Catheter Related Problems in Pediatric Oncology Treatment

A Technical Investigation Performed at Uppsala Akademiska Sjukhus

Jenny Fjärstedt
Abstract

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In this project, problems related to loss of free flow in central venous catheter and implanted subcutaneous ports have been investigated. The catheters investigated in this project are intended for children with cancer diseases. The initial hypothesis was that the length, radius and curvature of the catheter would affect the flow. Two other things that can have a negative impact on the flow are if the catheter is squashed or kinked. Experiments and simulations have been performed in order to test the hypothesis and investigate how a deformation of the catheter affects the flow. The results from the experiments and simulations show that the length and radius of the catheter have major impact on the pressure drop, and hence the flow. The curvature of the catheter has less impact on the flow as long as the catheter is not kinked. Experiments with squashed catheters show a decrease in outlet pressure with a decrease of the catheter lumen.
Sammanfattning

Resultaten från experiment och simuleringar visar att kateterns längd och radie har störst effekt på tryckfallet och därmed flödet. Krökningen på katetern har mindre betydelse, så länge katetern inte är veckad. Experiment med klämd kateter visar att utloppstrycket minskar med minskad kateterlumen.

Acknowledgements
I would like to express my sincere appreciation to the manufacturer B Braun Medical and the children surgical department for providing me with the different types of catheters, which allowed me to perform the experiments.
My special thanks are extended to the staff of the pediatric oncology department, who always gave me a good reception and thoroughly answered my many questions.
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Introduction

Many patients with diseases that hospitalize them for a longer time often get in contact with a catheter of some kind. If the treatment includes a lot of infusion of medication and blood samplings it is common to use some kind of central venous access device. But the use of catheters is sometimes problematic. The catheters could cause problems in different ways and stop working, leading to disruption of the patient’s treatment. This is of course not good for neither the patient nor the hospital, leading to increased hospital stay associated with increased cost and risk of infections and longer recovery time.

Patients with diseases such as cancer are immunocompromised because of their tough and long treatment with chemotherapy, it is therefore important to eliminate unnecessary risks when it comes to the surrounding treatments. Some problems are related to the catheter the patients receive in the beginning of the treatment, sometimes already during the disease investigation. If these problems are severe or reoccurring the catheter might have to be replaced, for children this is done under anesthesia. Apart from the cost for the operating theater time and delay of the treatment, this causes mental stress for the patient and it is always hard to explain to a child what happened and why you need to expose him or her for the same pain again.

These facts are what sprung the idea of this project: to investigate the behavior of central venous catheters and see if there is an explanation to the problem where the solution could be of help for the patients and staff at the clinics. In this project the investigated catheters are intended for children since the project is performed on behalf of a pediatric oncology department.

Background

The Pediatric oncology department

Every year about 300 children develop some form of cancer; most of them are between 2 and 6 years old [1]. The most common cancer disease for children varies with age, although brain tumors affect children of all ages. For infants, leukemia, neuroblastoma (tumors in nerve tissue close to the spine), and kidney tumors appear most frequently and at higher ages bone tumors become more common [1]. The treatment of a child with cancer differ from the treatment of an adult, because the children are still growing and have their whole life ahead of them leading to a lot of different factors having to be taken into account [1].

There are six centers for pediatric oncology in Sweden, and the Children Hospital in Uppsala is one of them. The department for Children blood and tumor diseases treats about 55 patients each year, between the ages of 0 to 18 years. They receive patients from a large region to provide diagnoses, give treatments and do follow-ups.

A multi-professional team has been following the staffs’ work at the department for pediatric oncology at Uppsala University hospital for six weeks. During this time, notes have been kept regarding improvements that could help both the staff in their work but more importantly help the patients. The long list of notes has been divided into different categories and one of these included projects suited for master theses. One of these projects was to investigate catheter related problems.
The problem was from the beginning formulated quite wide and complex: “Why is it not always possible to aspirate blood from a catheter?”, but have during the project been reformulated to investigate what could be the technical problems with a catheter. In order to answer this question, experiments and simulations of different aspects that might influence the function of the catheter have been performed. Previous studies have been focused more on the medical problems, meanwhile this projects’ main focus have been on the technical part. Here, the main problem is the mechanical occlusions that might stop the catheter to function properly concerning the material and its dimensions.

During this project, interviews with the staff at the Pediatric oncology department at Akademiska Sjukhuset in Uppsala have been very helpful in order to get a good insight into their routines. The staff’s thoughts and experiences have been the base for the work of this project, and may not be the general opinion at other, similar oncology departments. Henceforth, any references to nurses, clinic etc. refers to the Pediatric oncology department with staff

**Catheter types**

A central venous catheter (CVC), seen in Figure 1, gives access to the central venous system via a thin single or multiple lumens tube placed under the skin, usually entering the jugular vein or subclavian vein. The tube is then tunneled through the vein further to superior vena cava and the tip of the tube is positioned where the superior vena cava enters the heart in the right atrium [5].

A subcutaneous venous port (SVP), seen in Figure 2, is a reservoir made from metal or plastic with a septum of silicone implanted under the skin at the upper chest. The catheter tube attached to the reservoir is inserted in a vein, most commonly the jugular vein, subclavian vein or right into superior vena cava. The tube is then tunneled further to superior vena cava’s inlet of the right atrium. To access the vein you punch a needle through the skin and the septum until it reaches the bottom of the reservoir. The ports are available with single or double reservoir and the size is chosen with respect to the size of the patient and the planned treatment [4].

The placement of the catheter tip at the inlet of the right atrium allows for quick distribution of the infused drug into the body, which is important when administrating chemotherapy drugs.

Placement of a central venous access device is very common for treatment of cancer in children, because most of the treatments are based on infusion of fluids: chemotherapy, antibiotics, nutrition and other medications. The catheter is placed already during the investigation of illness, and the aim is to be able to use the catheter during the whole treatment period. The treatment for leukemia, for example, is about 2.5 year, during this time a lot of complications can occur.
There have been studies on which of the catheter types are the best, comparing the pros and cons for each type according to infection and failure rate, which is more comfortable for the patient and much more. This project does not take any stand for that, here we focus on the function of the catheter with respect to curvature, length and radius of the tube.

Figure 1 Some pictures of central venous catheters (CVCs)

Figure 2 Some pictures of different subcutaneous venous ports (SVPs)
Previous research
To get an overview of what has been done on the subject, articles have been studied, most of them published on Pubmed [2]. The articles have been chosen with the criteria to include either children and/or cancer patients, and studying catheter related problems. [4, 7-10] The most frequent problems related to catheters after insertion are:

- **Infections**
  When inserting and managing the catheter it is of great importance to work antiseptic in order to minimize the risk of catheter related infections, especially for patients with suppressed immune system. Infections are easy to detect by analyzing blood sample.

- **Oclusion (medical)**
  A stoppage in the catheter tube could be caused in different ways. Thrombosis (blood clots formation in the tube) is one problem that sometimes can be remedied by injection of heparin that dissolves the clot, the thrombosis could lie in the tube or in the vein the tube is located in. Infusion of different drugs and fluids could also cause drug precipitate if the drugs are not compatible. Infusion of nutrition can leave residues on the tube wall.

- **Oclusion (mechanical)**
  There could also be something wrong with the catheter tube or the port reservoir that cause problems. The tube could be squashed, for example between the collarbone and the first rib, or there could be a kink on the tube causing the occlusion. These two mechanical occlusions could sometimes be remedied by the patient moving the head, arm or shoulder [5].

- **Air in the system**
  Leaving the valve open could cause air to be sucked through the catheter system and in to the blood system. This can also occur during insertion or removal of the catheter. To prevent this, the patient should (if possible) lie in a horizontal position while managing the catheter [5].

- **Tip of catheter stuck to the blood vessel wall**
  Due to capillary force, the tip of the catheter could get stuck to the vessel wall. This will cause an obstruction to inject, or in some cases make it impossible to aspirate blood through the catheter even though the nurse could still be able to flush the system with eg. saline.

- **Dislocation of catheter**
  This problem occur when the outer part of the catheter get hooked up in something when the patient is moving, or because the bandage keeping the CVC in place has loosened [5].

- **Extravasation**
  If the port needle is inaccurately placed (not into the reservoir) or the tube has detached from the port, infusion could go elsewhere than in to the blood system which could cause problems. Other reasons for extravasation could be dislocation of the tip outside the blood system or breakage of the catheter [6].

- **Breakage of catheter**
  Most patients have their catheter for a long time, often several years. There is always a risk that the catheter could break, for example by getting squashed between the collarbone and first rib or by other factors in the patients daily life. [6] The catheter could also break due to excessive use of force, for example by using a too small syringe or, that the outer parts of the catheter get hooked up in something or get wrenched (deliberately or by accident) [5].
Main focus in these articles has been on catheter related infections and occlusion caused by thrombosis, probably because these problems are easy to detect by a blood sample or ultrasound.

According to the summary of earlier studies in the article of H.-C. Jan et al. [4] the complication rate for subcutaneous ports is 6-21%, but these studies had limited patient participation and the follow-ups were performed just a short time after completed treatment. During H.-C. Jan et al’s long-term study between 1990 and 2008 they had a patient population of over 1200 adults with breast cancer, all with an implanted port, where they achieved an even lower complication rate (3.42 % during 1990-2001 and 1.23% during 2002-2008) than their pre-study showed. They suggest that well trained surgeons is a big contributing factor to this low rate, and the decrease between the two time periods could be referred to a new standard of taking out the port 6-12 months after completion of treatment. The catheters are sometimes left in the body in case of a relapse, and there are studies proofing that the most relapses occurs within a few years form the first illness. Earlier, the port could remain in the body for years after the treatment had ended, which explains why breakage was a common problem in the first time period.

25% of the central venous access devices investigated in A.J. Ullman et al’s study failed before finished treatment, but the total implanted ports (SVP’s) had the lowest failure rate of 0.15 out of 1000 catheter days [5].

**How to solve the problems when they occur**

If complications occur leading to that the CVC or SVP cannot be used, the patient cannot receive treatment, nutrition, antibiotics, fluids or other medications needed. Cancer patients do already have weak immune system, and are therefore extra sensitive to infections and other complications. An infection or occlusion could lead to the need to replace the access, which delays the treatment. The implantation of a venous access for children is always performed under anesthesia, which involves a risk, is costly and provides a mental strain on the child and the family. Replacing the catheter also entails a high cost: operation theater time, surgeons and nurses, monitoring equipment, sterile surgical equipment and sterile disposables. The more often the catheter has to be replaced, the harder the procedure gets, because the vein could become faulty or insufficient [7].

**Interviews with the nurses**

The catheter does not always have to be changed when inflicting problems. The nurses have some tricks of their trade to try to get the catheter to work again. To get an overview of these methods and their range of use, interviews with the nurses at the clinic have been performed.

A mechanical flushing technique could be used where saline is flushed through a pumping motion instead of a continuous motion. This can remove coatings and solid accumulations of thrombus, fibrin etcetera. Another way to remove coatings in the catheter is to use a smaller syringe while flushing. This allows for a higher inflow pressure, but it is not recommended by the manufacturer to use syringes smaller than 10 ml because it could break the catheter system. If the nurse suspects clogging of the catheter he or she could inject Actilyse (which dissolves blood, fat and fibrin and is used as a general cloth dissolver) and let it act for about 30 minutes before trying to flush the system again. Patients receiving nutrition and fluids (parenteral nutrition or total parenteral nutrition) seem to have more problems with clogging of the catheter.

If there are suspicions that the catheter might be squashed, the patient could move around a bit,
tilting or turning the head or moving shoulder and arm on the same side as where the catheter is located. The idea is to release the catheter tube from its malfunctioning position. If one of these methods is successful, the treatment could go on as planned and there is no need to change the catheter unless the problem is reoccurring. Problems like this may take time to fix which will delay other treatments and/or appointments with doctors and also stress the patient. Different studies have been performed to see what could prevent clogging of the catheter, for example “heparin lock”, “ethanol lock” (to dissolve fat that could be attached to the inner catheter walls), but no method have provided good enough evidence of preventing the problems. At the clinic, the staff experience that the mechanical flushing technique is a more effective way to clean the catheter from clogging and only places a “heparin lock” when the patient have finished a treatment session and is going home for a longer time.

Some of the nurses who have worked at the clinic for a long time and experienced different kinds of port needles experiences that it is harder to be sure that the needle is correctly placed in the reservoir and that the tip has reached the bottom using the current model of needle. This rather new model is designed to damage the membrane less while inserting and withdrawing the needle into the port. It is also a better protection, preventing accidental stings or scratches the patient (or the nurse her/himself) during withdrawal of the needle. The difficulty of placing the port needle differs from patient to patient. For patients with more subcutaneous fat or patients that have grown a lot since the port placement, it is generally harder to locate the reservoir than on patients that are skinny. The problem of placing the port needle is sometimes reoccurring for the same patient, but sometimes it happens randomly and without any patterns. The newer nurses who have only experienced the current model of port needle complain less about the difficulties with inserting the port needles, but they mention that there could be problems sometimes.

The most common problem according to the nurses, and the first answer they give when asked about problems with catheters, is to not be able to aspirate blood from the catheter whilst still being able to flush the system. The nurses always aspirate some blood before each infusion to ensure that the placement and functionality of the catheter is correct. The cause of this could be different, but one suspicion is that it could be cause by the catheter tip being sucked to the blood vessel wall. When trying to aspirate blood, the tip is sucked even harder to the wall, but when flushing the tip is released. A group of nurses estimate the rate of this problem to occur in about 1 out of 10 cases, for some patients it occurs more often than with others.

The nurses do not experience any pattern with regards to the patient’s cancer type in any of the problems mentioned above. But there tend to be a bit more problems with the smallest children given the smallest catheter tubes, mostly CVC.

Overall, there are more problems with infections at the clinic now than it was 5-10 years ago. The clinic has communicated this to the surgical department where the catheters are placed, but they have not found any change in the routines that could be the cause. The surgeons suspect that it might have something to do with the material and the quality of the catheters that causes the infection, but these are just suspicions and there is not statistical record to prove this for sure.

The most frequently used catheter type used at the clinic is the SVPs, but there are also CVCs with single and double lumen (lumen is referred to as the cavity of the catheter tube). Some nurses
experience that there are more reoccurring problems with the CVCs, which is in accordance with the literature study.
The doctor’s choice of catheter type is based on the size of the child and the planned treatment, in general the smaller children (younger than one year) get a CVC. They keep it until they have outgrown it or it has to be replaced because of dislocation or dysfunction, and then it is changed to a SVP instead. Children older than one year most often get a single lumen SVP.
The use of the catheter varies with what type of treatment the patient receives. In some cases, it is used daily for several months but some patients only come to the hospital somewhere between once a week to every sixth week for treatment. Sometimes the problem starts already when the patient is coming back from the surgical department, but most problems occur during the treatment.

To get a better view of how the catheter is placed in the body I had the opportunity to participate as a spectator during an insertion of a CVC on a child. This provided me with a good understanding of the procedure during the operation. One important routine is the x-rays taken after the insertion of the catheter to confirm a correct placement. The catheters come with a radiopaque marking, making it possible to see the catheter on the x-ray picture [3]. I was given some of these post-insertion x-rays for patients of different age representative for the usual placement, and also some non-representative to see how it could look if the insertion is made in another vein or tunneled in a different way. These types of x-rays and some surgical pictures from H.-C. Jan et al.’s study [4] have been the basis for the development of the experiments and the simulations. In Figure 3, two of the more typical placements could be seen.

Figure 3 Two representative X-rays of patients with inserted subcutaneous venous ports.
**Theory**

In fluid mechanics there are some important characteristics of the fluids studied, the first one being the density of the fluid. If the flow occurs during changed density it is called a “compressible flow”. In the blood circulatory system there are small variations in the pressure, but they can be neglected and the blood can be seen as an incompressible fluid [11].

Viscosity describes the “thickness” of a fluid and its inner resistance to flow or, more correctly speaking, the inner friction in the fluid. For blood the viscosity depends on the proportion of red blood cells, hematocrit, as well as the diameter of the blood vessels, higher percentage of red blood cells gives a higher viscosity. In our smallest vessels, the viscosity is not as dependent on the hematocrit level. The viscosity also describes the friction force between different layers of fluid, moving with different velocity.

The last property to have in concern while studying fluid mechanics is the shear stress. In general, shear stress is the force per unit of cross sectional area that shears a body without any volume change. The shear stress, $\tau$, could be described as the product of the viscosity, $\eta$, and a velocity gradient $\delta v/\delta y$, according to

$$\tau = \eta \frac{\delta v}{\delta y}. \quad (1)$$

More specific for fluids, the shear stress occurs where the fluid is moving along a solid boundary.

Our blood can often be treated as a Newtonian fluid, like almost all common fluids, which means that the shear stress of the fluid is proportional to the shear rate. In the normal case, the shear rate in our circulatory system is high enough to regard the viscosity as independent of the shear rate.

A fluid flow could be described as either laminar or turbulent. The Reynold’s number, $Re$, give us an estimation of the type of the flow, with a Reynold’s number under 20 000, the flow is laminar but if it exceeds 20 000, the flow is turbulent. It can be calculated if we know the density, $\rho$, the pipe diameter, $D$, the viscosity and the average velocity, $v_m$, for the fluid using this formula

$$Re = \frac{\rho D v_m}{\eta}. \quad (2)$$

A turbulent flow is a random flow like a vortex and cannot be described using classical mathematics. However, for turbulent flow in pipes, there is a connection between pressure drop along the pipe and the flow rate according to

$$(p_1 - p_2) = f_f \frac{L}{R} v_m^2, \quad (3)$$

where $p_1$ and $p_2$ is the pressure drop, $f_f$ is the friction force due to the pipes inner wall and the Reynolds number, $L$ is the length of the pipe, $R$ is the pipes radius.

---

**Properties of the blood**

<table>
<thead>
<tr>
<th>at normal body temperature</th>
<th>Density</th>
<th>1060 kg/m$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscosity</td>
<td>3·10$^{-3}$ Ns/m$^2$</td>
<td></td>
</tr>
</tbody>
</table>
We know that parts of the cardiac cycle consist of turbulent flow and it also appears in ramifications of the blood vessels, but in most of our vessels the flow is regarded as laminar.

![Image](https://via.placeholder.com/150)

**Figure 4** The flow profile in a pipe

For a laminar flow, the fluid flows in parallel layers and the flow profile is usually described as parabolic, as seen in Figure 4. The force, \( F_p \), driving the fluid along the pipe could be described as

\[
F_p = (p_1 - p_2)\pi R^2. \tag{4}
\]

Studying a small cylinder with pipe radius \( r \), the fluid is exposed to a frictional force, \( F_f \), according to

\[
F_f = \tau 2\pi r L. \tag{5}
\]

With \( r = y \) from Equation 1 we can insert the expression for the shear stress and set \( F_p = -F_f \) which gives us

\[
(p_1 - p_2)\pi r^2 = -2\pi r L \frac{\delta v}{\delta r}. \tag{6}
\]

Solving for the gradient and integrating give us an expression for the velocity with respect to the radius according to

\[
v(r) = -\frac{(p_1 - p_2)r^2}{4\eta L} + \text{constant}. \tag{7}
\]

Introducing a boundary condition \( v(R) = 0 \) we get

\[
v(r) = -\frac{(p_1 - p_2)}{4\eta L} (R^2 - r^2). \tag{8}
\]

Integrating over the cross sectional area give us a volume flow, \( Q \), as follows

\[
Q = \frac{(p_1 - p_2)}{4\eta L} \int_0^R (R^2 - r^2) 2\pi r dr = \frac{\pi R^4(p_1 - p_2)}{8\eta L}. \tag{9}
\]

This last equation is called “Poiseuilles equation”, which is a common equation in the study of laminar flow through pipes.

If we regard the flow as stationary (i.e., having so small variations over time it could be seen as unchanging) and incompressible, the mass flow will be the same along a pipe, which gives us the equation

\[
Q = A_1 v_1 = A_2 v_2, \tag{10}
\]
where $A$ is the cross sectional area and $v$ is the flow rate. This is the “Continuity equation”, which is used to relate the velocity changes when a fluid moves from one section with larger cross sectional area to a smaller, or the other way around. This equation states that the mass is conserved during the flow.

When the blood flows through the vessels, the pressure decreases as it moves along the vessel walls. This is due to a frictional force between the fluid and the walls which leads to a decrease in the flow rate. If the flow rate should be maintained, the difference in pressure must increase by the same factor as the resistance from the friction increase, which means the heart must work harder. The friction force depends on the length of the pipe, the inner diameter of the pipe and the viscosity of the fluid, as seen in Equation 5 above. For a larger vessel, a relatively smaller amount of the blood has contact with the walls and is therefore less exposed to friction, which leads to higher flow rate. In smaller vessels, the amount of blood in contact with the walls is relatively higher and the friction acts more on the blood leading to a lower flow rate [9]. Due to the frictional force, the flow velocity close to a surface is zero. In a pipe, the velocity of the fluid varies along the radius of the pipes inner diameter being zero at the walls and the maximum flow rate at the center of the pipe.

Although catheters are made of soft materials, such as silicon and polyurethane, making them easily bendable, there is a limit to how much they could be bent without affecting the cross sectional area and thereby the flow in the catheter. This limit depends on the material in the tube, the inner and outer dimensions and if the tube is reinforced with some other material. If the tube has been kinked, meaning that it has been over bent, the cross sectional area is changed from circular to elliptical. In Equation 4, which describes the force driving the fluid forward, we can identify the cross sectional area as the area of a circle; $\pi R^2$, but if the tube is kinked, the shape of the cross sectional area is more shaped like an ellipse and we need to replace this part of the equation with the area of an ellipse;

$$A_{\text{ellipse}} = \pi ab$$  \hspace{1cm} (11)

with $a$ and $b$ as seen in Figure 5. Bending the tube to a kinked state will reduce the flow, but if the kink is too sharp it will collapse the tube and the flow is stopped.

**Simulations**

The software used for the simulations in this work is COMSOL Multiphysics, with a license provided by Uppsala University. In order to build the geometry, a CAD program was initially considered, but in the end COMSOL’s own work space showed to be the easier and more time efficient way to work since small changes of tube diameter, length, bending radius etc. has to be implemented between the simulations. The tube is drawn in a curved geometry using a half helix turn and two cylinders of different length (see Figure 6) similar in shape as that seen in the x-rays in Figure 3. The major radius of the helix can be varied easily, same as the length and radius of the tube. The physics used for these simulations is COMSOL’s “Fluid flow” in stationary studies and the geometry is given an inlet and outlet boundary condition chosen to be the two ends of the tube. The material used for the flow is water, and the walls have a non-slip boundary condition applied as default.

For the simulations, an inlet pressure condition of 2000 Pa is used, this is a value seen as “normal” during the experiments and also approximately what the nurses applying while injecting fluids using
a syringe (some nurses where asked to test it using the DPI to get a reference to what is “normal”, more thorough explanation of the DPI is presented in the section “Experimental procedures”) and the outlet condition is set to a velocity of 0.1 m/s to be able to measure the pressure drop during the flow through the tube. A value for the velocity in vena cava, where the flow exits, was found in O. Sand et. al’s book [12] to be 0.5 m/s which is used as a guide line when setting the outlet velocity. However, simulating with 0.5 m/s gave unrealistic results, and thus the velocity was decreased to 0.1 m/s.

The curvature of the tube was firstly varied without consideration the total length of the tube, and secondly with a fixed length. For comparison, a straight tube with equal tube radius is simulated for the same lengths as the curved tube. During these simulations, the tube radius is set to 0.5 mm, a value similar to that of the catheters used in the experiment. Another simulation is performed to see how the radius of the tube affects the pressure drop.

COMSOL is designed to converge to a result, for this project the relative fine radius in proportion to the length made it possible to run the simulations using a so called normal mesh. A mesh convergence study could be performed by using finer meshes until the same result is obtained for two consecutive mesh grades, then the next finest mesh could be used for further simulations in order to achieve a shorter simulation time.

![Figure 6](image.png)

Figure 6 A screenshot from COMSOL of the curved geometry used in the simulations, here with a curvature radius of 20 mm and 300 mm length
Results

In line with the presented theory, it can be seen in the velocity plots from the simulations (Figure 7) that the velocity of the fluid close to the walls is zero due to the friction force and radically increasing towards the center of the tube.

![Figure 7](image)

Figure 7 The radial change of velocity due to the friction force along the walls

With the geometry shown in Figure 6, simulations with different radius of the curvature were made, firstly without respect of the total length of the tube. This resulted in an increase of the pressure at the outlet due to the total length getting shorter (the two cylinder’s length were unchanged, but the length of the bend decreases when changing its radius). In Figure 8 we can see that the reduced length gives a rise in outlet pressure.

![Figure 8](image)

Figure 8 Bent tube with decreasing length by decreasing the radius of the curvature
If the length is kept constant by adding the reduced length from the decreased curvature to one of the cylinders, we get approximately the same outlet pressure for all the different curvatures, as can be seen in Table 1, the values only differ within an interval of 6 Pascal. The placement of the bend was also simulated, without any effect on the result, placing the curvature in the middle or closer to the inlet did not change the value of the outlet pressure at all.

Table 1 Measurements while keeping the length constant while varying the radius of curvature

<table>
<thead>
<tr>
<th>Radius (mm)</th>
<th>Length (mm)</th>
<th>Outlet pressure (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>300</td>
<td>865</td>
</tr>
<tr>
<td>20</td>
<td>300</td>
<td>865</td>
</tr>
<tr>
<td>15</td>
<td>300</td>
<td>862</td>
</tr>
<tr>
<td>10</td>
<td>300</td>
<td>859</td>
</tr>
<tr>
<td>5</td>
<td>300</td>
<td>864</td>
</tr>
</tbody>
</table>

The results from the bent geometry were compared to a simulation of a straight tube using only one cylinder. The length was first set to 300 mm, but the resolution of COMSOL made the geometry edgy and uneven and not circular anymore, so the first simulation was run with a length of 290 mm. In Figure 9 we can see that the values behave the same way as expected from the earlier simulations with the bent tube (seen in Figure 6). As the inlet pressure is kept constant at 2000 Pa, an increasing outlet pressure equals a decreased pressure drop along the tube when the tube gets shorter.

![Figure 9 Outlet pressure increasing while decreasing the length of the geometry](image)

We can actually see in Equation 5 that both the length and the radius do affect the frictional force and varying the radius of tube in the curved geometry, but fixing the length, gives us values of the pressure drop as seen in Figure 10.
Experimental procedures

In order to be able to connect the simulations to reality and to see if there could be any relation between the resistance when injecting fluids into the tube and the type of problem, experimental testing has been done. The goal was to see if the resistance or pressure needed to inject fluid could tell us what type of problem is present and by that be able to form an action plan for the nurses to solve the problem.

A generous donation from the manufacturer B Braun Medical of two SVPs of different size and from the children surgical department of two different CVCs has made it possible to do practical testing on catheters. The dimensions of the catheters could be seen in Table 2 and more details of the subcutaneous ports could be read in B Braun’s product brochure [3]. In the table the size unit is given in French, Fr, as is common for catheters. French is a measure of the diameter of the lumen, and to get the diameter in millimeters we can divide the given French size by 3. The given measurements from the product brochures for the inner and outer diameter of the catheters are listed in the table.

Table 2 List of the catheters and their dimensions

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Size</th>
<th>Outer diameter</th>
<th>Inner diameter</th>
<th>Length</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SVP</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B. Braun Medical</td>
<td>8.5 Fr</td>
<td>2.8 mm</td>
<td>1.1 mm</td>
<td>800 mm</td>
</tr>
<tr>
<td>B. Braun Medical</td>
<td>6.5 Fr</td>
<td>2.2 mm</td>
<td>1.0 mm</td>
<td>800 mm</td>
</tr>
<tr>
<td><strong>CVC</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bard Medical</td>
<td>9.6 Fr</td>
<td>3.2 mm</td>
<td>1.6 mm</td>
<td>900 mm</td>
</tr>
<tr>
<td>Cook Medical</td>
<td>3 Fr</td>
<td>1.0 mm</td>
<td>0.56 mm</td>
<td>650 mm</td>
</tr>
</tbody>
</table>

Figure 10 Pressure drop when varying the radius of the curved geometry
When comparing the catheter tube’s flexibility in room temperature, the 9.6 Fr CVC showed to be more flexible than the SVPs. Between the two SVP:s there is a slight difference, even though they are made of the the same material, the 8.5 Fr feels a bit more flexible, possibly due to the dimensions of the catheter.

To see if there are any big differences in the bendability and stretchability of the catheter tubes at their operating temperature, an incubator was used. The catheters where placed in the incubator at 37 °C for 15 minutes, 9 minutes to stabilize the temperature (after opening the door to the incubator) and 6 minutes to make sure the material in the tube had absorbed the temperature of 37 °C. The softness of the material did not change much when heated to body temperature. However, this was performed as a simple test by feeling the heated tubes and a piece of reference tube at room temperature. There was no particular change in bendability possible to feel by human fingers, although the tubes were a bit easier to stretch lengthwise when heated, especially the 9.6 Fr CVC.

To measure the outlet pressure at the catheter tip, a DPI 705 Pressure Indicator (seen in Figure 11) was used. Because the catheter is only designed to be used inside the body, some adaptions had to be made to be able to test them out of their intended environment. For two of the catheters, the 9.6 Fr CVC and the 8.5 Fr SVP, a piece of an aggregate originally intended for an infusion pump was used. The 3 Fr CVC was given an aggregate intended for a syringe pump and for the 6.5 Fr SVP, a piece of tube and a tube connection were used to serve as an attachment between the catheter tube and the DPI. Even though the adapters where made from different pieces, the length was equal for all of the catheters. The different adapters are seen in Figure 12.

Normally when the nurse injects a fluid in the catheter the fluid flows freely in to the veins without stop or resistance (apart from the resistance from the frictional force along the walls). Measurements with the DPI where performed using a closed system, meaning that when injecting fluid with the syringe, there was no way for the fluid already in the tube to “escape”. This means that a pressure is built up in the tube which is what the DPI measures. To have some consistency in the measurements, the same amount of pressure from the syringe was applied each time by looking at the syringes scales when applying the pressure. In most of the experiments, pressures corresponding to a 0.2 or 0.4 ml injection have been used.
The outlet pressure when using different sizes of syringes was measured with the tubes laying free without sharp bends or any kinks. Syringe sizes used for this test were 3, 5, 10 and 20 ml, all commonly used at the clinic. First a maximum pressure was tried for each catheter with each syringe, but some of the adapters did not hold for such high pressure. The highest achieved pressure without the system breaking was noted. Then a more normal pressure was applied and measured. Some nurses were asked to apply their usual pressure when infusing fluids to get a reference of what could be seen as a normal pressure. The DPI gives fluctuating values, and thus the measurements have been rounded to a stable value shown at least three times.

**Results**
Comparing the use of different syringes we can establish that a high outlet pressure is easily achieved using a 3 ml syringe; the outlet pressure for the 3 ml syringe was about four times as high as the outlet pressure given by the 20 ml syringe for all four catheters when applying a “normal” inlet pressure. Some of the catheters’ adapters turned out to be harder to fit properly to the catheter tip for there not to be any leaks, the final value was taken just before the breaking point. The maximum achieved pressure tended to be higher as the syringe size was decreased, as seen in Table 3. These results confirm the recommendation from the manufacturers not to use smaller syringes than 10 ml, in order not to risk breaking the catheter due to high pressure. It also confirms the nurses’ disregard of this recommendation during clogging of the catheter, using a smaller syringe would be more efficient to clean the tube.
Table 3 Typical values when the tube is free and without any sharp bends. We could clearly see that it is easier to reach a high pressure using a small syringe.

1 Until the adapter leaked or loosened
2 Until the DPI warned for “A”, meaning the pressure is too high

<table>
<thead>
<tr>
<th>Syringe size</th>
<th>20 ml</th>
<th>10 ml</th>
<th>5 ml</th>
<th>3 ml</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Braun 8.5 Fr</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>0,27¹</td>
<td>0,38¹</td>
<td>0,30¹</td>
<td>0,35</td>
</tr>
<tr>
<td>Normal</td>
<td>0,06</td>
<td>0,10</td>
<td>0,12</td>
<td>0,2</td>
</tr>
<tr>
<td><strong>Braun 6.5 Fr</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>0,28¹</td>
<td>0,26</td>
<td>0,2</td>
<td>0,2</td>
</tr>
<tr>
<td>Normal</td>
<td>0,07</td>
<td>0,09</td>
<td>0,11</td>
<td>0,18</td>
</tr>
<tr>
<td><strong>Bard 9.6 Fr</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>0,30</td>
<td>0,40</td>
<td>0,45</td>
<td>0,5</td>
</tr>
<tr>
<td>Normal</td>
<td>0,05</td>
<td>0,15</td>
<td>0,17</td>
<td>0,2</td>
</tr>
<tr>
<td><strong>Cook 3 Fr</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>0,28</td>
<td>0,40</td>
<td>0,50</td>
<td>0,7</td>
</tr>
<tr>
<td>Normal</td>
<td>0,08</td>
<td>0,10</td>
<td>0,15²</td>
<td>0,25</td>
</tr>
</tbody>
</table>

Bending of the tube
A setup with ordinary drinking straws was created by taping eight pieces of straws next to each other (making the spacing approximately 0.5 cm center to center) and then slice them lengthwise to create a slit suitable to place the catheter in. The inlet of the catheter was fixed and the tube placed in the first channel (to the left in the Figure 13) were then it remained for the whole experiment, the rest of the tube where placed backwards through one of the straw channel creating a loop about 20 cm from the inlet. The size of the loop was varied by moving the backward bent part of the tube between the different channels (seen in Figure 14). A pressure corresponding to an injection of 0.2 or 0.4 ml with a 10 ml syringe was applied. The pressure was measured for all catheters placed in all straw channels. When the tube was placed in the last channel (number 7), the tube moved the end of the straw channels a bit for the three thicker catheters, this was caused by tube material’s unwillingness to bend sharply.
Figure 13 Measuring in all the different channels of the straw setup. The different channels have been numbered from the outer one to the right.

Results
The measured values did not provide any certain conclusions; the measurement values remained approximately the same for the different placings in the channels. No pattern of the pressure decreasing or increasing (seen in Figure 15) with a sharper curvature could be found and the values only appear to vary with the human factor and coincidences. More detailed measure values could be found in Table 4 (in Appendix).

Figure 14 The straw setup for measurements with the tube in different channels, from left: the tube in channel 1, 4 and 7 (numbering seen in Figure 13)
Figure 15 The results of measuring the outlet pressure with different curvature of the tube, numbering of the channels could be seen in Figure 6. Here with an inlet pressure corresponding to a 0.2 ml injection.

Kinked tube
In order to evaluate the impact of a changed cross section, the catheter tubes where bent sharply at the middle, but not so much that it would totally stop the flow, and a piece of tape was used to fix the kink (see Figure 16). The outlet pressure using a 10 ml syringe was measured for all catheters. Control measurements where performed afterwards to be able to compare the pressure with reduced lumen and with full lumen. In this test, the exact reduction of the lumen was not measured, the idea was to simply create a narrowing and see if it would affect the pressure.

Without using the DPI, the impact from the changed cross sectional area of the tube on the flow when bending it was tested. Again a piece of tape was used to keep the shape, after which the shape was transferred to a paper to make it easier to measure the radius of the curvature. Using a caliper the dimension of the tube was measured corresponding to the distances 2a and 2b in Figure 5.
Results
For the 9.6 Fr CVC the pressure with and without the kink was unchanged (testing with a pressure corresponding to an injection of 0.2 ml and 0.4 ml), suggesting that the kink was not sharp enough to affect the cross sectional area of the lumen so much that it would reduce the outlet pressure. For the 3 Fr CVC only a pressure from a 0.2 ml injection was possible, the difference between a kinked tube and the normal case was quite small; 0.15 MPa respectively 0.18 MPa, corresponds to a change of 16%. For the two SVPs the largest difference was for a 0.2 ml injection; for the 8.5 Fr catheter the pressure was decreased to half of that of the normal case, and for the 6.5 Fr catheter if was reduced by about a quarter of the normal case. When increasing the pressure corresponding to a 0.4 ml injection, the pressure for the 8.5 Fr catheter was decreased to about a quarter of the normal case and the 6.5 Fr catheter gave approximately the same value as the normal case (probably affected by some human error).

When decreasing the curvature and calculating the area using Equation 11, we can see that the cross sectional area of the tube have a decreasing trend with decreasing curvature. Observe that this is the external distances measured on the outside of the tubes; assuming the inner walls behaves the same way. We can see in Figure 17 that in the beginning, the circular area is conserved but as the bent is forced to be sharper, the tube begins to be kinked and the area is more shaped like an ellipse. The abnormal pattern in the graph for the 3 Fr CVC could be due to the fact that the tube is very thin and the changes while bending the tube is extremely small and therefore hard to measure exactly. It could probably also be because of the material’s properties affecting the outer area.
Figure 17 The cross sectional area of the tubes as the curvature is decreased until kinked.
**Squashing the tube**

A narrowing of the catheter tubes was created by using a caliper, which provided both tool to narrow down the lumen and at the same time keeping track of how much the tube was squashed (see Figure 18). Narrowing refers to a place where the tube is squashed from the outside in one direction at one place, causing the cross sectional area to take on a more elliptical shape until it is totally squeezed together and the whole lumen is cut off. A 10 ml syringe was used for all catheters, the applied pressure corresponded to an injection of a 0.2 ml and, if possible, a 0.4 ml injection. The outlet pressure was measured for the tube without any narrowing and, in steps of 0.2 mm, until the value of the outlet pressure was zero.

![The caliper used as a setup to narrow down the lumen](image)

**Results**

Inspecting the graphs (see Figures 19-22) over these measurements we can see that the initial narrowing is not affecting the pressure very much, it is just decreasing at relatively small rate. After a certain point the pressure decrease faster and eventually drops to zero, meaning that the whole lumen is totally cut off. The same pattern occurs for all catheters. The measurement values can be seen in Table 5 (in Appendix).
Figure 19 The pressure drop when narrowing the tube for the 8.5 Fr SVP

Figure 20 The pressure drop when narrowing the tube for the 6.5 Fr SVP
Figure 21 The pressure drop when narrowing the tube for the 9.6 Fr CVC

Figure 22 The pressure drop when narrowing the tube for the 3 Fr CVC

Air in the system
As mentioned earlier, air in the system could cause problems. In all experimentation methods presented above, the air bubbles have been kept as few as possible by flushing the system and tapping the syringe to remove bubbles before connecting it to the catheter and using the clamps connected to the catheters or the port needle. A test of the air’s impact on the pressure was performed for the 8.5 Fr SVP in a similar way like earlier tests, applying an pressure corresponding to an injection of 0.2 ml and 0.4 ml, only now with a bit of air in the tube. Firstly, the air bubble was located approximately at the middle of the tube (the exact placement was uncertain since the catheter tube is opaque), and secondly at the end of the system just before the DPI without any water between the air and the DPI.
Results
When the air was located in the middle of the tube the measurements were approximately equal to those without air. When the air was moved to the end of the system the pressure was raised more than twice by the 0.2 ml injection, whereas the result for the 0.4 ml injection was not possible to measure. Instead, as much pressure as possible (until the adapter broke) was applied, resulting in approximately an injection of 0.3 ml, which also provide a raised pressure comparing to no air in the system.

Curtailment of the tube
As a last experiment, a practical examination of the results seen in the simulation was to shorten the tube. This was saved for last because it had to be done by cutting the tube, which would make it impossible to repeat any of the earlier experiments (if needed) with the same length of the tube. The 8.5 Fr SVP had markings on the tube every fifth centimeter, so these was used to shorten the tube by five centimeters at a time between each measurement. The 9.6 Fr CVC did not have any markings, so the tube was measured from the inlet to be 30 centimeter and then marked every fifth centimeter. A pressure corresponding to an injection of 0.2 ml where applied to the 8.5 Fr SVP. For the 9.6 Fr CVC, both 0.2 and 0.4 injection pressures where applied.

The curtailments had to be done at the end of the catheter tip where the adapter was connected, meaning that each curtailment was followed by a reassembling of the adapter and the catheter tip. Because both the 3 Fr CVC and the 6.5 Fr SVP adapters were hard to get on tight enough to not leak, these catheters where not tested during this curtailment experiment.

Results
As expected from the simulations, the pressure drop along the tube depends on the length of the tube. A shorter tube means less contact between the liquid and the walls, and therefore less friction resisting the flow, and thus a higher pressure at the outlet when given approximately the same inlet pressure. This was also shown by the experiment, and the results for the 8.5 Fr SVP and the 9.6 Fr CVC could be seen in Figure 23.

![Figure 23](image-url)

*Figure 23* The outlet pressure for different lengths of the tube with the 8.5 Fr SVP and the 9.6 Fr CVC. As expected, the outlet pressure rises when the tube gets shorter.
Discussion

As both the simulations and the experiments show, the pressure drop depends more on the length of the catheter than on the curvature. It is not until there is an actual kink on the catheter tube we could see influence on the pressure at the outlet. It is likely that such a kink would be visible on the x-rays taken in the operational theater and that the surgeons would make corrections if needed. Problems occurring directly after insertion are improbable to be caused by the surgeons’ work concerning the bend of the tube, because such a kink would never be sent away from the operational theater knowingly. If the tube is squashed, for example against some bone tissue, this may not be clearly visible on the x-rays, since the x-rays are only taken straight from the front of the chest and from the side.

The fact that the pressure is dependent on the length and radius of the tube make us think about the choice of catheter given to the patient. The size of the patient affects the length of the tunneling as well as the surgeon’s choice of placement of the subcutaneous port or the exit hole through the skin for the central venous catheter. The radius of the tube is well documented by the manufacturer regarding which flow to be used in each catheter, but there is also a choice made depending on the size of the patient. Given that the length and the radius affect the pressure at the outlet located in the inlet of the heart, the wrong choice of catheter could lead to tissue injury by the chemotherapy drugs.

Earlier studies have mostly been focusing on the medical part of the problems; infections and thrombosis, whereas in this work a more technical approach has been used. The experiments have been performed with the same catheters as used at the clinic, although studied in a laboratory environment and not in the body. The experiments and simulations have confirmed the theory for fluids in pipes, mostly with respect to the length and radius of the tube, which are parameters easy to vary. The curvature of the tube has shown to be of minor importance as long as there is no actual kink on the tube.

Further research

The initial aim to be able to form an action plan for the nurses from the results of the experiments proved to be hard. There are many factors to weigh in that might affect the result, but in the future it would be optimal to have some kind of device which could measure and tell the nurse what is the most likely problem and how the nurse could solve this problem. However, much more experiments must be performed in the right environment in order to be able to create this kind of device.

One problem not included in this work is when the tube is sucked to the blood vessel wall. This is harder to investigate because the problem is located inside the body and inside the vessel. Maybe a better documentation of when this is suspected to have happen could lead to a better understanding of the problem and possibly, if needed, lead to a modified product from the manufacturer. Maybe the choice of material and formation of the tube tip could affect the sucking?

It is possible that the phenomenon that the velocity of a fluid close to the wall of a tube is zero and that the smaller the tube is, the larger amount of fluid is in contact with the wall could be a reason that some fluids are more probable to clog the tube. For example, the smaller patients are given a thinner catheter tube and it is also those patients who receive most nutrition through their catheter. Maybe the flow rate could be an explanation to why this problem is more common for these
patients. It could be valid to rethink the choice of catheter dimension if it is known beforehand that the patient will receive nutrition frequently. However it is easier to achieve a high flow rate in the thinner tubes (without risking to break the catheter), which could be enough to compensate for the clogging. This must be further investigated with more accurate collection of statistics for the specific group of patients in order to achieve a reliable explanation.

To get an even better overview of what is the most common problem and if there is any returning pattern on what the reason behind it would be, a more specific study on the catheter related problems should be performed. As one nurse suggested, the patients could be given a diary managed by the nurses, the patient and the patients’ parents. Today, there are notes kept about the catheter related problems in the Patients Recordings among with all other notes of the treatment. A diary about just the catheter would make it easier to follow up the problems related to the catheter and maybe enabling us to see patterns on when a certain problem occur. This would also give a better statistic record about the different problems and provide a priority plan for what is most important to work on. A study like this have to be long term, preferably during the entire treatment, and was hence not started during this project.

If the experiments in this work are to be repeated, it is suggested to use a syringe pump. This would make the inlet pressure more even and eliminate the human error. However, hand injections such as used in this work are what is done at the clinic. A more advanced DPI could have given a view of the pumping motion the nurses use to mechanically flush the catheter tube to clean the system.

The simulation part could be extended. For example a simulation of a blood clot inside the tube could be run to see how the flow is affected by different size or shape of the clot. As mentioned earlier a mesh convergence study could be performed to get more reliable results, and using a more powerful computer would speed up the simulation time.

**Conclusions**

This project has shown that in the technical aspect, the length and radius are the most important properties of a catheter tube. Curvature (and loops) will not affect the flow through the catheter significantly, unless there is an actual kink on the tube that would be visual on an X-ray.

The results of this project could give the clinic a hint of what to have in mind when choosing the catheter for the patient. The length and radius of the tube have to be weighed in along with the planned fluid flow and type of fluids according to what will suit the individual patient best.
References


### Appendix

**Table 4** Measured values bending the tube in different channels (see numbering in Figure 5)

<table>
<thead>
<tr>
<th>Unit (MPa)</th>
<th>Injection</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Braun 8.5 Fr</strong></td>
<td>0.2 ml</td>
<td>0.145</td>
<td>0.167</td>
<td>0.165</td>
<td>0.147</td>
<td>0.164</td>
<td>0.168</td>
<td>0.162</td>
<td>15 cm from inlet</td>
</tr>
<tr>
<td></td>
<td>0.4 ml</td>
<td>0.169</td>
<td>0.160</td>
<td>0.161</td>
<td>0.154</td>
<td>0.157</td>
<td>0.157</td>
<td>0.148</td>
<td></td>
</tr>
<tr>
<td><strong>Braun 6.5 Fr</strong></td>
<td>0.2 ml</td>
<td>0.080</td>
<td>0.092</td>
<td>0.093</td>
<td>0.080</td>
<td>0.082</td>
<td>0.078</td>
<td>0.083</td>
<td>15 cm from inlet</td>
</tr>
<tr>
<td></td>
<td>0.4 ml</td>
<td>0.125</td>
<td>0.108</td>
<td>0.110</td>
<td>0.120</td>
<td>0.110</td>
<td>0.124</td>
<td>0.114</td>
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<tr>
<td><strong>Bard 9.6 Fr</strong></td>
<td>0.2 ml</td>
<td>0.065</td>
<td>0.067</td>
<td>0.070</td>
<td>0.065</td>
<td>0.070</td>
<td>0.065</td>
<td>0.057</td>
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<tr>
<td></td>
<td>0.4 ml</td>
<td>0.125</td>
<td>0.108</td>
<td>0.110</td>
<td>0.120</td>
<td>0.110</td>
<td>0.124</td>
<td>0.114</td>
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</tr>
<tr>
<td><strong>Cook 3 Fr</strong></td>
<td>0.2 ml</td>
<td>0.110</td>
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<td>0.128</td>
<td>0.122</td>
<td>0.115</td>
<td>0.118</td>
<td>20 cm from inlet</td>
</tr>
</tbody>
</table>

**Table 5** Measurements given in MPa from narrowing the tube

<table>
<thead>
<tr>
<th>Diameter (mm) / injection</th>
<th>SVP</th>
<th></th>
<th>CVC</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8.5 Fr</td>
<td>6.5 Fr</td>
<td>9.6 Fr</td>
<td>3 Fr</td>
</tr>
<tr>
<td></td>
<td>0.2 ml</td>
<td>0.2 ml</td>
<td>0.2 ml</td>
<td>0.4 ml</td>
</tr>
<tr>
<td>3.2</td>
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<td></td>
<td></td>
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<tr>
<td>3.0</td>
<td></td>
<td></td>
<td>0.08</td>
<td>0.140</td>
</tr>
<tr>
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</tr>
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<td>0.060</td>
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<td>0.120</td>
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