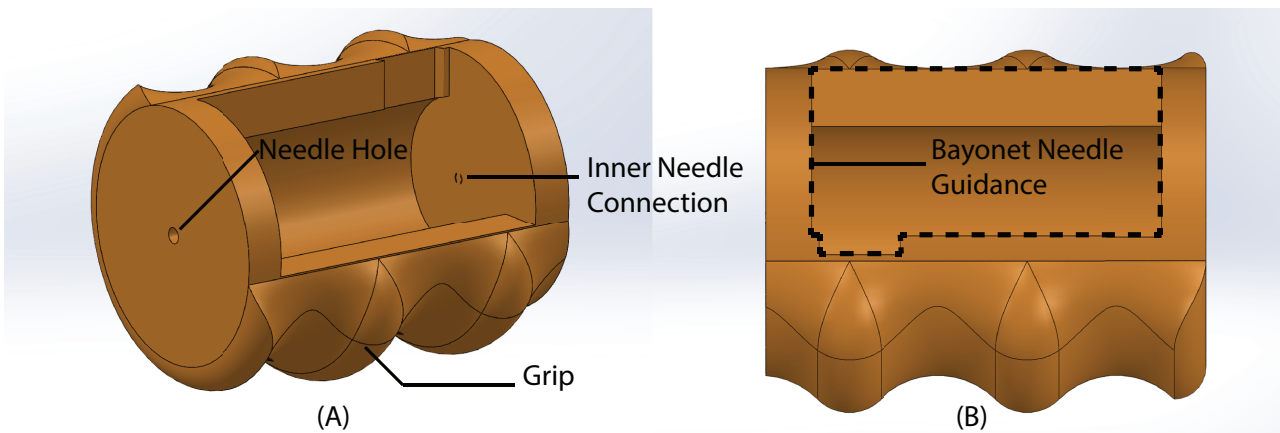


Figure 2.11: The grip part. (A) shows the tip part in dimetric view. (B) is a top view of the grip. Visible are the needle hole for the needle assembly, the inner needle connection in the back of the grip and the bayonet needle guidance path, which guides the bayonet needle.

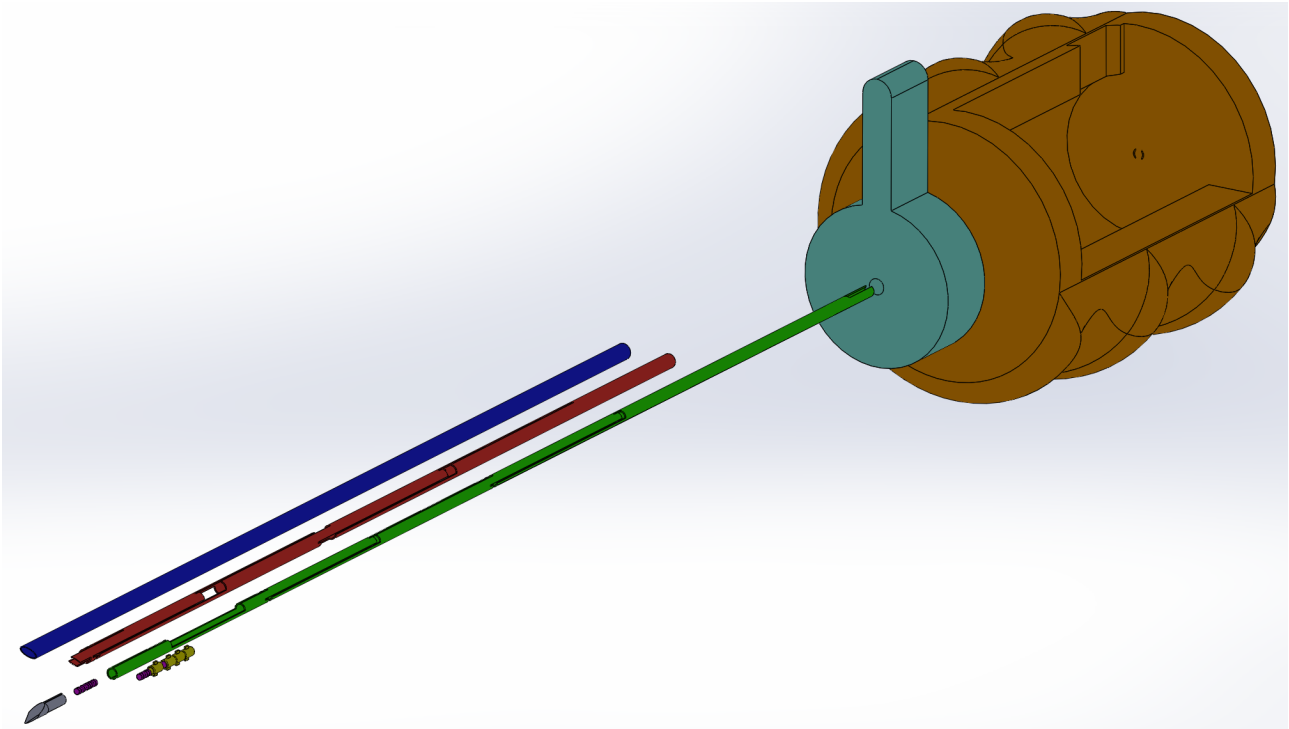


Figure 2.12: An exploded view of the device

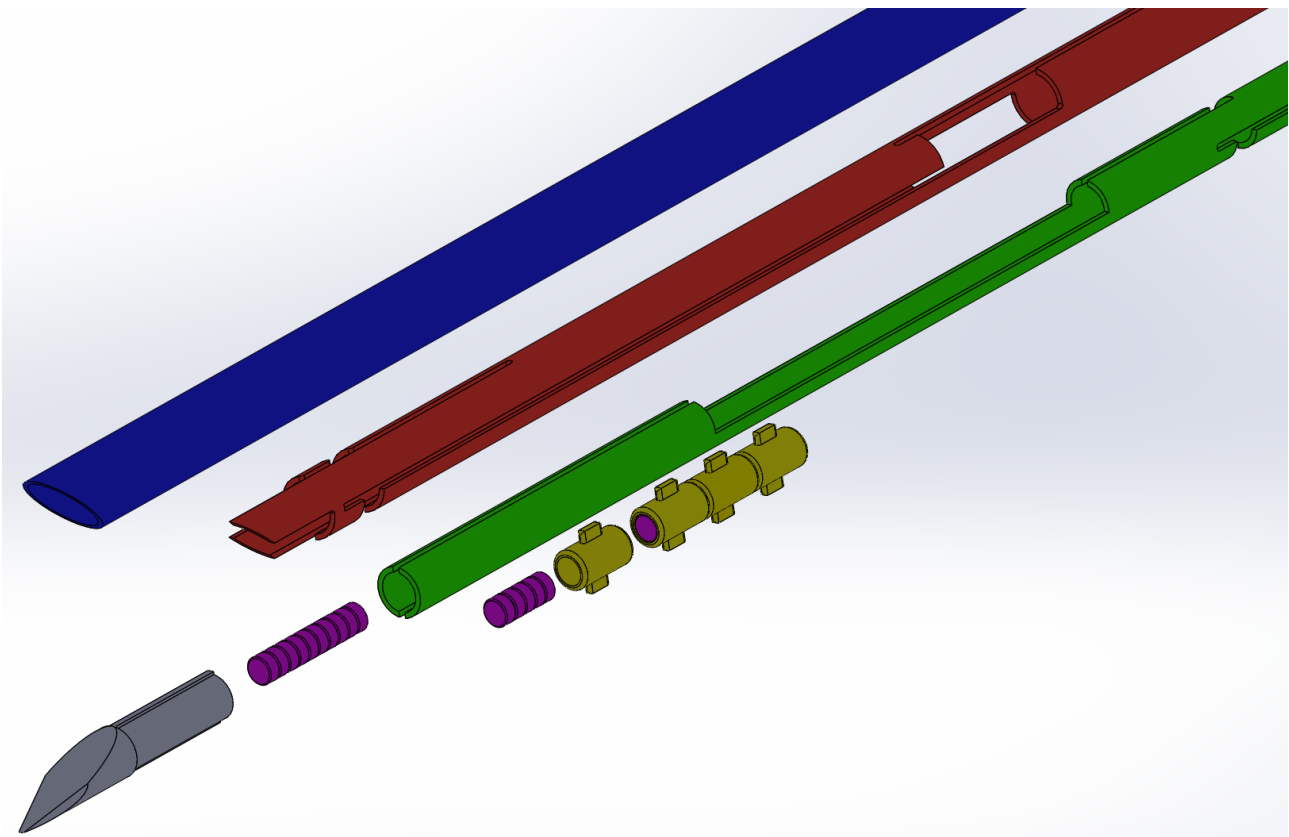


Figure 2.13: The grip part. (A) shows the tip part in dimetric view. (B) is a top view of the grip. Visible are the needle hole for the needle assembly, the inner needle connection in the back of the grip and the bayonet needle guidance path, which guides the bayonet needle.

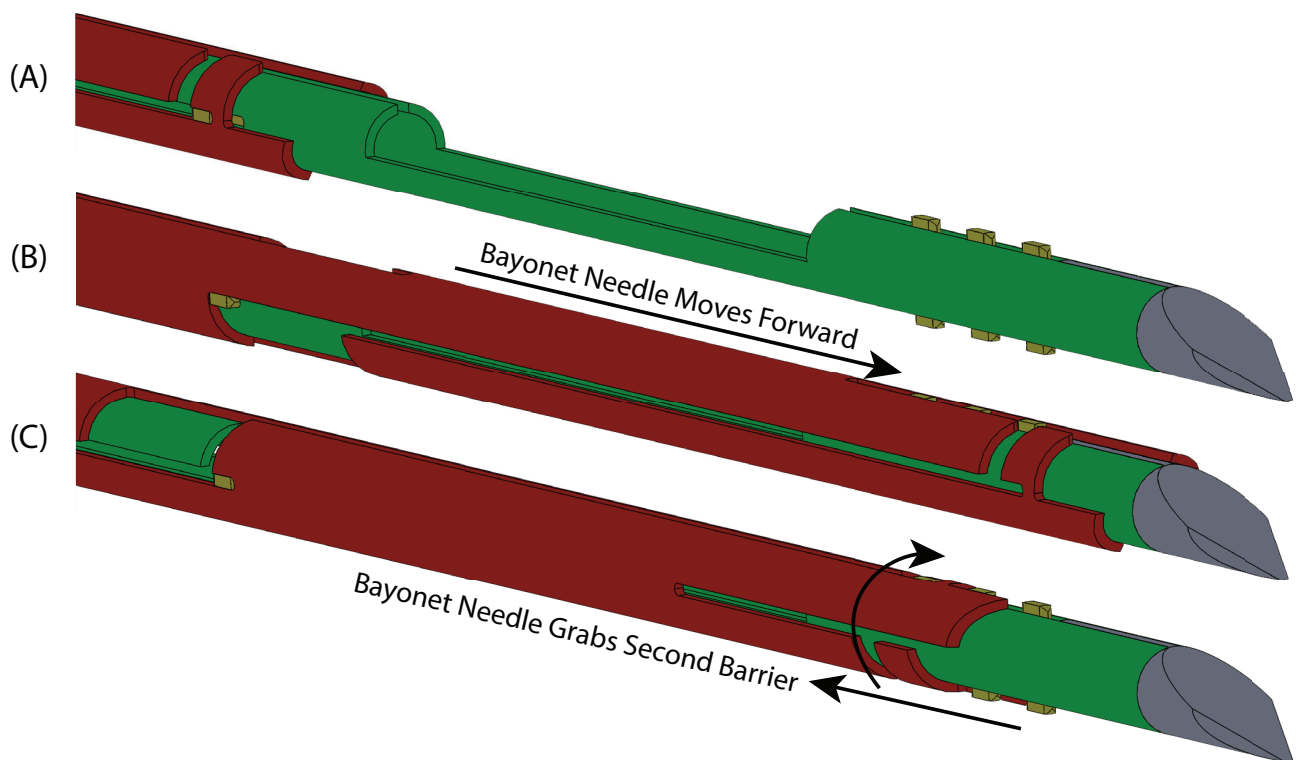


Figure 2.14: An overview of the mechanism in the tip. (A) the first barrier and biopsy is already transported backwards. In (B), the second biopsy is taken when the bayonet needle moves forwards and cuts through tissue. In (C) the bayonet needle turns 90° to grab the second barrier and then the bayonet needle pulls both the first and second barrier and biopsy backwards.

3. Prototypes

3.1 First Proof-of-Principle Prototype Objective

A proof of concept prototype was developed to demonstrate the bayonet concept for a core biopsy needle with a biopsy storage system. The objective is to show that the concept of barriers with bayonet pins, that are capable of being transported axially through the movement of the outer needle was possible. For this purpose, a proof of concept prototype was produced through 3D printing.

3.2 First Proof-of-Principle Prototype Design

The design, of which an exploded view can be seen in Figure 3.1, of the needle was adjusted heavily to facilitate the constraints of the 3D printer. The needle was kept at a length of 130 mm, but the number of biopsies taken was reduced to 3. The outer diameter was scaled up to 40 mm, in order to facilitate a minimum wall thickness of 5 mm throughout the device. This wall thickness should ensure sufficient strength despite the 3D printing process and the material characteristics of plastic. The length of the barriers was increased in order to compensate for the loss in aspect ratio, since the device is scaled radially by a factor of over 20, while it is not scaled axially.

Furthermore, two flanges were added to the bayonet needle, and the tip was adjusted and two supports were added such that the device could be used on a table top. These flanges ensure that the inner needle and outer needle do not create a ‘drawer effect’ by

keeping their axes on the same height.

The barriers were adjusted to have holes that do not run through the entire barrier. Likewise for the tip. This way, the number of magnets in each barrier and in the tip can easily be tuned to achieve the desired behavior: only one barrier should move at a time, when the bayonet needle grabs one. A second or a third barrier should not stick to the first through magnetic force.

3.3 First Proof-of-Principle Prototype Evaluation

In the evaluation of the proof of concept prototype, it was checked whether the mechanism would work, and whether it would work smoothly. All parts were printed with a 0.2 mm gap such that minimal post-processing was required to fit the parts together. The magnets were kept in the barriers using small pieces of tape. After removing some of the rough edges of the support material created during the 3D printing process, all parts were able to move smoothly. The bayonet needle was able to grab only the front barrier during a rotation and was also able to transport the barrier back smoothly. Performing the movement as if a second biopsy was taken went smoothly too. The second barrier was able to be grabbed, while the first barrier remained in place and did not lock the mechanism. While pulling the bayonet needle back after the second biopsy movement, both barriers were transported backwards by the bayonet needle. The device showed that three biopsy movements can be made smoothly.

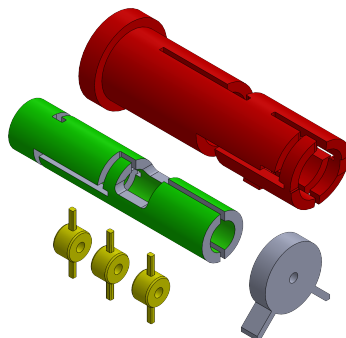


Figure 3.1: An exploded view of the design of the Proof of Concept prototype.

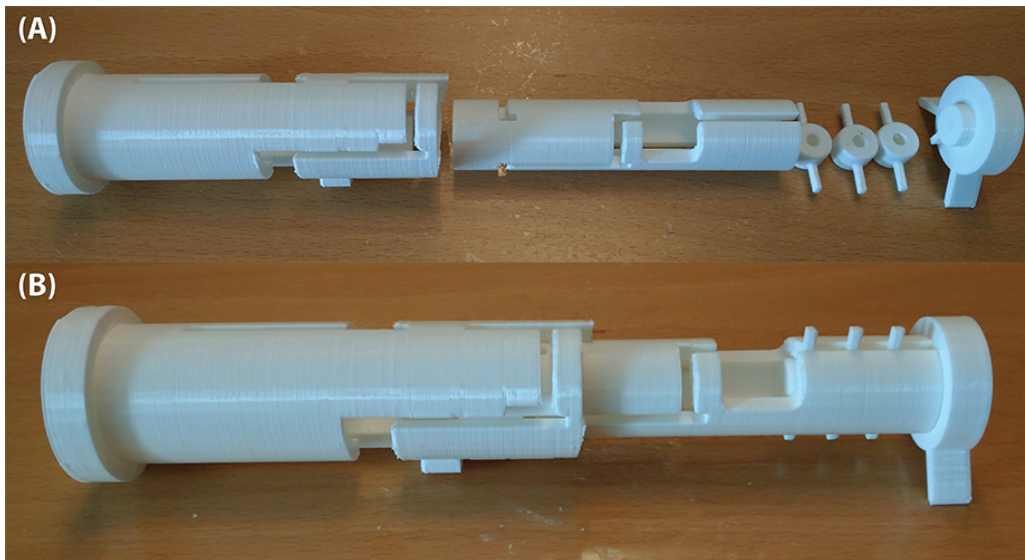


Figure 3.2: An view of the 3D printed version of the first proof of principle prototype. (A) shows the parts aligned axially. From left to right, the bayonet needle, inner needle, three barriers and the tip are visible. (B) shows aforementioned parts assembled with the barriers stored in the tip of the inner needle.

3.4 Final Prototype Objective

The objectives of developing a functional prototype were to evaluate the functionality of the biopsy transport and storage system, as well as feasibility and manufacturability of the conceptual design. It was decided to scale up the device in order to speed up the manufacturing and assembly process. The results of the transformation from conceptual instrument design to prototype are described in the next sections.

3.5 Final Prototype Design

The prototype design mainly consisted of re-dimensioning the design to fit available materials and to align manufacturing methods and design with the assembly process.

An exploded view of the prototype design can be found in Figure 3.7. The bayonet needle is a standardized 10x0.75 mm capillary tube. It can be seen in Figure 3.4. The inner needle is a standardized 8.5x1.5 mm capillary tube. These two tubes are coaxially assembled. The barriers (Figure 3.3) are 6 mm in outer diameter and house 1 mm thick, 2 mm outer diameter neodymium magnets. The barriers, including the magnets, are coaxially assembled in the tip of the inner needle. The slots of the inner and outer needles were cut out by means of wire EDM (Electrical Discharge Machining). The tip of the device was 3D

printed and houses a pocket for a stack of 2x1 mm neodymium magnets. The tip can be secured to the inner needle with a steel pin to facilitate disassembly, if that is required.

The inner needle and bayonet needle have been redesigned for a device that is able to take 3 biopsies. This simplifies the design of the bayonet needle, maintaining an equal slot width throughout the maze in the needle (Figure 3.4). Furthermore, the barriers have been increased in length, such that the bayonet needle requires less cut-outs to avoid contact with other barriers. This simplifies the production of the bayonet needle significantly. The number of barriers has been reduced to 2. This is the maximum number of barriers that can be in the device before the design of the bayonet needle has to be adjusted (i.e. the limit for constant slot width of the maze). 3 biopsies was chosen to be representative for a device that would be capable of performing 5 biopsies.

The actuation of the device is performed through a handle. This handle was 3D printed and fixed unto the bayonet needle through screws. This facilitates ease of assembly and disassembly during the experiments. The handle does not connect directly to the inner needle. The handle and the bayonet needle are free to move around, since the movement is mechanically restricted inside the needle by the barriers' pins. Therefore, there is no need for a grip to restrict movement of the handle for this prototype.

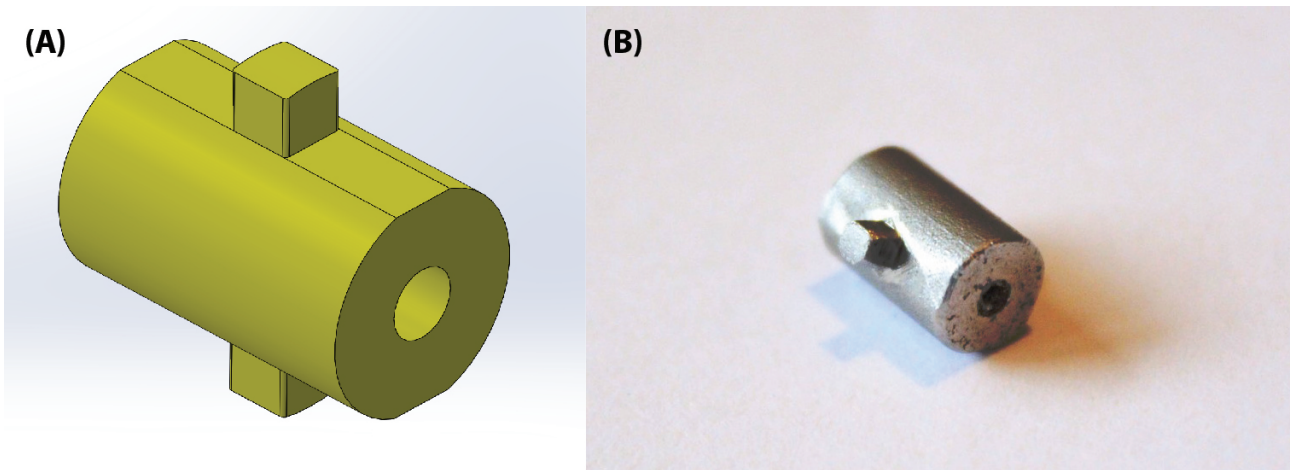


Figure 3.3: (A) is a view of the adjusted barrier part for the final prototype. The barrier is elongated (increased aspect ratio) to avoid the ‘drawer effect’. (B) shows the manufactured barrier part.

3.6 Final Prototype Development and Assembly

All parts, except for fasteners, have been produced at DEMO, TU Delft. The barriers were 3D printed out of metal (Figure 3.5). This greatly increases the ease of production of these parts. The bayonet needle and the inner needle have been produced out of stainless steel capillary tubes. Through wire EDM, the slots have been produced. The inner needle is discolored to alleviate internal material stresses of the capillary tubes. The reason is because the tubes are not produced seamlessly (a weld can be spotted inside the tube). During the wire EDM process, the closed contour of the tip is broken, and the internal material stresses cause the tip of the needle to split open and

out, making it impossible for the bayonet needle to be coaxially assembled onto the inner needle. The outer needle and handle have been merged and have been 3D printed in a single part. The 3D printed plastic is sufficiently transparent to facilitate inspection of the barrier during device operation. The handle and outer needle part is assembled onto the bayonet needle with two screws. These two screws are inserted into two helicoils inside the plastic and clamp onto the bayonet needle.

The magnets have been glued into the barriers and the tip with a tiny drop of Loctite 403. The tip of the needle is also adhered into the inner needle with a tiny amount of Loctite 403, since the assembly of the barriers can be done through the side notch.

The tubes, barriers and tip are illustrated in Figure 3.7. In Figure 3.8, the complete assembly is shown.

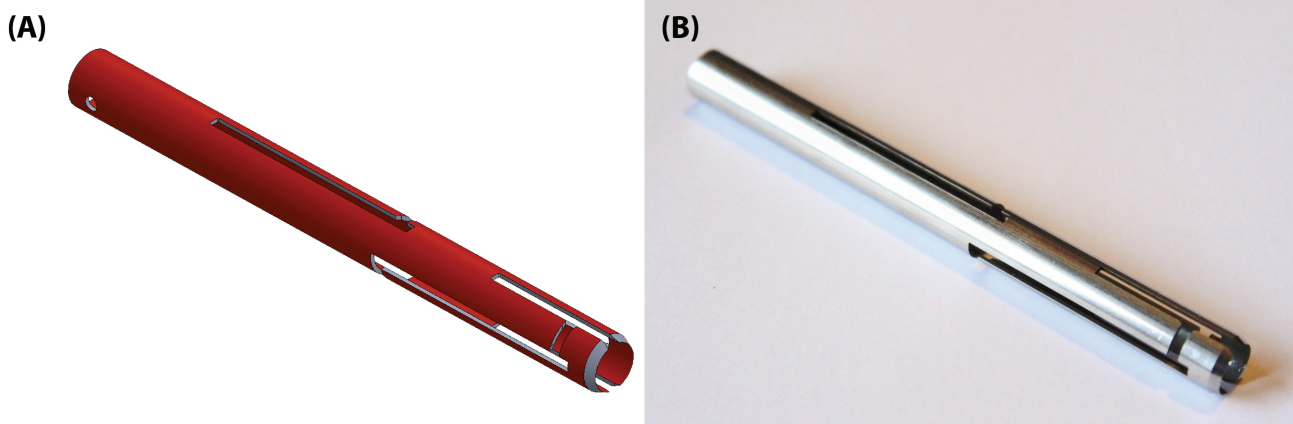


Figure 3.4: (A) is a view of the adjusted bayonet needle for the final prototype. The cut-outs at the tip have been simplified due to the elongated barriers from figure 3.3. (B) shows the stainless steel tube that has been manufactured for the final prototype.

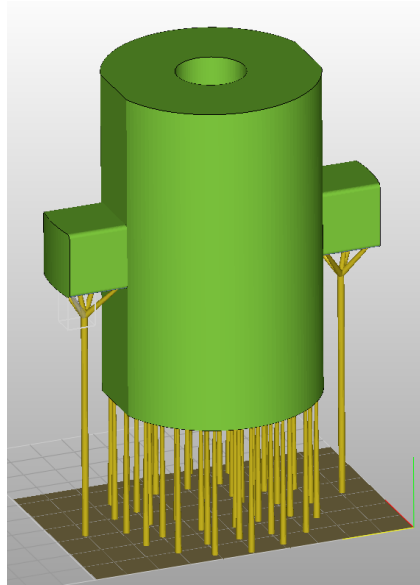


Figure 3.5: Support structure for printing of the barrier of the prototype.



Figure 3.6: Side view of the bayonet needle of the prototype. (A) shows the sideview of the design of the simplified bayonet needle for the final prototype. The cut-outs at the tip have been simplified due to the elongated barriers from figure 3.3. (B) shows the stainless steel tube that has been manufactured for the final prototype.

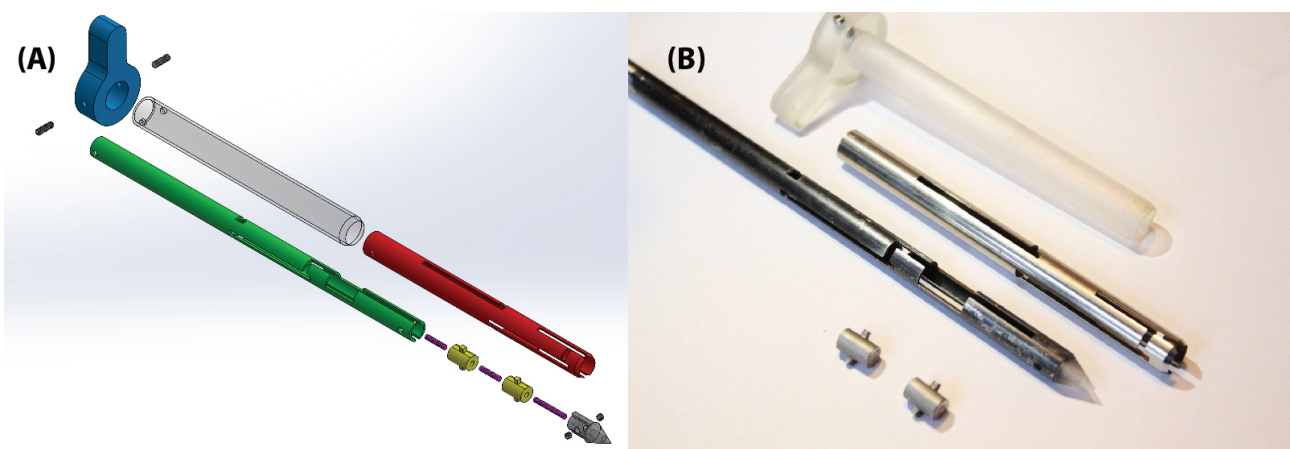


Figure 3.7: Exploded view of the prototype. (A) shows the exploded view of the design. (B) shows the exploded view of the manufactured prototype. Note: the transparent outer needle and the rotation handle have been merged in the final prototype. Additionally, in (B), the magnets are not visible since they are already assembled in the barriers and the tip, and the tip is installed in the inner needle.

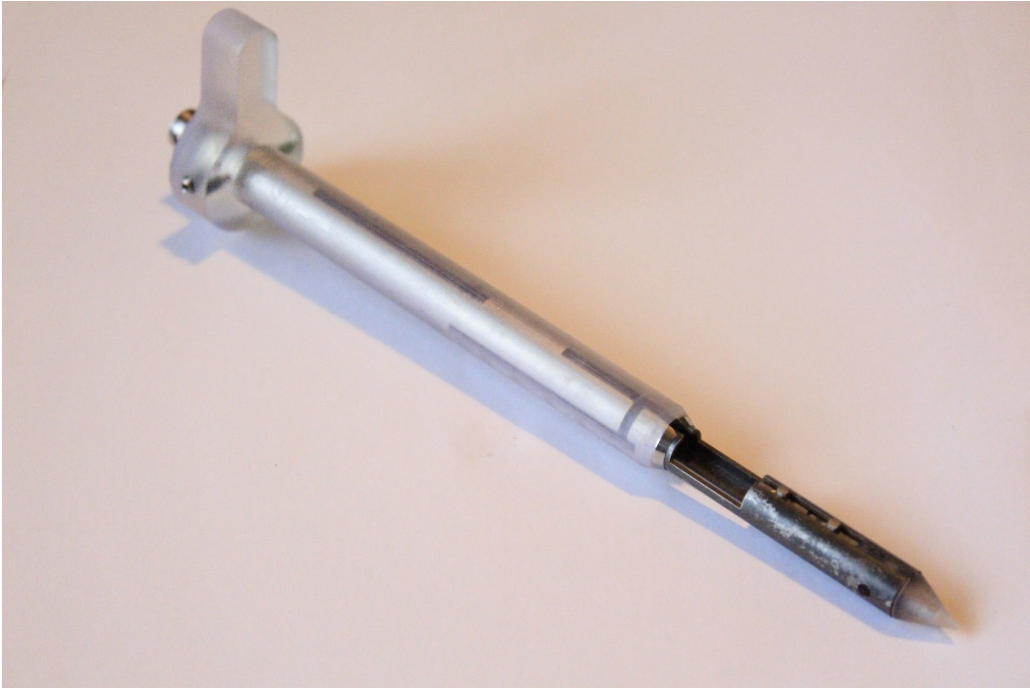


Figure 3.8: Assembled final prototype in its open position.

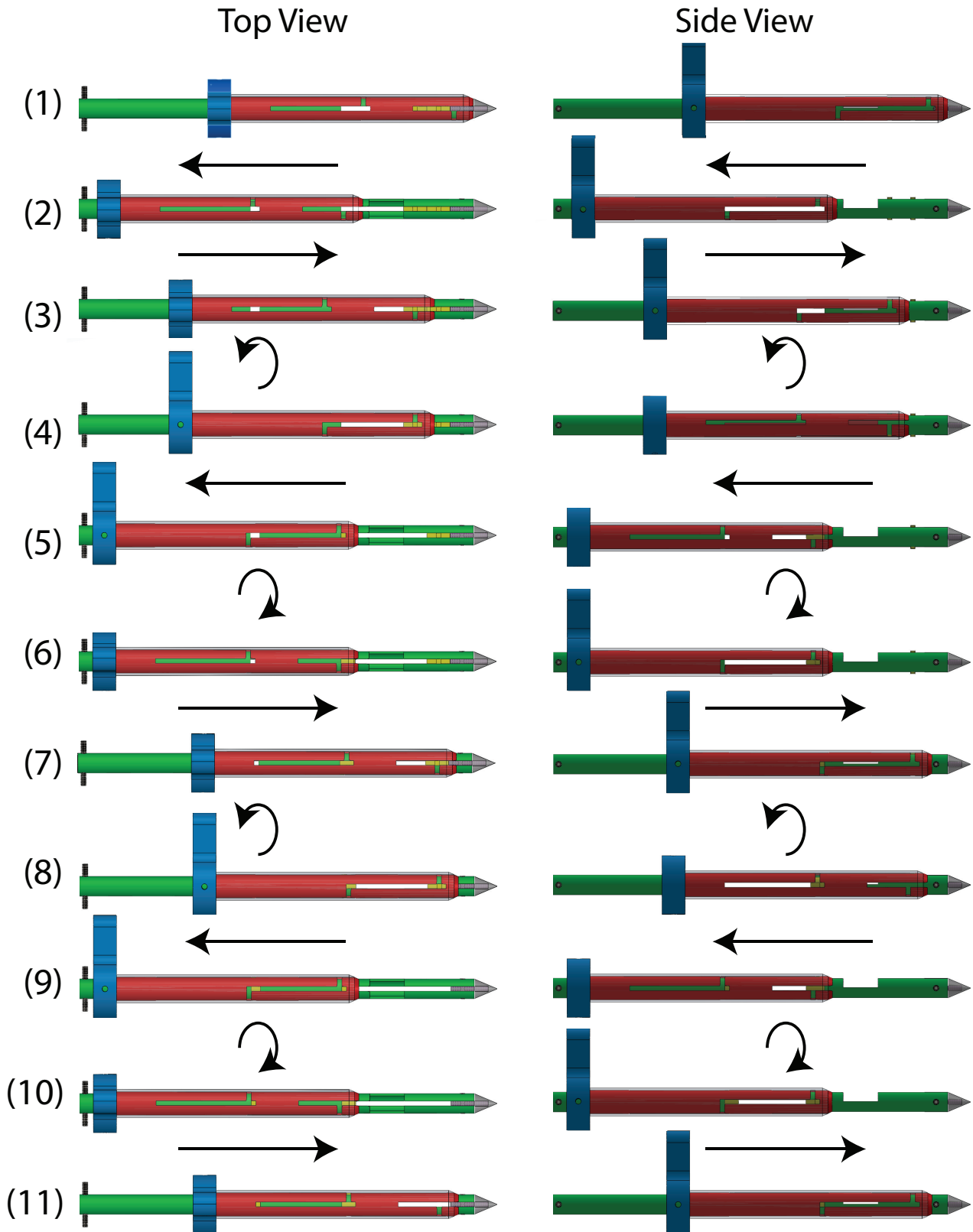


Figure 3.9: An overview of the movement of the final prototype when taking three biopsies. In (1), the needle is in its closed position. In (2), the bayonet needle retracts to allow tissue to form into the side notch. During (3), the tissue that formed into the side notch is cut off. In (4), the bayonet needle is grabbing onto the first barrier. (5) is the bayonet needle pulling the barrier and the biopsy back. (6) locking away the barrier by turning the bayonet needle 90°. (7)-(10) is a repetition of (3)-(6). (11) is cutting of the final piece of tissue.

4. Experiment

4.1 Goal of the Experiment

The goal of the experiment was to evaluate the final prototype in two steps. The goal of the first set of experiments is to evaluate the biopsy performance of the final prototype in different types of gelatin. The goal of the second set of experiments is to evaluate whether the final prototype was able to take and store three biopsies inside a single needle. This chapter describes the design, setup, execution and results of these experiments.

4.2 Biopsy Performance Experiment Design

For the experiment, three different gelatin test materials were created using everyday gelatin powder and water. These gelatins were created as follows: Test 1 was the recommended ratio of powder to water with 20 g per liter (2 wt% gelatin). Test 2 was 30 g per liter (3 wt% gelatin) and Test 3 was done with 40 g per liter (4 wt% gelatin). The prototype is then inserted and attempts to biopsy each of the gelatin blocks three times. The prototype is then retracted. The biopsies are then retrieved from the needle.

Biopsy Performance

The biopsy performance of the device is determined by the size of the biopsies that are obtained by the device, as well as the integrity of the pieces of biopsy taken. Due to the increased size of the needle, compared to a normal needle, the biopsying mechanism might not work as well. This performance metric is mostly used to check which gelatin concentration is optimal to achieve a biopsy result as well as pieces of gelatin that do not fall apart upon removing them from the needle.

Biopsy Performance Results

The gelatin of Test 1 (2 wt% gelatin) was not strong enough. The biopsy mechanism did not 'cut' through the gelatin. Rather, the gelatin squeezed into the needle through both the side notch and the slots of the maze. Retrieving the biopsies in pieces was next to impossible. Test 2 (3 wt% gelatin) resulted in big chunks of gelatin inside the needle. Some pieces fell off but the biopsies were relatively big and did not fall apart upon touching them. For Test 3 (4 wt% gelatin),

the gelatin was so stiff that it hardly entered the side notch upon biopsying. This test yielded no results in terms of biopsied pieces of gelatin. As a result, the biopsy transport and storage test in the next section will be done using the gelatin concentration of Test 2 (3 wt% gelatin).

Biopsy Transport & Storage Experiment Design

The biopsy transport and storage mechanism experiment is designed in such a way that three distinctly coloured biopsy pieces should be retrieved from the needle to showcase the possibility of biopsying three distinct pieces of tissue, without removing the needle. For this, a setup has been created using multicolored gelatin, stacked inside a regular drinking glass. The concentration of the gelatin is the same as in Test 2 (3 wt% gelatin). Additionally, everyday food coloring has been used to create red, yellow and blue gelatin. The results can be seen in the next section.

Biopsy Transport & Storage Results

The result of the biopsy transport and storage result can be viewed in Figure 4.2. With the 3 wt% gelatin, derived from the first experiment, the final prototype was able to biopsy and retract three pieces of distinctly colored gelatin from the drinking glass, without removing the needle in between biopsies. Upon removal, the blue and yellow pieces of gelatin were larger and had a higher integrity than the red pieces.

The bayonet mechanism worked well in all three tests. In Test 2, the device was able to extract three (intact) pieces of gelatin from the test sample and transport and store them inside the inner needle. The biopsies were extracted from the inner needle by removing the bayonet needle and cover. The first biopsy can be easily extracted using a knife. The second one can be extracted by sliding the barriers back out of the inner needle. The third biopsy was the hardest to extract, by shaking it out. A photo of the three pieces can be found in Figure 4.2.

4.3 Discussion

The validation of the final prototype was set up in two steps because of the larger scale of the device (12 mm diameter) compared to a traditional core biopsy device (1.4-2.2 mm diameter). This larger scale introduces problems for the biopsying mechanism, since

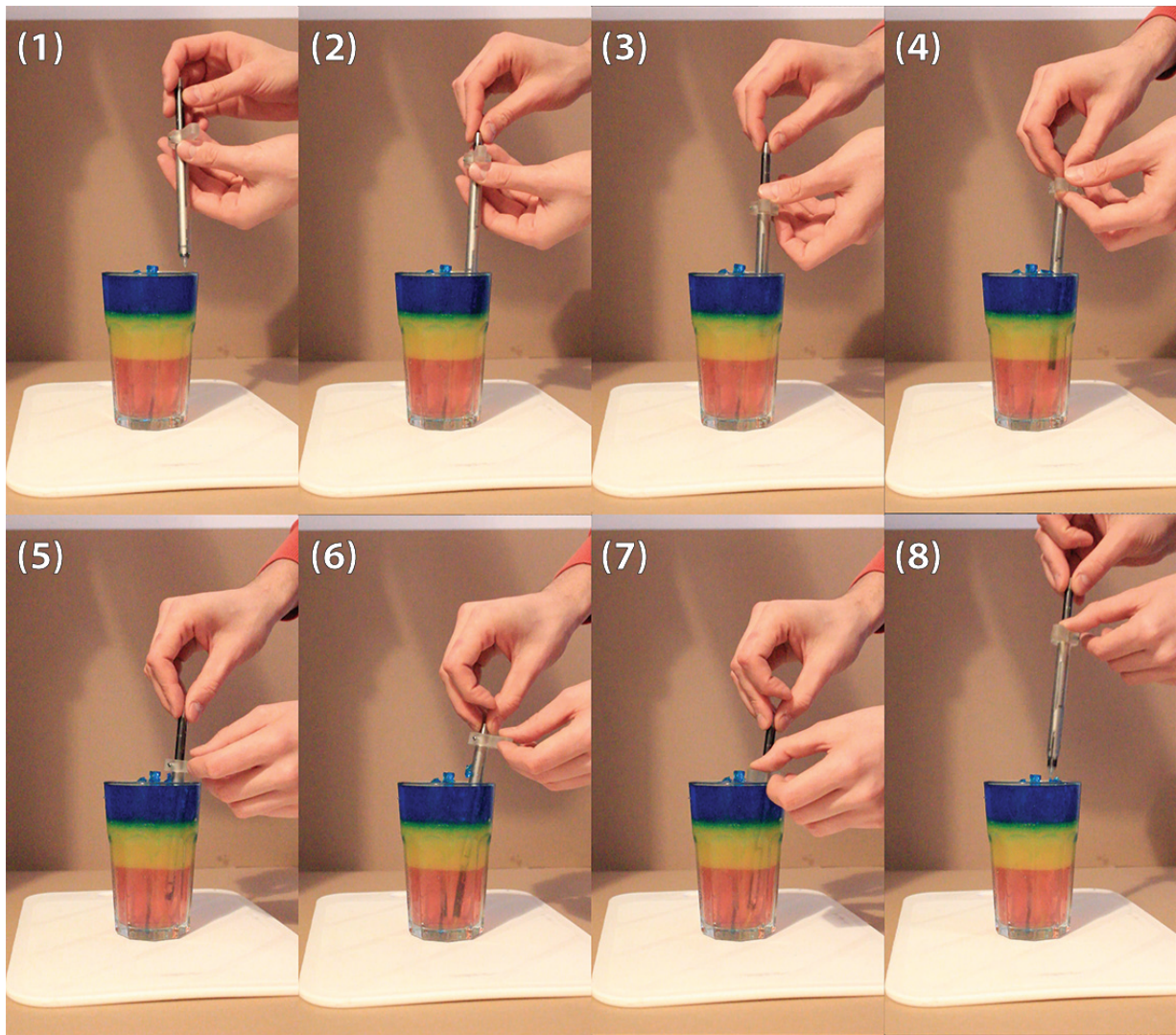


Figure 4.1: The experimental procedure. In step (1), the device is inserted. (2)-(7) are biopsy and transport steps for the blue, yellow and red gelatin layers. (8) shows the needle being retrieved from the gelatin.

the material has to displace roughly 10 mm more to reach the bottom of the side notch, compared to a traditional needle. This meant that finding a concentration of gelatin that allows the biopsy mechanism to operate similarly to a true-to-scale biopsy device in real tissue, was important to demonstrate that the biopsy transport and storage system works as intended.

The goal of this prototype is not to display excellent biopsying mechanics. Rather, the goal is to be able to transport and store the taken biopsies within the needle. With this goal in mind, the device performs excellently and is able to (independently) transport the different pieces of biopsy backwards through the needle during operation. When the scale of the device is reduced, a new test can be done whether the elongated tip introduces major problems for the biopsying mechanism.



Figure 4.2: The result of the biopsy transport experiment. Visible is the glass with the multicolored gelatin, the biopsy needle and the three differently colored pieces of gelatin, extracted from the glass using the biopsy needle.

5. Discussion

Throughout this study, it has been explored if and how a biopsy storage system for a core biopsy device can be developed. To evaluate the potential of this design study, both the instrument design and the functioning of the prototype will be discussed and recommendations are done for future development.

5.1 Device Manufacturing

Although the final prototype was designed and built for an outer diameter of 10 mm (excluding the transparent outer needle), which is five times larger than a traditional core biopsy device (2 mm), the manufacturing methods used were largely similar to the production of a true-to-scale device. According to the expert's opinion at DEMO (manufacturer of the prototype), the device can easily be shrunk down at least half its size.

The wire EDM manufacturing method should work even for the small scale of 2 mm. The limitation of the design of the prototype, and the device in general, shall be the barriers and the magnets that they house. Finding magnets of smaller size will not be an issue, they are readily available. However, the magnetic force of the magnets drops together with the area of the magnets. The barriers, currently built into a 10 mm scale device, were 3D printed and it is uncertain yet whether this process will also suffice at a scale of 2 mm outer diameter. A suggestion for the smaller scale barriers would be to micro-machine the barriers, or perhaps produce them through high quality injection moulding.

For the inner, bayonet and outer needles, it will in fact be easier to find off-the-shelf capillary tubes, since smaller increments of diameters are available at smaller diameter tubes. Regarding those capillary tubes: since the inner needle and bayonet needle are spliced open, internal material stresses will be set free. This can be a problem for the bayonet and outer needle to properly slide over the inner needle. A production method could be used to not fully splice the inner needle. Otherwise, reconnecting the spliced tip with a tip seems to alleviate the problem quite a bit. Another method of solving this internal stress is to heat up the material to alleviate internal stresses (as has been done for the final prototype).

5.2 Device Functionality

Biopsying and Transport Mechanisms

The final prototype showed an excellent transport mechanism. The prototype was supple and smooth to operate and gave clear haptic feedback during operation. The bayonet mechanism design ensures that the bayonet needle cannot turn unless a barrier is grabbed. The effectiveness of the biopsying mechanism is hard(er) to analyze, considering the scale of the final prototype. At a smaller scale, a redesign of the tip might be necessary, and a test should be done in more representative breast tissue with a smaller scale device. Questions still remain, such as: will the tissue form into the inner needle with an elongated tip? Will the barriers remain in place? Currently, the final prototype shows that *if* tissue somehow accumulates inside the notch, that the transport mechanism is capable of moving and storing the tissue. However, a problem arose using the device upside down. Gravity could cause the barriers to slide down unintentionally. Adding additional complexity to the maze so barriers cannot fall due to gravity if the needle is used upside down can solve this problem.

Biopsy Removal

Currently, removing the biopsies from the device takes longer than taking the biopsies. In the final prototype, the easiest way to remove all biopsies, is to completely remove the bayonet and outer needle from the device and manually grab the barriers and maneuver them to the tip again. That means that there is still one biopsy stuck deep inside the inner needle. An adjustment to the maze or the handle has to be made to simplify the actions required to remove the biopsies from the inner needle, and thus speed up the process. For example, the maze should have one extra slot at the end, through which a tool can be stuck to push the last biopsy forward. Alternatively, a different biopsy removal tool can be made, in which the core biopsy device can be inserted and it holds onto all the barriers as you push out the biopsies at the tip. This challenge can perhaps be tackled in conjunction with a new grip design.

This grip could have two paths: one for taking biopsies and guiding the bayonet needle into the right places to grab the barriers and to perform the biopsies, and another path to follow to remove the barriers and biopsies from the device. Alternatively, a differ-

ent grip can be put on if the two paths are too conflicting. Another solution is to possibly create more side notches that are never exposed unless the bayonet needle is removed. Then you would be able to retrieve biopsies just like a normal side notch needle. It could, however, significantly negatively impact the stiffness of the inner needle.

5.3 Conceptual Limitation: Optimum Number of Biopsies in Device

Due to the concept of storing a stack of barriers in the tip of the needle, the tip is elongated. Due to this elongated tip, the throw distance of the bayonet needle is increased. An optimum number of biopsies arises, because more barriers means longer tip, which means greater throw distance, which means longer mazes and fewer spaces for barriers to move into. Currently, five biopsies can easily be taken with a needle of 130 mm long inner needle (Conceptual Design). The true optimum might depend on more than just needle geometry. In case the length of the tip is determined by stiffness, by strength, or by different barrier geometry (barrier length), the possible number of biopsies that can move inside the inner needle might be different. A barrier geometry example: if the barriers do not display any drawer effect, perhaps their length can be reduced. A reduced length of the barriers means more barriers can be stacked inside the tip, and a higher number of biopsies can be taken. It remains to be tested and evaluated of how much importance the issue of an elongated tip is, if the biopsy number needs to be higher than five. Currently, assuming this new type of needle can acquire the same volume of tissue per biopsy, this new type of needle is designed to already take up to five times more tissue than a traditional side notch needle.

5.4 Other Recommendations

There are a few more recommendations on several parts of the design. Firstly, the barrier pins. Ensuring that the barriers run smoothly through the slots could be improved greatly by making the barrier pins round so they are self aligning with the slots of the needles. Secondly, a revisit of the biopsy mechanism and transport mechanism should be done, in combination with a spring-loaded needle: re-add the function of a spring for the purpose of cutting through tissue, and design a transport mechanism that can work in conjunction with a spring-activated biopsy move-

ment. Currently, the function of this spring is omitted, because it does not necessarily contribute to the functionality and design of a biopsy storage system. In a practical device, however, such a mechanism is necessary. The concept of the barriers and magnets should be reevaluated. Try to find a different way that does not use magnetic force to hold the barriers in place in the tip of the device. Magnets can influence imaging techniques and possibly nearby pacemakers: an alternative would be a great addition. Perhaps a solution with a slot in the tip that can compliantly release the barriers could remove the need for magnets.

Research about the aspect ratio of the barriers needs to be done to check how long the barriers have to be to in order to avoid the 'drawer effect'. In the prototype version, the barriers were made long enough to simplify the bayonet needle, by removing the need for a clearance cut, and that was the main reason. If shorter barriers perform just as well, this could reduce the tip size for barrier storage and allow for more biopsies to be taken in a single needle. An other recommendation would be to create a biopsy needle for more than three biopsies. Right now the prototype was made for three biopsies with two barriers. This eliminated the need for bigger gaps in the bayonet needle, as shown in the Design chapter. The 'drawer effect' needs to be tested in conjunction with the bigger gaps to see if this would form a risk of the barriers flipping or moving out of place. This 5-biopsy needle can be based off of the design from Chapter 2.8, which is already designed for 5 biopsies. A final recommendation is to try to design a device based on a BioPince working principle. Currently, the design is based on the side notch needles. Perhaps the working principle of the BioPince needle can be adjusted to also allow for a repetition of biopsying, thus creating an alternative biopsy storage system for a core biopsy device that cuts from the front (the tip) rather than the side (side notch).

6. Conclusion

This design study set out to design and prototype a core biopsy device that is capable of taking and storing multiple biopsies within a single device and a single insertion. To create meaningful design requirements, breast biopsy was chosen as an area of interest. After a range of concepts were created to solve the problem of transporting a biopsy in a core biopsy device, three of the concepts were prototyped with the aid of cardboard designs. After this prototyping, the bayonet concept was chosen to be the only suitable solution for the design of a biopsy storage system. This concept was developed into a design that not only allowed transport of a single biopsy, but rather multiple biopsies. The design consists of three needles, a tip, four barriers, and a grip and handle. The first needle is the inner needle, which houses the tip, the barriers, the side notch for biopsies, and a maze to guide the barriers. The second needle is the bayonet needle, which is able to cut through tissue and grab the barriers in order to transport biopsies backwards. The third needle is the outer needle which covers the gaps of the bayonet needle. This design was then prototyped into a scaled 3D printed version (25 times larger than a real biopsy needle) to proof the concept. On the basis of the lessons learned from this proof-of-concept prototype, a prototype was manufactured at a scale five times larger than a real biopsy device, using the same manufacturing methods as would be used for a real biopsy device with a biopsy storage system. A few simplifications were done to increase manufacturing speed, while still proving the concept. In the experiment, it was shown that it is possible to take and store three biopsies within a single needle using the prototype. In conclusion, this study has shown that it is possible to design a core biopsy device that is capable of taking multiple biopsies within a single needle insertion. This device increases biopsy volume per needle insertion and allows multiple biopsies to be taken from either the same, or different locations in the body during a single insertion. In the future, a core biopsy device with a biopsy storage system can be used in medical research, to ensure that the same tissue site was biopsied. If production costs can be low enough, it could also be used to replace a traditional core biopsy device that is capable of acquiring higher tissue volume per needle insertion than a traditional core biopsy device.

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A. Concept Choice Elaboration

This appendix includes all concepts for transportation that were created during the project. These concepts are displayed in Figure A.1, Figure A.2 and Figure A.3. In this appendix, all concepts are rated on several criteria as can be seen in Table A.1.

- Scalable for multiple biopsies
- Radially scaling mechanism
- Use of radial mechanisms
- Cartridge system or external power

For the *scalable for multiple biopsies* category, the concepts were judged based on their expected ability to allow multiple biopsies to be taken through the conventional side notch. If adjustments need to be made to the cutting location, method or a concept was simply intended for single use, then that concept receives a (-). Any concept that was deemed possible to scale up for multiple biopsies received a (+).

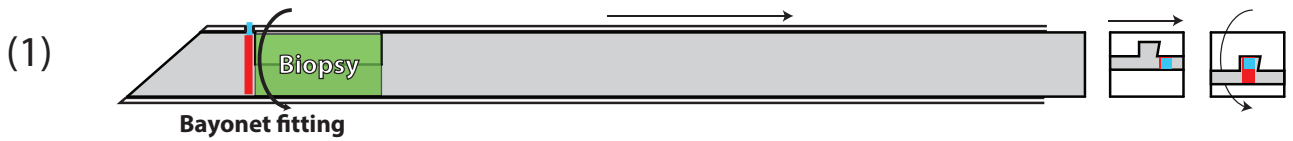
For the *radially scaling mechanisms* category, concepts were judged somewhat in conjunction with the scalable for multiple biopsies category. Is a concept able to take multiple biopsies without scaling radially? I.e. would extra tubes, rods or cables have to be introduced inside the needle in order for the concept to be able to take more than a single biopsy? If that is the case, then a concept received a (-). Preferably, to uphold a high level of biopsy volume, a concept does *not* scale radially when scaling up for multiple biopsies. In that case, it receives a (+).

For the *use of radial mechanisms* category, all concepts were judged based on the prevalence of a radial mechanism. In general, radial mechanisms, even compliant ones, are hard to manufacture and realize on a micro scale. If a concept used radial mechanisms, such as gears, hinges (including compliant hinges) or a similar radial mechanism, it receives a (-). If no radial mechanism was present, or if the radial mechanism is judged as feasible, then it received a (+).

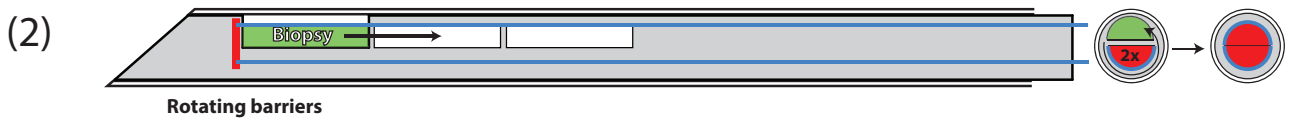
For the *cartridge system or external power* category, the concepts are judged based on their reliance on external power sources such as electricity, (pressurized) air, vacuum or water. Additionally, if a concept is only able to take multiple biopsies by using a cartridge system, i.e. remove the entire internal volume of the core biopsy device and replace it with an 'empty' mechanism, it was judged as a (-). Any concept that does not rely on external power or a cartridge system was judged with a (+).

In case a (+/-) has been assigned, it is because the outcome is expected to be neutral or uncertain. It means a solution is not impossible, but rather likely undesirable. These solutions are anticipated not to be insurmountable, but they will likely result in a less than ideal working of the core biopsy device.

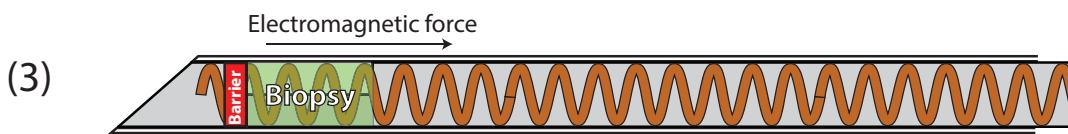
Based on the criteria table, one concept has been chosen: the bayonet fitting concept.



Bayonet fitting: outer needle has small 'hooks' and grabs barriers backwards



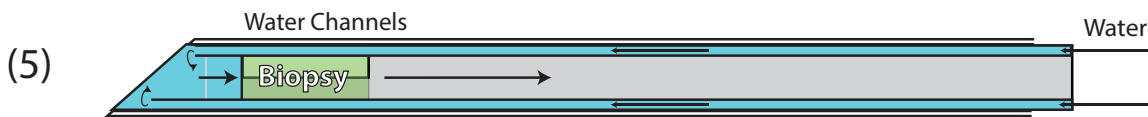
Two half barriers rotate to become a needle wide barrier which can be pulled back



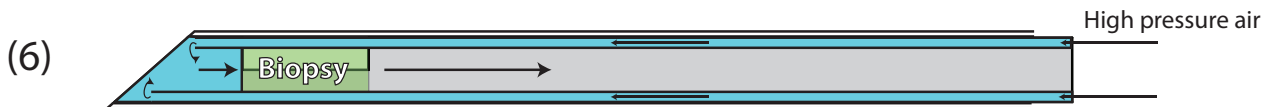
Barrier is moved through coil with electromagnetism



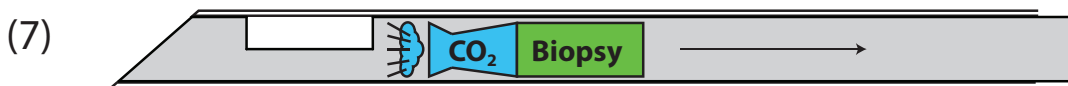
Preloaded spring pushes barrier



Water behind biopsy



High pressure behind biopsy

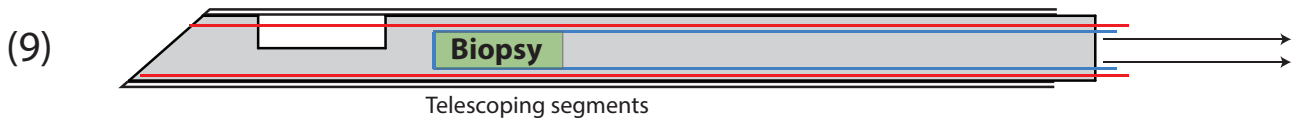


Pressurized biopsy container pushes biopsy forwards

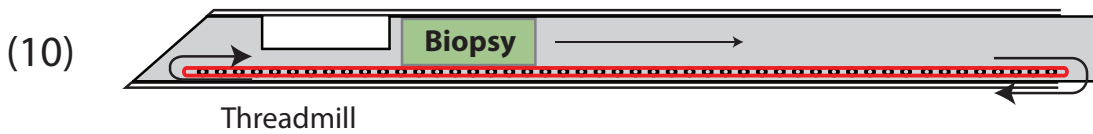


Diaphragm movement: diaphragm, like in a camera, creates a barrier

Figure A.1: Overview of concepts.



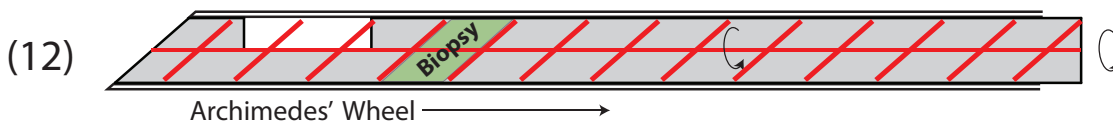
Telescoping elements slide biopsy out



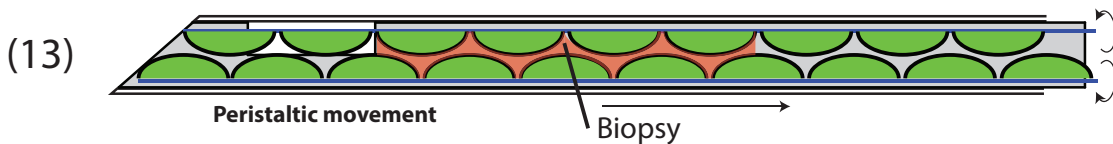
Threadmill transports biopsy out of the needle



Philips elevator principle. Like a threadmill with chambers



Archimedes' wheel transports the biopsy out of the needle



'Peristaltic movement': two rotating shafts push biopsy forward



Needle contains biopsy chambers. Revolver mechanisms presents next empty chamber



No pressure: vacuum assisted



Biopsy+barrier is pulled by cables

Figure A.2: Overview of concepts.

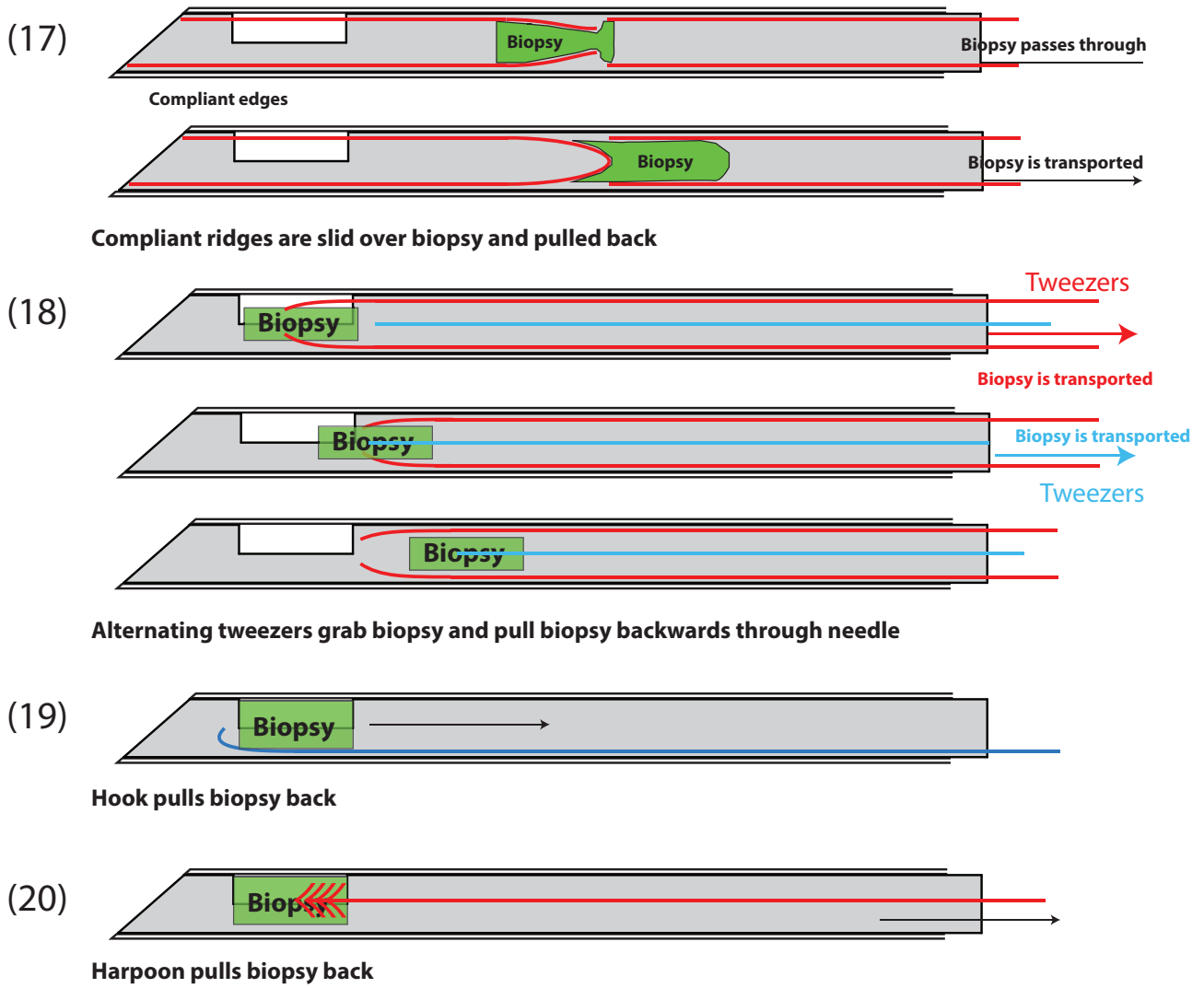


Figure A.3: Overview of concepts.

Table A.1: My caption

Concept	Description	Scalable for Multiple Biopsies	No Radially Scaling Mechanism	No Radial Mechanism	No Cartridge or External Power
1	Bayonet fitting	+	+	+	+
2	Rotating barriers	-	-	-	-
3	Electromagnetic coil	+	+	+	-
4	Preloaded spring barrier	+	+	-	+/-
5	Water-jet push	-	+/-	+	-
6	High pressure air push	+	+/-	+	-
7	Pressurized air container	-	+	+	-
8	Diaphragm barrier	-	-	-	+
9	Telescoping segments	+	-	+/-	+
10	Threadmill transport	+	+	-	+/-
11	Philips elevator	+	+	-	+/-
12	Archimedes' wheel	+	+	-	+/-
13	Peristaltic movement	+	+	-	+/-
14	Revolver	+	-	-	+
15	Vacuum assisted	+/-	+/-	+	-
16	Barrier cable pull	+	-	+	+
17	Compliant ridges	+/-	-	-	+
18	Alternating tweezers	+/-	-	-	+
19	Hook	+/-	-	-	+
20	Harpoon	+/-	-	-	+

B. Rapid Prototyping Concept Development

To get a better touch and feel of the concepts that were developed, a number of prototypes have been made to test some mechanisms. These prototypes were made of cardboard, cups, pop-sickle sticks, tape and paper, but nevertheless provided insight into the viability of the concepts.

B.1 Bayonet Fitting Concept

Cardboard Prototype

For the bayonet fitting concept, a cardboard tube was used in combination with some cardboard coffee cups. To replicate the inner needle, the solid cardboard tube was used. To replicate an outer needle, a piece of paper was folded around the cardboard tube. The barriers with the bayonet pins were replaced by coffee cups that had a pop-sickle stick stuck through them. Long cut-outs were made in both the cardboard tube and the paper tube to design the bayonet fitting.

This early concept showed that it is possible to pull the coffee cups through the inner cardboard tube by pulling on the pop-sickle sticks with the paper tube. An other insight is that the internal material stresses of the cardboard tube appeared as soon as a cut was made and that this would be a problem as well in manufacturing. The cardboard tube would split open as soon as a cut was made. An other insight was, if multiple coffee cups had to be pulled back, the alignment of the coffee cups was extremely important, such that they lined up with the the slots in the paper tube. This would be a challenge to solve.

Laser Cut Prototype

Because of the promise of the cardboard and paper tubes that this concept was made of, a laser cut prototype was made. Rather than inner and outer needles coaxially rotating around each other, this prototype was made up of a 'base' with a slot in it for the barriers, some 'walls' to support the 'outer needle', which was essentially an outer needle with a slot in it, but then flattened out. An addition was made to keep the barriers together with the help of magnets. The magnets ensured the barriers would stick together and not randomly fall out of the device.

A few insights from this prototype:

- The outer needle, or the top plate, had hardly any stiffness left due to the cut that was made.
- If multiple barriers are stacked behind each other, a small gap needs to exist on the top of the barriers for the outer needle to be able to grab in between the barriers.
- There needs to be a cut-out zone if multiple barriers are stacked up against each other, otherwise not a single barrier could be grabbed.
- Barriers need to be grabbed from both top and bottom. In this prototype, they were pulled from the top. Because the magnets held the barriers back in the center, a small moment was applied to the barriers which caused them to tip over.
- Aligning the barriers for multiple was still hard. The barriers were able to move some, which caused the outer needle to be unable to grab multiple barriers.

B.2 Radial Barrier

One concept was to be able to slide a tube or rod underneath the biopsy chamber, throw up a barrier and then pull that barrier back. For this purpose two cardboard prototypes were made. The first prototype was made consisted of a long piece of cardboard. With a half thickness slice through the back of the cardboard, a compliant hinge was created. By cutting out 'pull-tab', the barrier could be put up by pulling on the pull-tab.

To evolve this concept one step further, the idea was implemented in a coffee cup. Several cut-outs and pull tabs later, that have been rejoined by the taping a ring on it to connect all the pull tabs, the prototype was

done. Quickly it became apparent how precise the different pull tabs and cut-outs would have to be aligned. Furthermore, the strength and stiffness of the barriers was hard to control, since thin pieces of paper are being put up straight and are by definition not stiff in this direction. The only way to solve this is using a structure in the orthogonal direction of the paper.

This prototype quickly lead to the conclusion, among with advice from the professor, that small scale radial mechanisms such as these hardly ever work and that it is much wiser to think tangentially and axially, than it is to think of radially scaling or radial mechanisms.

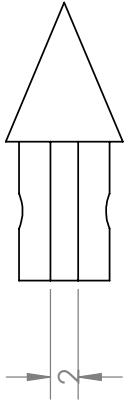
B.3 Rotating Barriers

An attempt was made to create rotating barriers inside the original cardboard tube used for the bayonet fitting concept. It quickly became apparent that, despite it being possible, the internal structure of the needle would be too complex to manufacture. The barriers would have to be able to slide underneath the space where a biopsy is taken (reducing biopsy volume), then turned around to create a needle wide barrier, and then be pulled back. This would require a 'floating' internal structure inside the needle. This concept is simply not feasible.

C. SolidWorks Drawings Prototype

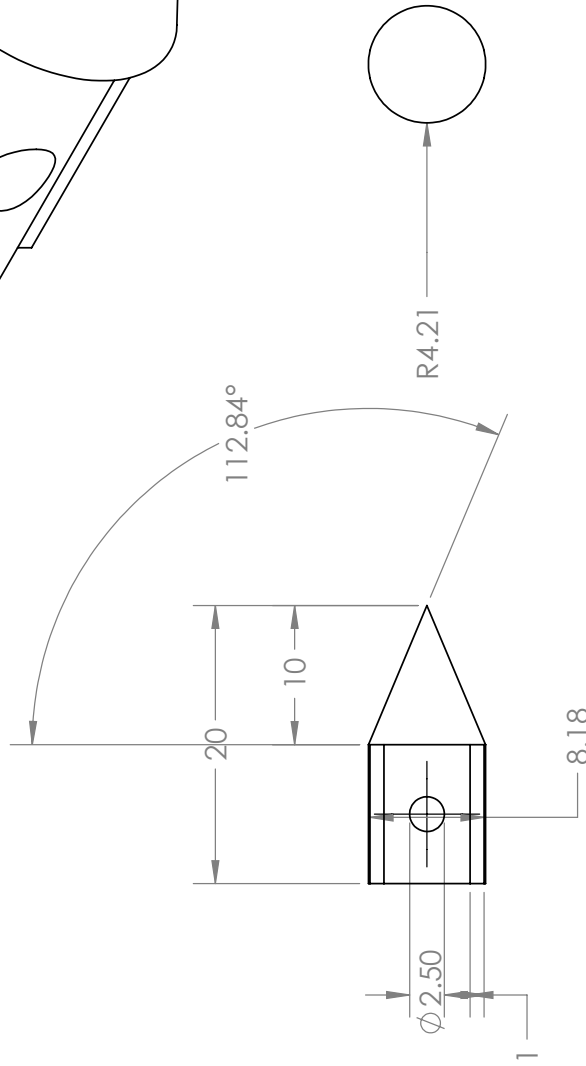
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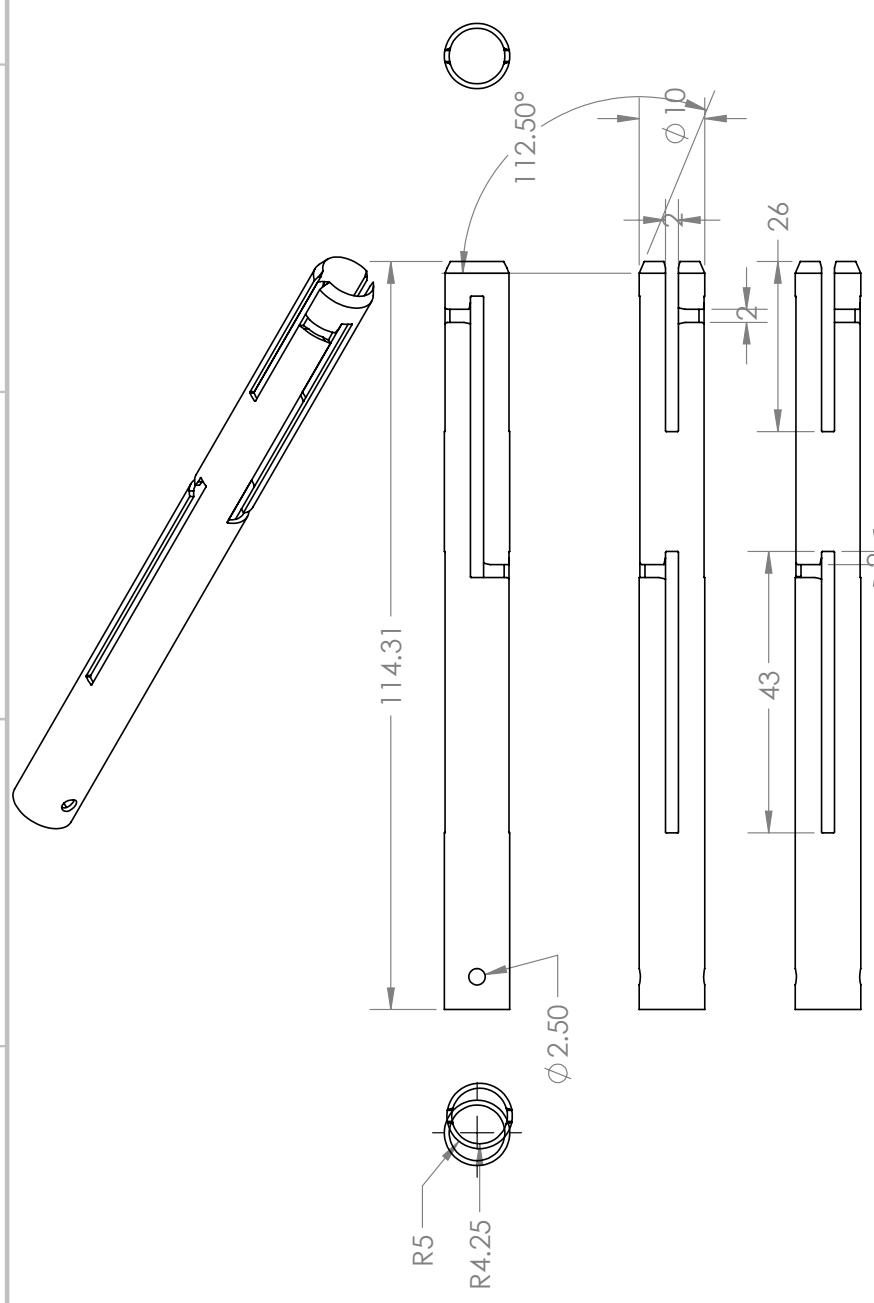
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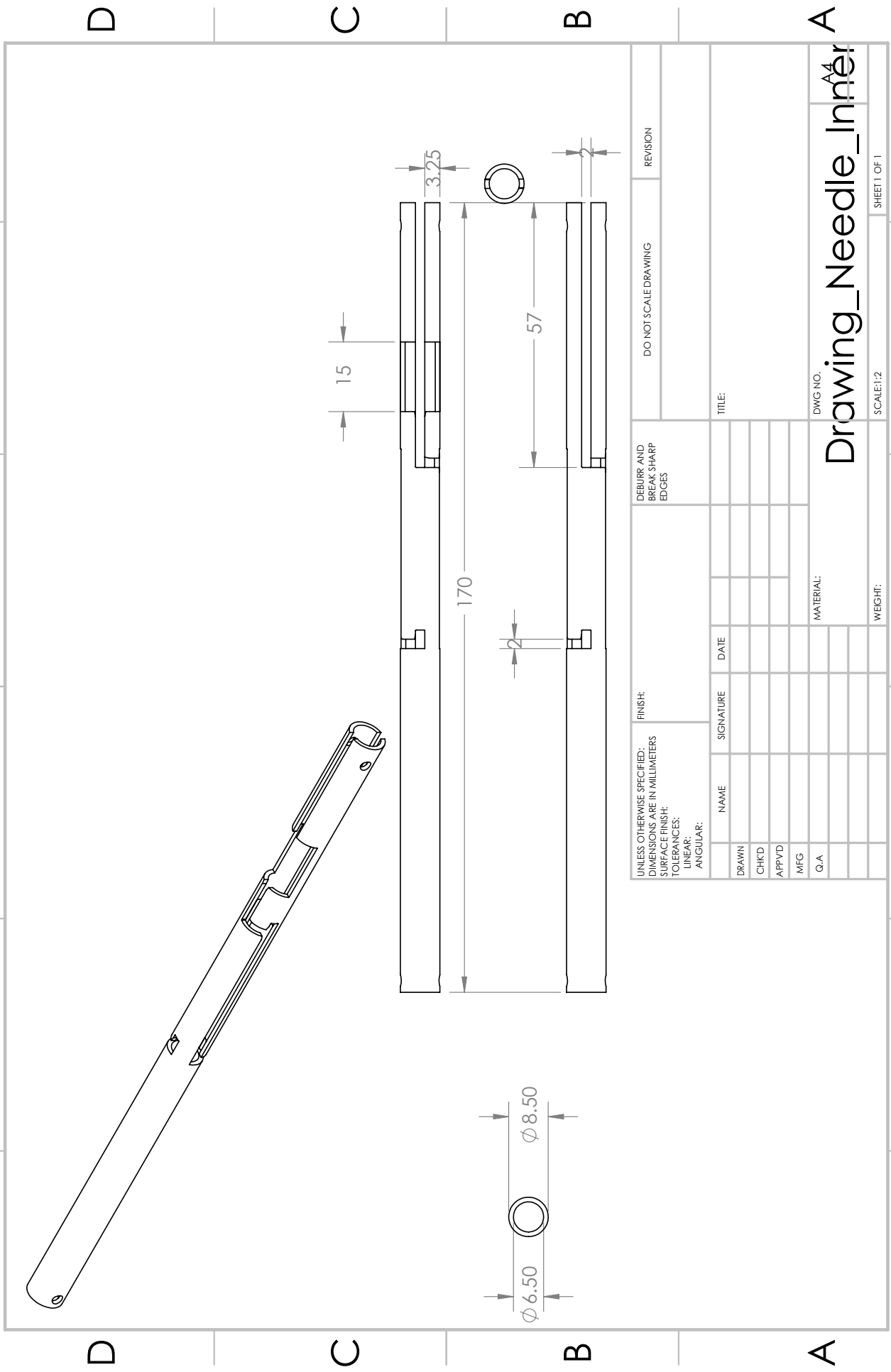
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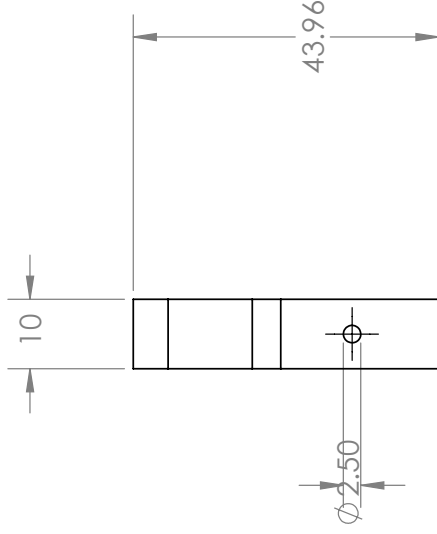
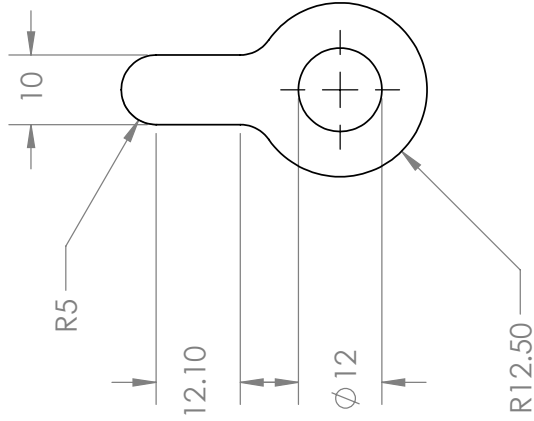
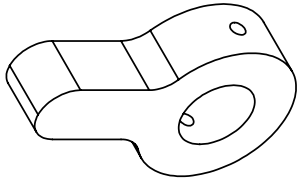
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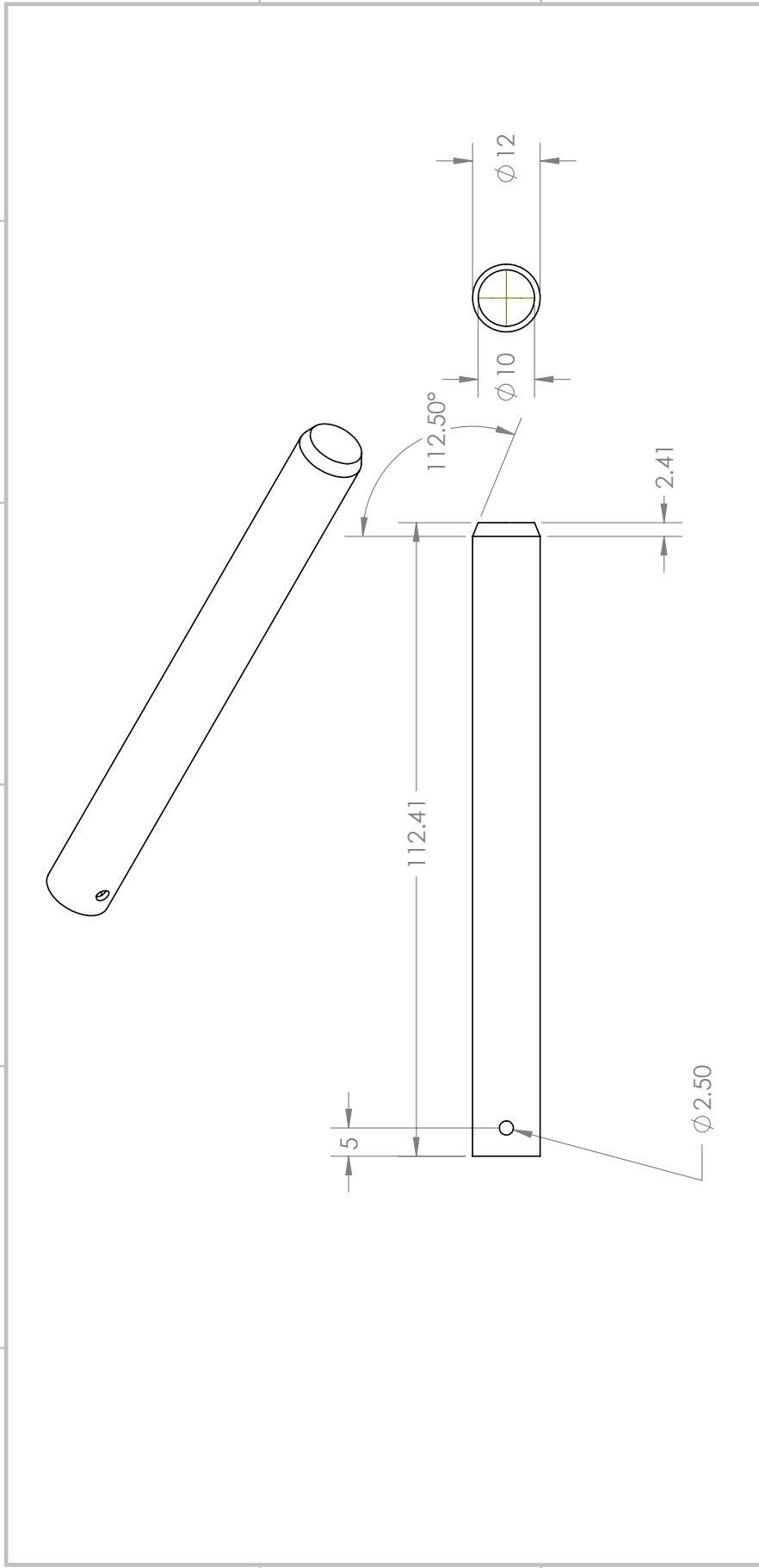
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