Graduation project : Biomedical Engineering TU Delft

Effective cleaning of hollow medical devices using fluid mechanics

Nabil el Hasnaoui

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TU Delft

Effective cleaning of hollow medical devices using fluid mechanics

Graduation project

by

N. el Hasnaoui

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This thesis is confidential and cannot be made public until October 1, 2021.

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Preface

In this part of my report, I would like to take the opportunity to express my gratitude for all the chances I got. A person who seeks knowledge has the ability to achieve anything a person wishes for. This thesis would not have been possible without the help of my supervisors, whom I would like to acknowledge their invaluable guidance and patience throughout the thesis. In particular, I would like to thank ir. Robertson for his support, continuous guidance, meticulous suggestions and astute criticism.

Finally, I would like to express my gratitude for the inexhaustible support of my parents, two siblings and my wife who pushed me forward and stood by my side to make sure I succeed every step of the way.…

N. el Hasnaoui
Delft, July 2021

Contents

Introduction

After a surgery, a medical device is contaminated with hidden or visible bio-burden, which contains hundreds if not millions of infectious organisms. The use of contaminated device could be fatal for patients. Over the years, more and more reusable surgical devices have become available for hospitals and the geometry of those devices have become more complex and contain crevices and lumens. This makes adequate cleaning challenging.

Occasionally, hollow instruments are insufficiently cleaned after a treatment. This could happen due to various reasons. The main reason is that during the cleaning process there is insufficient pressure and flow of fluid through the hollow devices. During the cleaning process, the flow and pressure are not monitored and therefore insufficient flow and pressure remains unnoticed. In addition, the chemicals used for cleaning, the device geometry and other cleaning parameters play an important role in the cleaning process. Before disinfecting medical instruments, thorough cleaning is essential, because organic and inorganic contamination, interfere with the effectiveness of sterilization.

The main problem in this thesis is that little is known about the extent to which cleaning parameters influence the cleaning process of hollow medical devices. There is no single clear approach to clean hollow instruments. Furthermore, there is a lack of translation of knowledge obtained by studies regarding this subject to practical guidelines. An example of this is the study of Hariharan et al. [8], who showed that that fluid shear plays an important role in the cleaning process. It is the dominant factor compared with the detergent at higher flow rates. However, for hospitals and manufacturers there are no strict regulations concerning the minimal flow rate or minimal wall-shear stress needed for cleaning hollow instruments. According to the international guidelines the instrument has to be visually clean after the cleaning process. This is difficult for hollow medical instruments since they are often inaccessible for visual examination. Moreover no specific mechanical properties for wash-disinfectors are found in the ISO standards and the responsibility lies with the manufacturers. It is worrying that it often happens that hollow instruments don't always leave the wash-disinfector after the cleaning cycle without dirt.

Experts in the field of medical instrument cleaning acknowledged the lack of information on the cleaning process of hollow equipment and requested for more research [2] [3]. The importance of adequate reprocessing of medical device is high and therefore appropriate guidelines are needed to prevent severe infections and disease transmissions between patients. Especially in times of disease outbreak as it is now (COVID-19 in 2020/2021), in-effective cleaning could be disastrous. For example, many studies have found that the explosion of Pseudomonas between December 2008 and August 2009 is highly correlated with the accumulation of biofilm due to insufficient cleaning and drying before storage [12] [16]. Particularly, in times of the COVID-19 it is an interesting graduation topic to get more insights into this field of study and to find perspectives for the future studies.

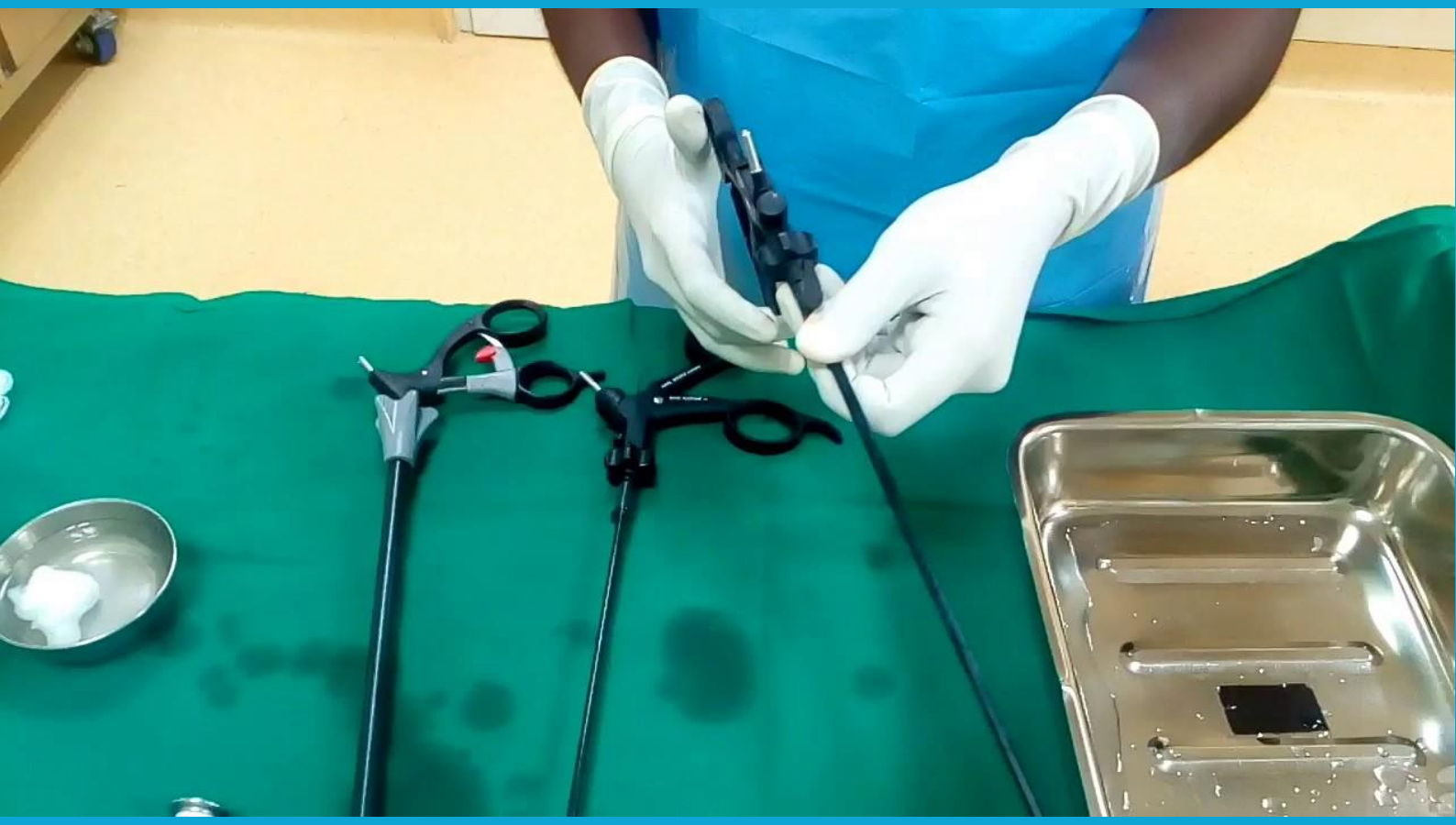
In this thesis, an experimental set-up was developed, which helps to investigate the effect of cleaning parameters on the cleaning performance of reusable devices with a complex geometry. With those results a guideline, regarding the cleaning parameters needed for specific instruments could be determined to provide effective cleaning. This experimental set-up could be used for the design of a new cleaning device and provides new insights that could be used for current wash-disinfectors in the Netherlands. In this thesis the experimental set-up was used to investigate the effect of flow rate on the cleaning performance. The journal article describes the method used to investigate the effect of flow rate. Furthermore, it shows and discusses the obtained results. The journal article should be seen as a separate part of the report. The design requirements, thesis process and the final design is described in the appendix.

Graduation project : Biomedical Engineering TU Delft

JOURNAL ARTICLE : The influence of flow rate on the cleaning performance

Nabil el Hasnaoui

2021



TU Delft

The influence of flow rate on the cleaning performance of hollow medical devices

Nabil el Hasnaoui, *Student Biomedical Engineering, TU Delft*

Abstract—Cleaning is an important factor in the reprocessing of hollow medical instruments. Inadequate cleaning disturbs the disinfection and sterilization process and increases the risk of cross-contamination. An automated washer-disinfector is often used for cleaning medical instruments, by using fluid flow. Fluid flow induces shear stress at the wall of medical instruments and is able to detach contamination from the surface. However, there is a lack of studies on the effect of flow rate on the cleaning performance. Also in the ISO standards, no flow requirements can be found to remove contamination. In this study, the relationship between the flow rate and removed mass fraction at different soaking times is investigated to get more insight in the effect of fluid flow on the cleaning performance. The results in this study show that, for smooth tubes with a diameter of 9 mm, the removed mass fraction increases for flow rates up to 7.1 L/min where after the removed mass fraction stagnates. An ANOVA test was performed in combination with a Tukey HSD multiple comparison test to determine significant effects. There is a significant difference in the mass fraction removed, by applying different flow rates ($F = 88.24$, $p = 9.49 * 10^{-33}$) and different soaking times ($F = 15.35$, $p = 2.8 * 10^{-6}$), with F as the test statistic from the F-test and p as the p-value. The Tukey HSD test shows significant difference comparing flow rates $\geq$ 5.9 L/min with flow rates $\leq$ 5.1 L/min. For cleaning with 7.1 L/min, 5.9 L/min or 8.0 L/min no significant differences in the results are found. Furthermore, no significant differences in the cleaning performance of flushing with 3.5 L/min compared to lower flow rates is found. Moreover, this study shows that there is a significant difference between soaking and no soaking. Comparing 5 minutes and 10 minutes soaking no difference are found. This study shows the effect of flow rate on the cleaning performance and it can be concluded that for adequate cleaning of hollow medical instruments the shear stress induced by the flow rate should be taken into account. The results in this study can be used as ground truth to compare to the cleaning performance of different complex geometries with each other. Furthermore, with the method described in this article the effect of more cleaning parameters could be investigated.

Index Terms—Cleaning of reusable medical devices, Effect of fluid shear stress, Reprocessing, Test soil for cleaning validation.

1 Introduction

Cleaning is not only the first, but also the most important step in reprocessing reusable medical devices [1]. Before sterilization thorough cleaning is required, because residual contamination remaining on the devices surface disturbs the effectiveness of sterilization. In hospitals and other clinics an automated washer-disinfector is used, which improves the consistency of cleaning medical instruments and is able to process more instruments in a given time period. An automated washer-disinfector includes fluid flow, which is an important factor to remove the debris from medical device surface. The mechanical force generated by a fluid flow helps to detach contamination from a surface and flushes the contaminants out of the hollow devices. The required shear stress for adequate cleaning of hollow instruments depends on multiple factors, such as the

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type and amount of contamination, the level of dryness, the surface roughness etc. For removing contamination a minimum fluid shear stress is needed.

In literature, there is lack of high-quality studies on the effect of fluid flow induced shear stress on the cleaning performance of hollow medical instruments. Two articles are found which try to point this subject. The first article evaluates the role of fluid flow-induced shear stress in the removal of contaminants from device surfaces [2]. In this article experimental setup has been built to investigate the relationship between the applied wall shear stress and the clot removal. The test section consisted of a transparent, straight, rectangular tube with an inserted test coupon. The test coupon is made of stainless steel and mimics the surface of a medical instrument. The test coupon is soiled with a artificial clot of 16 mg, 6,8 mg or 1 mg. The coupon is then exposed to the induced jet and enzymatic detergent and the residual contamination was measured. The results show that mass of removed contamination followed a linear relationship with the fluid shear stress. In this article, the fluid shear stress is measured using Particle Image Velocimetry (PIV). This study showed that the clot surface is removed with 67%, 77% and 95% for clots with initial masses of 16 mg, 6.8 mg, and 1 mg. With the help of fluid shear stress, the percentage of removed clot can significantly increase. The second study investigated the flow along a confined obstacle. A jet enters a square test section and creates a flow around an obstacle [3]. The goal of this study was to develop a database to validate numerical CFD models, which are used to simulate the cleaning performance of reusable medical devices with complex geometries. In this study a long-distance micro-PIV is used to determine the flow along a confined obstacle. Wang et al. (2019) concluded that the wall shear stress serves as a driven force to remove contamination. The wall shear stress is neglible in the so-called 'vena contracta area' and should therefore be avoided in the design of channel medical instruments.

The lack of studies on cleaning performance of hollow instruments is remarkable, since there are a lot of comparable researches performed on cleaning pipelines in the food industries [4][5][6][7][8][9][10]. Production lines in this industry are daily cleaned to ensure the safety of the products. Despite fluid shear plays an important role in the cleaning process and is according to Hariharan et al. (2018), the dominant factor compared with the detergent at higher flow rates there are no strict regulations concerning the minimal flow rate or minimal wall-shear stress needed for cleaning hollow instruments. According to the international guidelines the instrument has to be visually clean after the cleaning process, which is difficult for hollow medical instruments since they are often inaccessible for visual examination, moreover no specific mechanical properties for wash-disinfectors are found in the in ISO standards (see Appendix A) and the responsibility lies with the manufacturers. It is worrying that it often happens that hollow instruments don't always leave the wash-disinfector after the cleaning cycle without dirt.

The induced shear stress depends on the flow rate and the type of the flow. In the field of fluid dynamics, the Reynolds number is used as parameter to determine the type of the flow. When the Reynolds number is $<$ 2300, the flow can be considered as laminar. For Reynolds numbers $\geq$ 2300 but $<$ 4000 the flow is in a transitional state. If Re $\geq$ 4000 the flow is turbulent. It is known that turbulent flow leads to higher shear stresses. The formula of the Reynolds number is defined

as:

$$R_e = \frac{\rho V d}{\mu} \quad (1)$$

With ρ, the density of the fluid ($\frac{kg}{m^3}$), V is the mean velocity of the fluid ($\frac{m}{s}$), d is the diameter of the tube (m) and is the dynamic viscosity ($\frac{kg/m}{s}$).

In a previous study [11], performed in the Erasmus Medical Center in Rotterdam, the flow rate in a washer-disinfector was measured. In this study, the washer-disinfector was analyzed on their mechanical performance, by using a system, developed by Causa BV (Eindhoven, the Netherlands). The mechanical action of the washer-disnfector was determined as the flow (ml/s) and pressure (kPa). For tube with a diameter of 2 mm and 6 mm, the measured flow rate was converted 0.48 L/min and 0.66 L/min , respectively. For those flow rates and the corresponding tube diameter, the expected Reynolds number is calculated (4480 and 2053), with μ is 0.0011 $\frac{kg/m}{s}$. The flow pattern for the 2 mm tube is turbulent and for 6 mm tube this is laminar. This example just shows the importance of mechanical action guidelines in the ISO standards, since for laminar flow patterns lower shear stresses is expected.

The goal of this study is to get more insight in the effect of fluid flow on the cleaning performance of hollow medical devices. In this study an experimental setup, designed at an earlier stage of this project (see Appendix B), is used to determine the relationship between the flow rate and removed mass fraction at different soaking times. During this experiment, no detergent was used.

2 METHODS

For testing the effect of various flow rates through test tubes a circulating flow loop is used. For a specified time, flow fluids through the tube and generates a shear stress to remove debris from the surface. The experiment was performed at the TU Delft and takes the bio-safety, the protection of student/employees and the environment in- and outside the university against the micro-organisms, into account.

2.1 Flow loop

The experimental setup used for the experiments is shown in figure 1A. All the components are described below.

- A self-priming gear pump (Model UP3, MARCO s.p.a., Brescia, IT) was used to generate flow through the loop at different flow rates. The pump is controlled by a computer via LabVIEW (Version 18.0, National Instruments, United States). The pump is able to generate a flow up to 15 L/min, which is above the typical flow rate used for flushing (0.4-0.7 L/min [11]). Moreover, the pump is able to generate a constant flow, as well as pulsating flow patterns.
- To monitor the flow rate an ultrasonic flowmeter (110 series, NETIX, United Kingdom) was used. The flow rate is measured by using up- and downstream transmitted sound. Sound transmitted upstream is accelerated by the flow and sound transmitted downstream is decelerated. The resulting difference in time is converted into an output signal (A), by a micro-controller. The output signal is proportional to the flow rate. Here, 20 mA as output signal corresponds to a flow rate of 25 L/min. The flow meter is able to measure flow rates between 0.2 and 25 L/min.
- The stainless steel test tubes consist of three parts (see figure 1B). The first part (length = 100 mm, inner $\varnothing$= 9

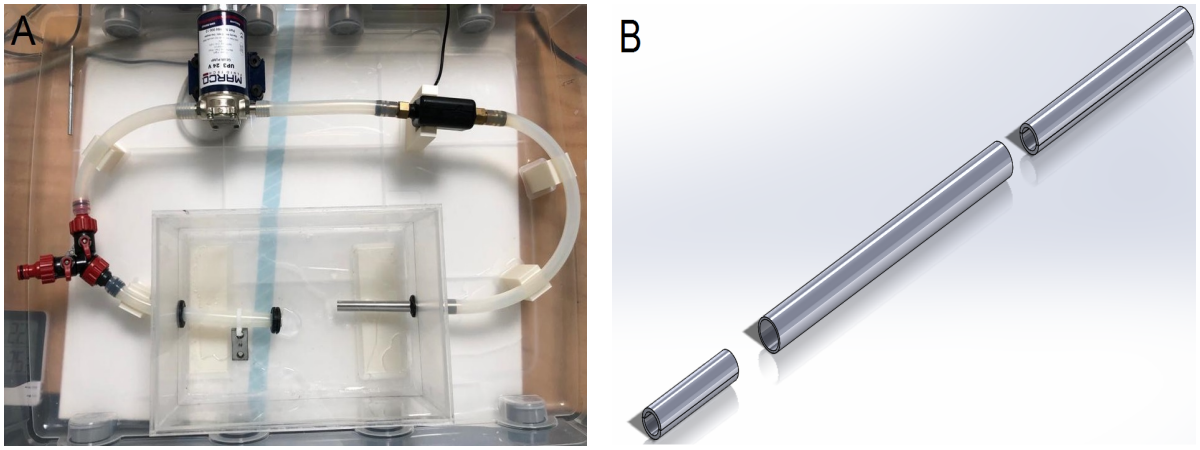

Figure 1: A) Test setup used to investigate the effect of flow rate on the cleaning performance B) Stainless steel tubes consisting of three parts (from left to right : 50 mm inner tube, 150 mm outer tube, 100 mm inner tube)

mm, outer ⌀= 12 mm) and second part (length = 50 mm, inner ⌀= 9 mm, outer ⌀= 12 mm) are enveloped by the third part (length = 150 mm, inner ⌀= 12 mm, outer ⌀= 13 mm). The inner tubes (Part I and Part II) have an inner surface roughness of 0,34μm - 0,37μm. The inner tubes are longitudinally cut to allow the tubes to be contaminated and visually inspected after cleaning. The total amount of test tubes used in this study is six.

- Tray : The shear stress in a tube is dependent on the pressure. To mimic the pressure drops in washer-disinfector a tray is designed where the flow through the tube debouches into the tray. The rectangular acrylic tray (30 cm x 20 cm x 15 cm) is connected to the tube at one side and to a tygon tube at the other side, by PVC grommets, to prevent leakage. Furthermore, there is a lid on the tray to prevent contamination flushing out of the tray.
- During the experiment the distilled water used for cleaning is refreshed every day. A 3-way stopcock is used to eliminated the water from the circuit.

2.2 Preparation of test soil

For this study, egg yolk is used as test soil. The test soil is prepared according to ISO/TS 15883-5 [12]. The eggs used in this study are white free-range eggs (Albert Heijn, Netherlands). The following steps are taken to produce the test soil :

- The egg is maintained in a water bath at a temperature of 20°C, for 30 minutes (see figure 3A). The temperature of the water is controlled by a temperature controller (STC 1000, Ketotek, China), which is connected to a water heater. This controller, turns the heater on, when temperature is $\leq$ 19°C and off when the temperature is $\geq$ 21°C. In this way, the temperature of the water is kept constant at 20°C.
- The egg is then heated with steam at 100 °C, for 4 minutes, using an electric egg cooker (262046, Princess, the Netherlands). (see figure 3B)
- The egg is cooled in water with a temperature of 20°C for 5 minutes.
- The egg can now be opened with sterile hand gloves and separated from the albumen. It should be noted that the

albumen is firm. The liquid egg yolk is poured into a plastic container and can be used to contaminate the test pieces. A syringe or needle can be used to help with the extraction of the egg yolk from the albumen (see figure 3C).

2.3 Deposition of test soil

Before applying the test soil on the test tubes, each test piece was cleaned, degreased and marked. After this, the initial weight of each tube was measured. Then, the test soil was applied by using a 5 ml-syringe (Omnifix, B Braun, Germany) and a metal mask. In figure 3A the metal mask is shown. The mask contains a 2.5mm x 40mm x 1mm hole in which the egg yolk was placed. The mask serves to keep the position of the test soil constant. Furthermore, the mask makes sure that the contamination is placed far from the cutting line of the tubes which might influence the flow pattern.

For a constant amount of test soil the deposition of test soil was performed on a weighting scale to keep track of the weight. Directly after soiling, the metal mask is removed and cleaned to be used for the next test tubes. The tubes are then placed in an oven and dried for 4 h at a temperature of approx. 37 °C and a relative humidity of approx. 46 %. The temperature in the oven is controlled by a temperature controller (STC 1000, Ketotek, China) (see figure 3B) and the relative humidity is controlled by a salt solution. A saturated salt/water solution is able to maintain particular value for relative humidity's in a closed environment. This mixture of distilled water and salt is able to absorb and adsorb water until a characteristic critical humidity is reach. Each type of salt has its unique critical humidity. According to Adams et al. [13], a solution of calcium-nitrate in distilled water has a relative humidity 46.7% and 35.5% for ambient temperatures of 30 °C and 40 °C, respectively. Therefore, a container with a 1212 g/L calcium-nitrate solution was placed in the oven, to control the relative humidity. The relative humidity is monitored using a digital thermo-hygrometer (Dostmann electronic GmbH, Duitsland) (see figure 3C)

2.4 Flow rate applied

Various flow rates were applied to determine the effect of flow rate on the cleaning performance of medical instruments. It is interesting to see the difference between the effect of laminar, transitional and turbulent flow on the removal of debris, therefore the flow rates are chosen in such a way that the effect of those flow patterns are included. The gear pump is current-controlled and for different current inputs, different flow rates are measured. The relationship between the current flow and flow rate is shown in figure 4. The flow rates used in this experiment are 0 L/min. 1.1 L/min, 2.1 L/min, 3.5 L/min, 5.1 L/min, 5.9 L/min, 7.1 L/min and 8 L/min. After flushing the test tubes dried for 16 hours in an environment with a relative humidity of approx. 46%, according to [12].

2.5 Flushing time

A pilot study was performed to investigate what flushing time suits the best for this experiment. Longer flushing times will improve the difference of the effect of different flow rates on the cleaning performance, but should not remove all of the debris on the test tubes. In this pilot study, 1, 3, 6, 8, 10 and 14 minutes of flushing is applied. A maximum of 14 minutes flushing time is tested, because this is the time used during daily practice. The result of the pilot study is shown in figure 5 As could be noticed after 14 minutes of flushing with a flow rate of 5.9 L/min there is still contamination visible. Therefore, a flushing time of 14 minutes is used in the experiments.

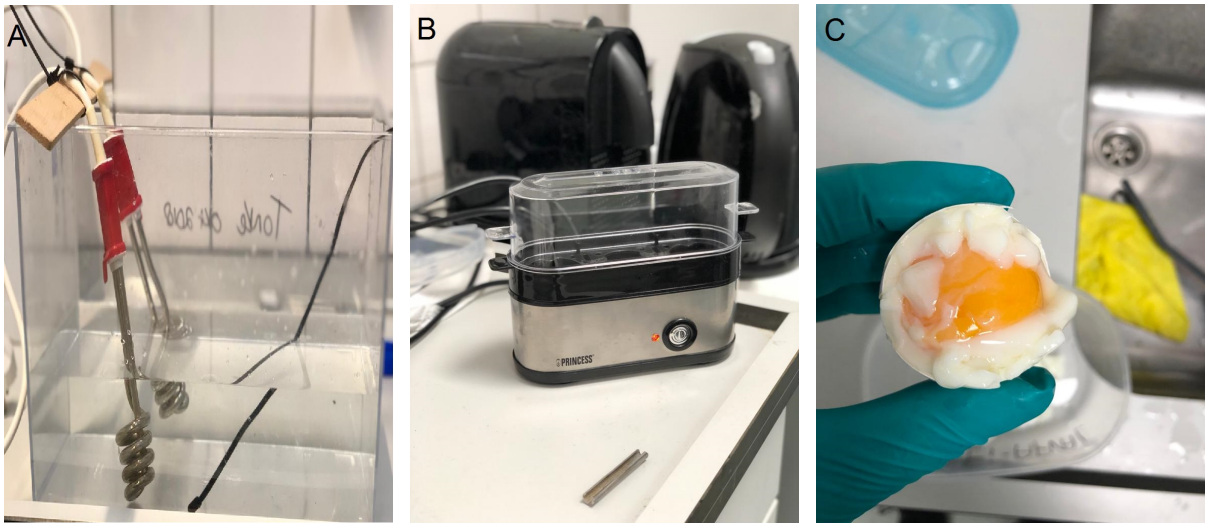

Figure 2: A) The temperature in the water bath controlled by a temperature controller and water heater. B) Electric egg cooker to heat the eggs with 100 °C steam. C) Egg yolk can be extracted from the firm albumen.

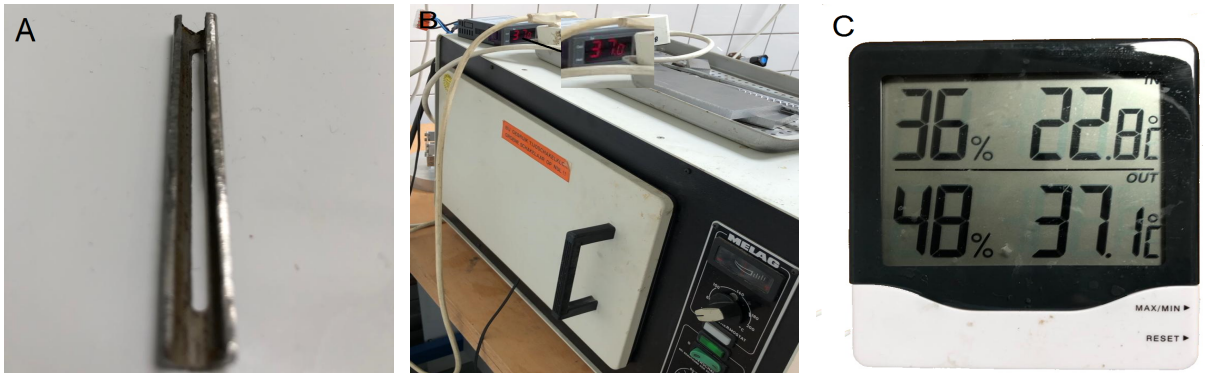

Figure 3: A) Metal mask used to placed the test soil on a constant position. B) Temperature in the oven controlled by a temperature controller (STC 1000, Ketotek, China) C) Digital thermo-hygrometer (Dostmann electronic GmbH, Duitsland)

2.6 Soaking time

In this study the soaking time is varied by 0 min, 5 min and 10 min. This allows to study the effect of the flow rate and soaking time on the mass fraction removed, as well as the effects of interactions between those two independent variable on the mass fraction removed. According to Hariharan et al. (2018) [2], the clot removal did not significantly decrease after 10 minutes soaking. Therefore, the maximum soaking time tested in this study is 10 minutes.

2.7 Amount of contamination

The amount of contamination applied before drying is ± 50 mg. This amount is chosen by trial and error, in which the egg yolk should cover a large surface, without soiling the edges of the tube. Figure 6 shows the results of flushed test pieces with an amount of ± 150

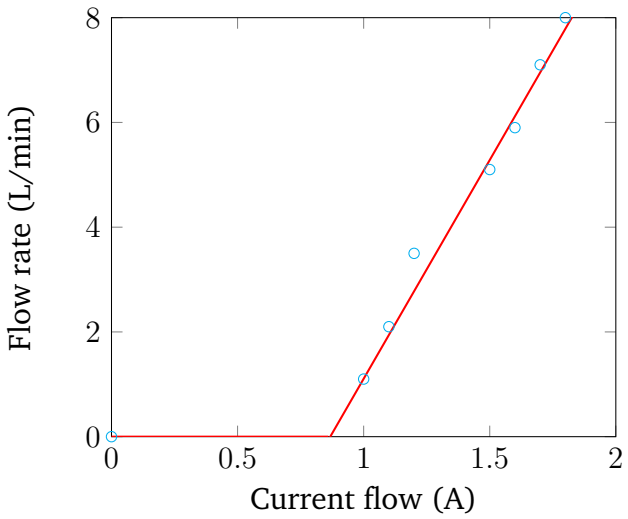

Figure 4: Relation between the current flow (A) and flow rate (L/min)

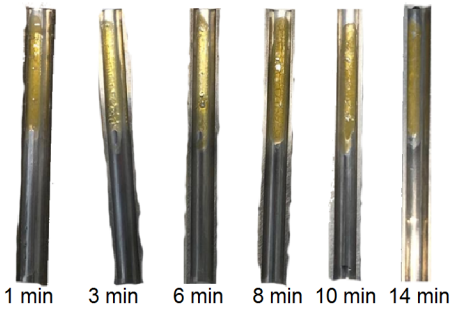

Figure 5: Results of flushing for different flushing time with a flow rate of 5.9 L/min

mg and ± 50 mg distributed on the test tubes. This concerns the weight before drying the contaminated test tubes. As could be noticed, applying ± 150 mg egg yolk, results into a thick layer with cracks in it, which was more difficult to clean. A smaller amount of ± 50 mg applied soil was chosen, since this more closely mimics the contamination that could be found on surgical instruments. After drying, the resulted amount of contamination on the test tubes was on average 28 mg, with a standard deviation of 9 mg.

Figure 6: A) ± 150 mg of egg yolk applied B) ± 50 mg of egg yolk applied

2.8 Safety considerations

Since animal products are used during this study, severe safety regulations are taken into consideration. During the preparation of the test soil, the soiling of the test tubes, the loading of the test pieces into the circulating flow loop and during the examination of the processed test tubes a protective coat, sterile hand gloves and a face mask are worn. The needles and egg residue were disposed in bio safety containers. In accordance with local procedures, the surface that have been soiled are cleaned using an appropriate disinfector.

2.9 Data-analysis

In this study, multiple experimental groups are investigated. Therefore, an Analysis of Variance (ANOVA) test is performed. The ANOVA analysis is able to indicate difference in the effect of flow rate or soaking time on the cleaning performance. However, for analyzing the differences among groups a "multiple comparison analysis" test is needed. The results in this study are analysed using a Tukey HSD ("honest significant difference"-test). This post-hoc test makes a pairwise comparisons among sample means. This is useful, since this study tries to identify differences between different flow rates and different soaking times.

The effect of flow rate is measured by weighting the mass of the soil before and after the tubes went through the cleaning cycle. For

each flow rate, four trials were performed, for each soaking duration.

3 RESULTS

In this study, A total of 96 test results were obtained using normal test tubes. Eight different flow rates were used for flushing the test tubes and the effect of three different soaking times was examined. Each combination was performed four times. During one test round, the cleaning performance of two test pieces with the same flow rate and soaking time could be examined at the same time.

In figure 7, an example of a test tube before soiling, with dried contamination and after cleaning is shown. The amount of contamination on the test tube after drying was 16 mg. After cleaning with a soaking time of 10 minutes and a flow rate of 5.9 L/min an amount of 11 mg was removed. Hence, the contamination on the test tube was reduced by 69%.

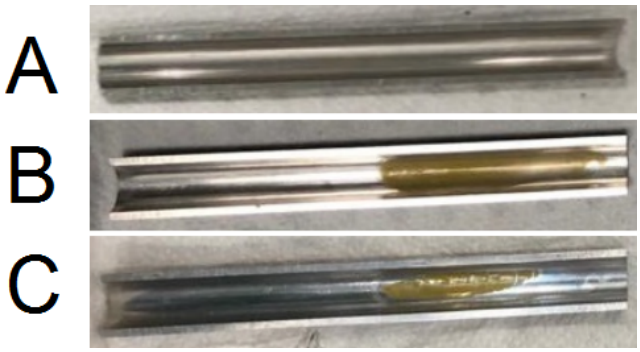

Figure 7: A) Clean test tube B) Test tubes with dried soil C) Test tube after cleaning

Figure 8 presents images of soiled test pieces after testing. Those images show the removal of contamination after 10 minutes of soaking and cleaning with a certain flow rate. The "reference" (see picture R) is a test tube with dried soil and displays the state of the test soil on the tube before cleaning. Images A-H are taken after cleaning and drying, according to section 2. In this figure, no clear reduction in contamination could be observed for lower flow rates (A-D). For higher flow rates, more clean surfaces is observed at the positions where there used to be egg yolk. Furthermore, It seems that tubes E, F and H contains the least residual contamination.

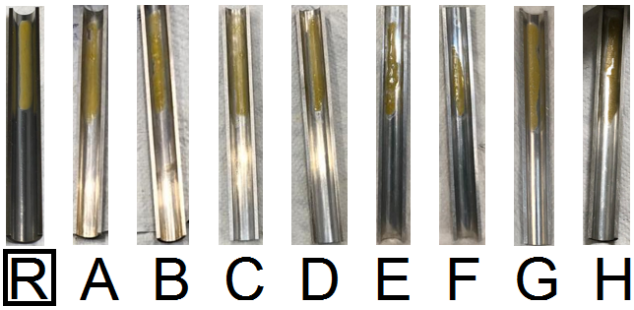

Figure 8: The result of 10 minutes of soaking and flushing with different flow rates is shown. R) Reference A) 0 L/m, B) 1.1 L/m, C) 2.1 L/m, D) 3.5 L/m, E) 5.1 L/m, F) 5.9 L/m, G) 7.1 L/m, H) 8.0 L/m

3.1 Effect of flow rate

The relationship between the removed mass fraction and fluid flow is presented in figure 9. This figure provides an overview of the raw data for three different soaking times. The mass fraction is defined as the ratio of removed mass to the initial mass of the contamination. For each flow rate four values of the removed mass fraction are obtained, since each experiment was repeated four times.

In figure 10, an increase of removed mass fraction could be noticed by increasing the flow rate. The mass removed as a function of flow rate is roughly exponential for flow rates up to 5.9 L/m is. The increase stagnates for flow rates from 7.1 L/min and higher. Furthermore, a large difference in cleaning performance is observed for flushing with a flow rate of 5.1 L/min compared to 5.9 L/min (for 5 and 10 minutes soaking). The average removed mass fraction for 5 minutes and 10 minutes of soaking and flushing with 5.1 L/min is 0.27 and 0.26, respectively. For

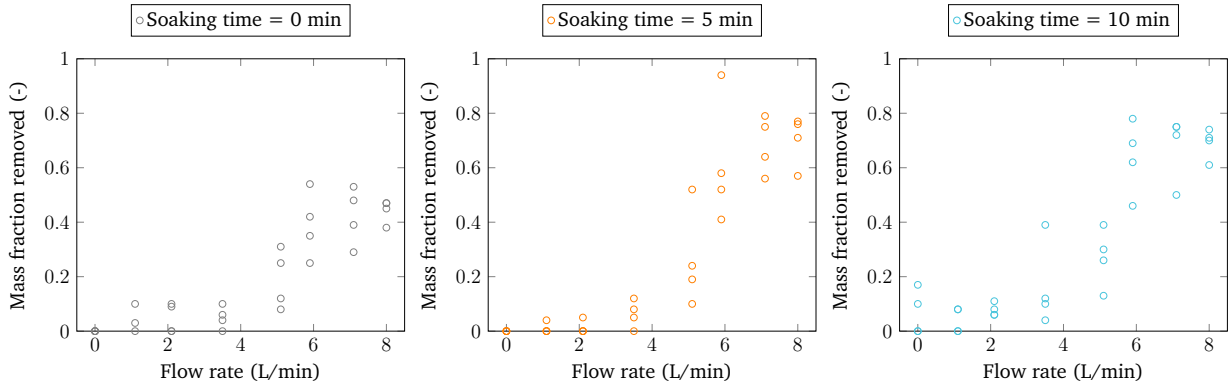

Figure 9: Raw data of test results

flushing with 5.9 L/min this is 0.61 and 0.64.

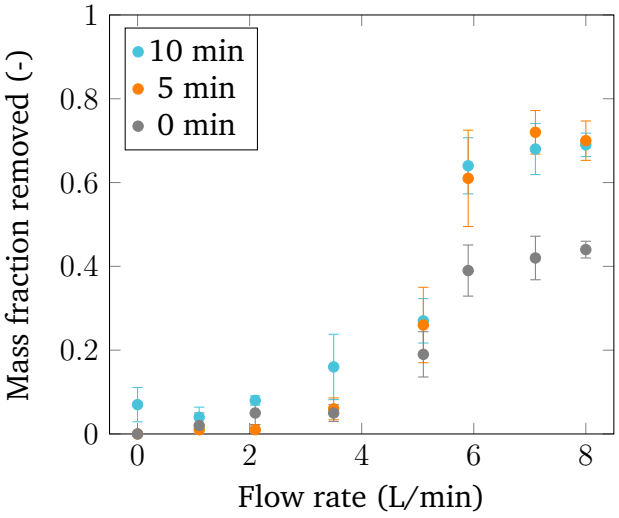

Figure 10: Average removed mass fraction with error bars

removed is shown in green. The green dot is the average of all results of the tests performed with the corresponding soaking time.

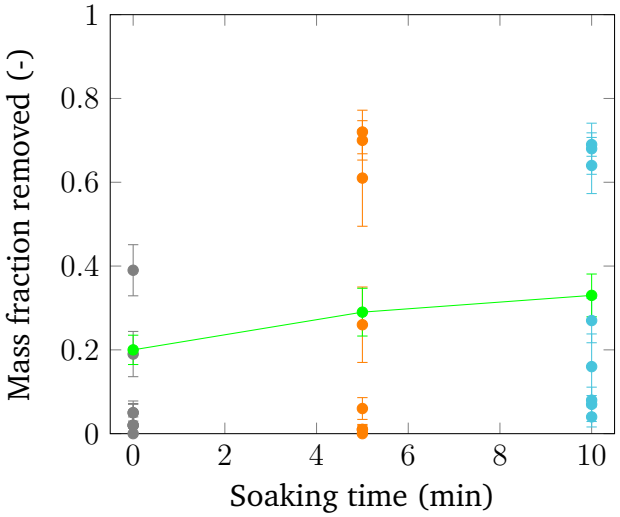

Figure 11: Average removed mass fraction for different soaking times with error bars

3.2 Effect of soaking time

The effect of soaking time regardless of the flow rate is shown in figure 11. The figure shows more removal of contamination by soaking the test tubes before flushing. Especially the difference between no soaking and 5∼10 minutes of soaking is clearly presented. Soaking increases up to 50% of the cleaning performance. In this figure, the average mass fraction

3.3 Statistical analysis

To understand the statistical significance of the results in this study an analysis of variance (ANOVA) is performed in combination with a Tukey HSD multiple comparison test.

The result of the ANOVA analysis is presented in table 1. In this table the effect of flow rate, the soaking time and the interaction effects

are shown. The abbreviations used in this table are explained in Appendix C

Comparing the F-value with the $F_{critical}$-value shows that the F-value for the effect of flow rate and soaking time is 88.2 (p<0.05) and 15.4 (p<0.05), respectively and higher than the $F_{critical}$-value. This means that there is a significant effect of different flow rates and different soaking time on the cleaning performance. The interaction effect shows a F-value 1.96 and p=0.04. The relationship between the flow rate and the removed mass fraction differs by the soaking time. Furthermore, the "Within-effect" is mentioned in the table, which shows the degree to which the effect of a parameter is different for different subjects. This is also known as the 'unexplained random error'.

Table 1: Two-way ANOVA table for the effect of flow rate on the removed mass fraction

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Flow rate	6.068377	7	0.866911	88.23703	9.49E-33	2.139656
Soaking time	0.301617	2	0.150809	15.34979	2.8E-06	3.123907
Interaction	0.263493	14	0.018821	1.915653	0.038573	1.831607
Within	0.707385	72	0.009825			
Total	7.340872	95				

In table 2 and 3, the results of the Tukey HSD test, performed on the effect of flow rate and soaking time, are shown. The absolute difference in this table is the difference between the averages of the two groups. If this value is larger than the critical value the means of those two groups are significantly different. An explanation of the abbreviations in this table and the calculation of the critical value is described in Appendix C. The Tukey HSD test (see table 2) showed that there is no significant differences in the cleaning performance between flow rates of 3.5 L/min and lower. From 5.1 L/min a significant differences is observed compared to lower flow rates. There is a significant difference comparing flow rates $\geq$ 5.9 L/min with flow rates $\leq$ 5.1 L/min. Furthermore, no difference were obtained comparing the cleaning performance of flushing with 7.1 L/min, 5.9 L/min, or 8.0 L/min.

Table 2: Tukey's comparison test on the effect of flow rate

Comparison		Absolute difference	Critical value	Result		
8.0	7.1	0.02	0.13	Mean is not significantly different	k	8
8.0	5.9	0.07	0.13	Mean is not significantly different	n.obv	12
8.0	5.1	0.37	0.13	Mean is significantly different	df	72
8.0	3.5	0.52	0.13	Mean is significantly different	MS	0.009825
8.0	2.1	0.57	0.13	Mean is significantly different	Combination	28
8.0	1.1	0.59	0.13	Mean is significantly different		
8.0	0	0.59	0.13	Mean is significantly different	Q (from Tukey q-table)	4.402
7.1	5.9	0.05	0.13	Mean is not significantly different		
7.1	5.1	0.36	0.13	Mean is significantly different		
7.1	3.5	0.50	0.13	Mean is significantly different		
7.1	2.1	0.57	0.13	Mean is significantly different		
7.1	1.1	0.57	0.13	Mean is significantly different		
7.1	0	0.57	0.13	Mean is significantly different		
5.9	5.1	0.31	0.13	Mean is significantly different		
5.9	3.5	0.46	0.13	Mean is significantly different		
5.9	2.1	0.50	0.13	Mean is significantly different		
5.9	1.1	0.52	0.13	Mean is significantly different		
5.9	0	0.52	0.13	Mean is significantly different		
5.1	3.5	0.15	0.13	Mean is significantly different		
5.1	2.1	0.19	0.13	Mean is significantly different		
5.1	1.1	0.22	0.13	Mean is significantly different		
5.1	0	0.22	0.13	Mean is significantly different		
3.5	2.1	0.05	0.13	Mean is not significantly different		
3.5	1.1	0.07	0.13	Mean is not significantly different		
3.5	0	0.07	0.13	Mean is not significantly different		
2.1	1.1	0.02	0.13	Mean is not significantly different		
2.1	0	0.02	0.13	Mean is not significantly different		
1.1	0	0.00	0.13	Mean is not significantly different		

The Tukey HSD test in table 3 compares different soaking times and its effect on clot removal. As could be noticed, there is no significant differences between 5 minutes or 10 minutes soaking. By comparing soaking (for 5 or 10 minutes) with no soaking a clear difference is obtained.

4 DISCUSSION

In this study, 96 experiments were performed to investigate the effect of flow rate on the cleaning performance. The results showed

Table 3: Tukey's comparison test on the effect of soaking time

Comparison		Absolute difference	Critical value	Result		
10 min	5 min	0.04	0.06	Mean is not significantly different	k	3
10 min	0 min	0.13	0.06	Mean is significantly different	n.obv	32
5 min	0 min	0.10	0.06	Mean is significantly different	df	72
					MS	0.009825
					Combination	3
					Q (from Tukey q-table)	3.377

clear effects of the flow rate and soaking time on the mass removal, as the removed mass fraction for lower flow rates (0 L/min - 3.5 L/min) lies between 0 and 0.16. For higher flow rates (5.9 L/min - 8.1 L/min) the removed mass fraction lies between 0.39 and 0.72. It can be noted that higher flow rates contribute to an increase of contamination removal. A statistical analysis on the results identified significant differences between each applied flow rate. The analysis indicates that there are no differences in applying 5.9 L/min 7.1 L/min or 8.1 L/min. Those three flow rates result in the same amount of removed mass fraction. The effect of flow rate is shown by comparing 5.9 L/min 7.1 L/min or 8.1 L/min with flow rates $\leq$ 5.1 L/min. When flow rates $\leq$ 3.5 L/min are compared to each other no differences in the removed mass fraction are obtained. This means that flow rates up to 3.5 L/min do not affect the removal of the contamination compared to no flow conditions. A flow rate of 5.1 L/min does improve the cleaning performance relative to $\leq$ 3.5 L/min.

Furthermore, the mass fraction remaining on the test tubes decreases when the test tubes are soaked prior to flushing. Soaking for 5 minutes and 10 minutes seems to provide the same effect, since no significant differences in means could be found between those two groups.

4.1 Limitations

Nonetheless, these results must be interpreted with caution and a number of limitations should be borne in mind. These limitations relate to the experiment as well as the treatment of the results.

4.1.1 Amount of debris

The cleaning performance is expressed as the removed mass fraction. The test tube were weighted before and after cleaning. Despite the applied weight was monitored during the soiling of the test tubes. The dry weight of the soil varies. The average weight after drying was 28 mg, with a standard deviation of 9 mg. Because of this some test tubes contained more debris than others.

4.1.2 Dimple in test tubes

The test tubes consist of three parts (outer part and two inner parts) and together they form a leak-proof prototype of a smooth medical device. In this study, it has been chosen to have this consist of three parts, so in future the effect of the position of soil on the test tube and its cleaning performance could be investigated. Between the two inner parts a dimple can be found. Even though, this might affect the flow pattern in the test tubes this dimple is neglected, since the test tubes are made by wiring sparking with high accuracy dimensions.

4.1.3 Uniform layer of contamination

Soaking is performed to soften and loosen the soil that may have dried on medical instruments. Soaking helps to release the bond between the surface and contamination. The needed duration of soaking depends on the layer thickness of soil and how long the test soil has been allowed to dry. In this study, the test soil was visibly not uniformly distributed on the tube. Next to this, the test tubes were soiled one after another and then placed in the

oven to dry. The time needed for soiling all the test tubes was about $\pm$ 45 minutes. After applying the egg yolk on the last tube, the first tubes were already dry. This might have played a role in the evaluation of the effect of soaking time. Diluting this test soil provides a more uniform layer on the test tubes. In figure 12, the difference between undiluted and diluted test soil is presented. A disadvantage of this method is that for diluted egg yolk the mass after drying is divergent.

4.1.4 Refreshing distilled water

For cleaning the test tubes, distilled water was used. In this experiment, water is flowing in a closed circuit through the test tubes. This is not in accordance with washer-disinfectors in hospitals, where fresh water is continuously flowing through the medical devices. Due to practical reasons, water was refreshed after one day of testing in stead of using continuous fresh water.

4.1.5 Composition of egg

Each day another egg was used to prepare the egg yolk. Even though the eggs were bought at the same supermarket and have the same expiration date. The composition of the egg used, at the time of preparing the soil, can change. As the egg ages, the yolk stays out more and more and becomes larger and more flaccid [14].

4.1.6 Normality of test results

One of the criteria for performing an ANOVA analysis is that there is a normal distribution within each group. Due to a limited amount of data, the normality can not be proven. However, an ANOVA is not sensitive to reasonable deviations from normality. Several simulation studies, where a variety of non-normal distributions were used, showed that the false positive rate was not affected by violation of the assumption of normality.

In this experiment, the focus was on the effect of flow rate on the cleaning performance at different soaking times. In practice, a detergent is often used for cleaning medical devices, while in this experiment only distilled water was used. It is expected that the use of a detergent will increase the removal of contamination and the flow rate will play a less dominant role. Furthermore, the wall shear is dependent of fluid properties. By using detergents the same flow rates, used in this experiment, will lead to a higher wall shear and therefore expected to removed more contamination. Even though the results can not directly be translated into practice, it raises awareness of the effect that the flow rate can have on the cleaning performance. Moreover, hemoglobin, carbohydrates and protein are often encountered on the medical devices after surgeries. Egg yolk is a test soil that is able to mimic the protein and carbohydrates on surgical devices, but does not contain hemoglobin. However. egg yolk was marked as an appropriate soil for worst-case scenarios, by the ISO-standards.

5 CONCLUSION

In this study, the effect of flow rate on the cleaning performance of hollow devices was investigated. An experimental method defined at an earlier stage in this study was used to obtain a relationship between the flow rate and removed mass fraction and what role soaking time plays in this.

5.1 Future work

With the method described in this article the effect of more cleaning parameters could be investigated, as well as other important factors such as the position of soil. These parameters can then be used to improve the reprocessing protocol.

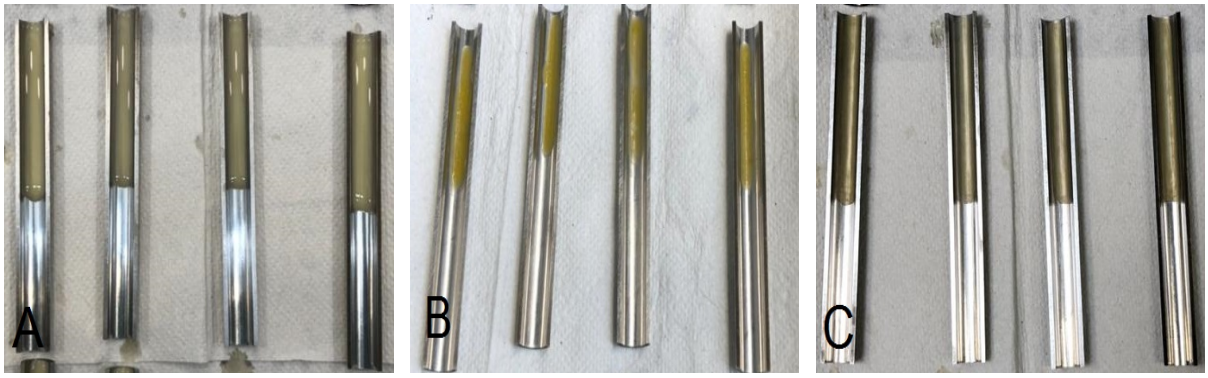

Figure 12: A) Diluted egg yolk applied on test tube B) Dry, undiluted egg yolk on test tube C) Dry, diluted egg yolk on test tube

5.1.1 Position of contamination

In this study, the egg yolk was located at the end of the test tubes. The design of the test tubes in this study allows to shuffle the test pieces and investigate the effect of clot removal when the tubes are contaminated in the middle or at the beginning.

5.1.2 Effect on complex geometry

The experiment was performed using "normal smooth tubes", while in practice complex instrument structures are found. This study can therefore be used to compare the effect of different complex geometries with each other, with the results in this study as ground-truth.

5.1.3 Different flow patterns

This experiment investigated the effect of constant flow on the cleaning performance. Steelco S.p.A (Italy) developed a new patented technology "Power Pulse Cleaning" and suggest that this technology generates strong pressure waves, which increases the velocity along the lumen walls. By using the method used in this study the effect of different flow patterns should be investigated. For one test tube this experiment was performed and the result is shown in figure 13 The test tubes was not soaked prior to flushing and a flow rate of 8 L/min was applied with an amplitude of 4.5 and a frequency of 0.5 Hz. As could be noticed, a large part of the test soil is removed by cleaning with a pulsating flow. Pulsating flow might be promising for the future of washer-disinfectors.

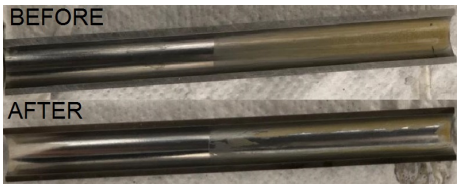

Figure 13: Before and after cleaning with a pulsating flow of 8 L/min with an amplitude of 4.5 and a frequency of 0.5 Hz

5.2 Conclusion

It can be concluded that the flow rate as well as the soaking time plays an important role in the removal of test soil from medical surfaces. Significant difference between different flow rates and different soaking times are obtained. Therefore, the shear stress induced by the flow rate should be taken into account for adequate cleaning of hollow medical instruments.

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A

Background information

In many low-resource settings inappropriate cleaning of medical devices is common practice and the procedures to clean are not standardized. Especially, low-resource hospitals do not have a CSSD department and assistant surgeons are cleaning the devices themselves in the OR after a surgery. The same devices are directly used for the next surgery. A CSSD consists of a soiled area, a clean area and a sterile area (see figure B.4). Dirty surgical devices from an OR enters the CSSD in the soiled area, where the devices will be disassembled. In this area, some surgical equipment will be condemned. There are various reasons for condemning medical equipment. The devices could be ”beyond economical repair”, this means that repairing those devices is considered to cost more than the current value of the device. Devices could be ”technical obsolete”, which means that service supports or parts are no longer available. Devices could also be condemned, because the clinicians or manufacturer recommend the replacement of the device for clinical reasons. The device is than ”clinically obsolete”. Furthermore, equipment could be damaged by contamination [10]. The equipment that is not condemned will be manually pre-cleaned in the soiled area.

After disassembly in the soiled area, the parts are going to the clean area. In this area the decontamination process starts. The decontamination process normally consists of 3 levels: 1) Cleaning, 2) Desinfection, 3) Sterilization. Cleaning is the first step in the decontamination process, which is described as the physical removal of foreign objects [11]. This will usually be done with a mixture of water, detergent and/or enzymatic detergent. Enzymes act as catalysts in the cleaning process and increases the speed of biochemical reaction between the contaminated material (usually composed of most proteins) and the protease that specifically decomposes the debris. With the help of a washer-disinfector (WD) the cleaning and desinfection of the device could be performed.

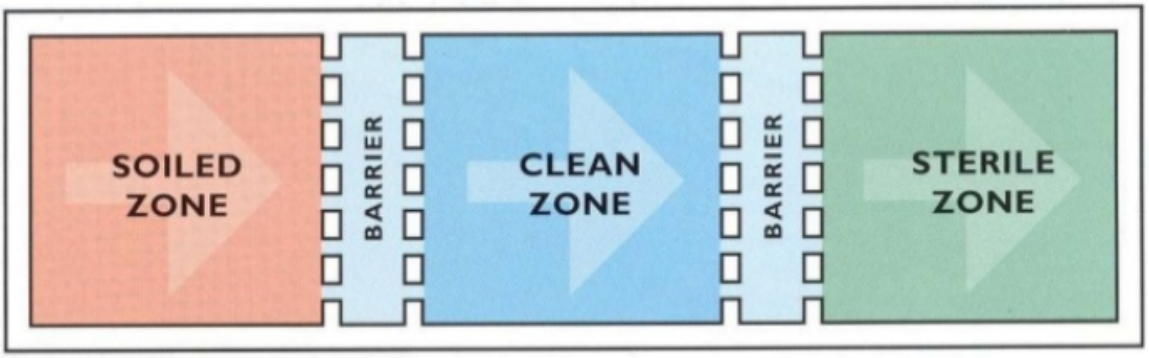


Figure A.1: A CSSD is divided into three areas : Soiled-, clean- and sterilization area

A WD is widely used in hospitals and other healthcare clinics for reprocessing medical instruments.

The WD cycle programs include a pre-rinse at low temperature and tap water is often used for this. Furthermore, it includes a wash cycle and a final rinse. During the wash cycle, the medical instruments are rinsed with detergent with temperatures between 55 °C and 85 °C) and a hot tap water rinse. At the end a final rinse will be performed. The final rinse is used to provide thermal disinfection. The final rinse is performed with water with an elevated temperature of 55 °C to 95 °C for about 1-10 minutes. With those steps all vegetative micro-organims should be killed and the bio-burden is decreased. Cleaning of a medical instrument could also manually be done or by ultrasonic cleaning. A combination of those cleaning methods are often used. After the decontamination process, surgical instruments and equipment can be moved to the sterilization stage. An important note to make is that adequate cleaning is extremely important before the instrument goes to the next stage, because organic- and inorganic materials interfere with the effectiveness of the sterilization process. Furthermore, if the soiled materials bake or dry onto the medical instruments, the process of decontamination becomes more difficult. The disinfection and therefore the desinfection- and sterilization process becomes less- or ineffective [14].

A.1. Hollow instruments

In hospitals a lot of surgical instrument can be found, which could all be categorised as solid or hollow. Most of the traditional devices are solid and it is relatively easy to check the device on remaining visible dirt and blood residuals.

Nowadays, many common surgical problems can be addressed by the laparoscopic approach. During a laparoscopic surgery, Minimally Invasive Surgery (MIS) instruments are used. A disadvantage of the use of those reusable MIS instruments is their clean-ability [13]. The possibilities of decontamination of these instruments are more difficult than traditional solid devices and is usually limited due to their design. Next to delicate instruments for keyhole surgery, also endoscopes and dental handpieces are hollow instruments. Not only the cleaning of those devices are challenging, but also the sterilization is difficult, since the inner surface can not be reached by the steam [17]. In figure A.2 a range of hollow instruments that could be found in practice are shown.

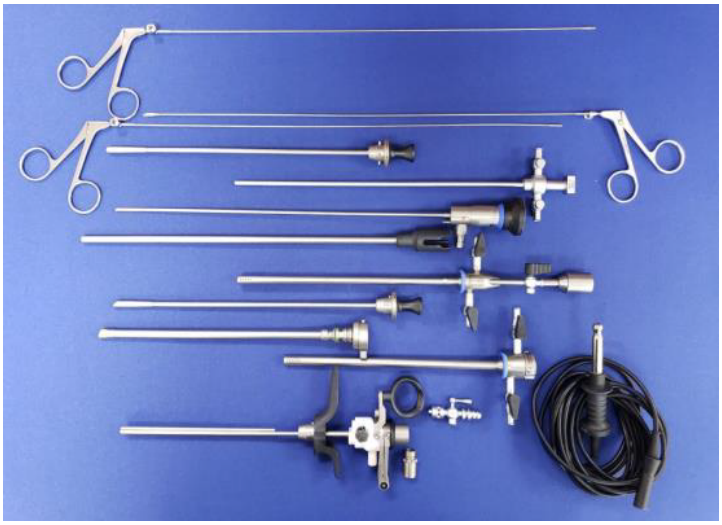


Figure A.2: Example of hollow instrument that could be found in practice

A.2. ISO-standards

International standards have been developed to reduce the large specific national standards, creating uniformity and clarity worldwide. General requirements for reprocessing medical devices are also documented in the International Standarization for Organization (ISO)-standards. ISO 15883 consists of seven parts in which the performance criteria for washer-disinfectors is described. Moreover, the performance requirements for the cleaning and disinfection of the washer-disinfector and test methods for cleaning validation and routine control of the device is described in ISO 15883. The following list

shows all the parts of this standard :

- Washer-disinfectors - Part 1: General requirements, terms and definitions and tests (ISO 15883-1:2006,IDT)
- Washer-disinfectors - Part 2: Requirements and tests for washer-disinfectors employing thermal disinfection for surgical instruments, anaesthetic equipment, bowls, dishes, receivers, utensils, glassware, etc. (ISO 15883-2:2006,IDT)
- Washer-disinfectors - Part 3: Requirements and tests for washer-disinfectors employing thermal disinfection for human waste containers (ISO 15883-3:2006,IDT)
- Washer-disinfectors - Part 4: Requirements and tests for washer-disinfectors employing chemical disinfection for hermolabile endoscopes (ISO 15883-4:2018,IDT)
- Washer-disinfectors - Part 5: Test soils and methods for demonstrating cleaning efficacy (ISO/TS 15883-5:2005)
- Washer-disinfectors — Part 6: Requirements and tests for washer-disinfectors employing thermal disinfection for non-invasive, non-critical medical devices and healthcare equipment (ISO 15883-6:2015,IDT)
- Washer-disinfectors - Part 7: Requirements and tests for washer-disinfectors employing chemical disinfection for non-invasive, non-critical thermolabile medical devices and healthcare equipment (ISO 15883-7:2016,IDT)

A.3. Cleaning parameters

To provide effective cleaning, many cleaning factors should be taken into account. The cleaning parameters can relate to the physical action for cleaning, the chemical action, the design of the instruments, or the properties of contamination. Flushing time, pressure, temperature and the velocity to generate wall shear at the boundaries of hollow devices are examples of parameters related to physical action. Important parameters to trigger the chemical action are the quality of water and the use of detergents [15]. The design of the device is also an important parameter. The length, the diameter and the geometry, such as scratches, ridges and edges influences the mechanical action. The surface roughness plays also an important role in the mechanical action as well as in the attachment of contamination [7]. Other parameters concerning the contamination is the level of dryness, amount of contamination and level of attachment to the hollow instrument [20].

A.4. Related work

In the next part of this thesis, the focus will be on the effect of flow rate on the cleaning performance, therefore studies on the effect of fluid flow was investigated in this thesis and gaps in those studies were identified. It can be concluded that there is lack of high-quality studies on the effect of fluid flow induced shear stress on the cleaning performance of hollow medical instruments. Two articles are found which try to point this subject. The first article evaluates the role of fluid flow-induced shear stress in the removal of contaminants from device surfaces [8]. In this article experimental setup has been built to investigate the relationship between the applied wall shear stress and the clot removal. The test section consists of a transparent, straight, circular tube with an inserted test coupon. The test coupon is made of stainless steel and mimics the surface of a medical instrument. The test coupon is soiled with a artificial clot of 16 mg, 6,8 mg or 1 mg. The coupon is then exposed to the induced jet and enzymatic detergent and the residual contamination is measured. The results show that mass of removed contamination followed a linear relationship with the fluid shear stress. The fluid shear stress is measured using Particle Image Velocimetry (PIV). This study showed that the clot surface is removed with 67%, 77% and 95% for clots with initial masses of 16 mg, 6.8 mg, and 1 mg. With the help of fluid shear stress, the percentage of removed clot can significantly increase.

The second study investigated the flow along a confined obstacle. A jet enters a square test section and creates a flow around an obstacle [18]. The goal of this study was to develop a database to validate numerical CFD models, which are used to simulate the cleaning performance of reusable medical devices with complex geometries. In this study a long-distance micro-PIV is used to determine the flow along a confined obstacle. Wang et al (2019) concluded that the wall shear stress serves as a driven force to remove contamination. The wall shear stress is neglible in the so-called 'vena contracta area' and should therefore be avoided in the design of channel medical instruments. The vena contracta is a region in the fluid flow where the diameter of the stream is minimal, and fluid velocity is maximal.

In Hariharan et al. [8], the effect of fluid shear stress on the cleaning performance in smooth tubes was evaluated and Wang et al. [18] studied the flow around a confined obstacle. As we noticed, there is lack of information about the effect of complex geometry in hollow instruments on the wall shear stress and therefore the cleaning performance in those complex tubes. To ensure effective cleaning and prevent cross-contamination of infections, an experimental set-up is necessary to investigate what fluid properties are needed for effective cleaning of lumen devices with a complex geometry.

The lack of studies on cleaning performance of hollow instruments is remarkable, since there are a lot of comparable researches performed on cleaning pipelines in the food industries [9] [1] [6]. Production lines in this industry are daily cleaned to ensure the safety of the products.

B

Design of experimental set-up

B.1. Design requirements

In this thesis, an experimental set-up was developed, which helps to investigate the effect of cleaning parameters on the cleaning performance of reusable devices. Considering the background information, design requirements were set out. The experimental set-up consists of various essential components. Therefore, the design requirements were divided into subsections : Flow induction, Test soil, Design of test tubes, Measuring cleaning performance.

Table B.1: Design requirements for the experimental set-up

Subsection	Requirements	Whishes
General	The experiment must be able to be reused repeatedly The setup could be built within the timespan of this project The costs of building the setup and performing the test experiment should be within budget.	
Flow induction	The 'flow generator' should be able to generate a flow rate between 0 LPM and 10 LPM. A constant flow could be introduced during the cleaning process Measurements of the flow rate near the region of interests is possible	It is desirable that pulsating flow could be generated
Test soil	The test soils is able to demonstrate the cleaning efficacy and appears in ISO/TS 158835:2005 The test soils can be disposed of as non-hazardous, non-clinical waste The test soil should be representative for realistic contamination after surgery The test soil should be visible and/or its weight is measurable	Preferably the test soil is common in the Netherlands and recommended by the CSSD
Design of test tubes	The surface roughness of the test tubes should be representative for medical instruments Hollow instruments with a diameter from 2 mm to 9 mm could be manufactured Instruments with a length of 100 mm to 400 mm could be fabricated The used material is representative for medical instruments The construction of the test tube should have a minimal undesired effect on the flow regime The design allow application and removal of contamination at various positions	
Measuring cleaning performance	The total experimental setup allows qualitative or quantitative measurement of remaining residuals. Measurement of residuals can safely be performed without risks of infections The way of measuring must be repeatable	

B.2. Conceptual design phase

This phase of the thesis consists of determining all the possibilities for each sub-function, described in the previous section. After this, a concept selection was made to come up with a final design of the experimental setup.

B.2.1. Conceptualization

In this project, the design of an experimental set-up is created by following the ACCREx-method to provide insight in all possible solutions. This method helps to identify gaps in literature concerning cleaning of hollow instruments. For each sub-function a selection of existing concepts is found and shown in a morphological scheme on the next page. This scheme provides a structured overview of possible concept solutions that will be analysed in chapter **??**. In this section a brief description of each solution per sub-function is given.

Flow induction

There are various ways to generate flow by using pumps. All the pumps can be classified in three different types : 1) Centrifugal pumps, 2) Positive-displacement pumps and 3) Axial-flow pumps. The three types of flow pumps are different in the way of displacing fluids.

Centrifugal pump The most common way of generating flow is by using a centrifugal pump, which is also known as radial-flow pump. A centrifugal pump is designed to move a fluid with the help of impellers. the fluid enters the pump along the center and is accelerated by the impellers. The energy used for the mechanical action of the impeller is converted to potential energy to move the fluid. In comparison to the other types of pumps, centrifugal pumps are usually specified for higher flows and for pumping lower viscosity liquids. A limitation of the centrifugal pump is that those pumps are not suited to any application where the fluid supply is intermittent, which is the case for pulsating flows [5].

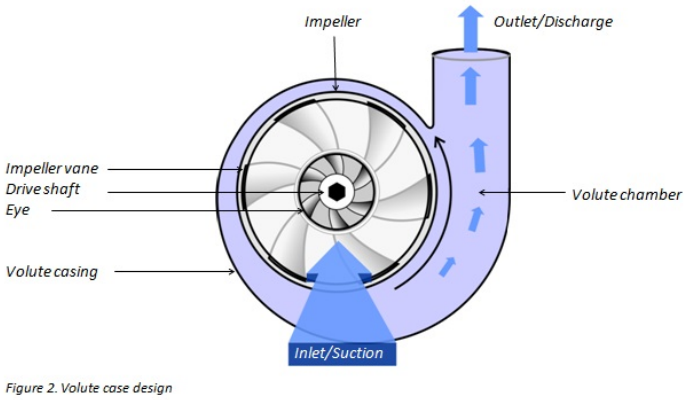


Figure B.1: Example of a centrifugal pump [**?**]

Positive-displacement pumps Positive-displacement pumps can move fluids by enclosing a fixed volume and enclosing this repeatedly. The fluid can then mechanically be transported through the system. The positive displacement pumps can be divided into two categories : reciprocating and rotary. Reciprocating pumps makes use of back- and forward movement of either a diaphragm, plunger or piston. The use of reciprocating positive displacement pumps are ideal for generating pulsating flow, where dosing is required. Rotary pumps are using rotating gears to transfer fluid. For those pumps, liquid is entering the the suction port and flows through the pump. In the pump, the fluid will be enclosed by the gears and forces the liquid out of the discharge port. The biggest advantage of this type of pumps is that fluids with higher viscosity can be handled and can efficiently generate lower flows.

Axial-flow pump A centrifugal pump often refers to a radial flow centrifugal pump, which are the most common types of pumps in use. But there is also an axial flow centrifugal pump and is often called

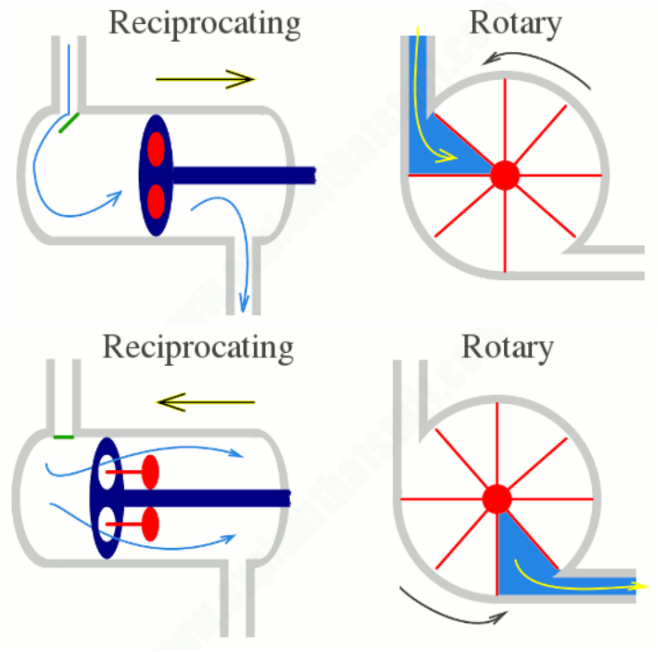


Figure B.2: A reciprocating- and rotational positive displacement pump [4]

a ”AFP”. The difference of those two types of pumps is that the fluid exits the pump along the same direction as the fluid enters the pump. Axial flow pumps operate at lower pressures and higher flow rates compared to the centrifugal pumps.

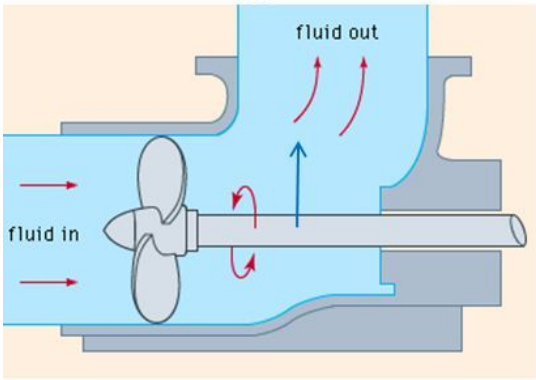


Figure B.3: Example of a axial flow centrifugal pump [19]

Test soil
In ISO-15883-5, test soils and methods to demonstrate the cleaning efficacy of washer-disinfectors are described. Test soils are intended to simulate worst-case scenarios. The removal of this test contamination is able to support the conclusion that all other residues that can possibly be encountered in practice will also be removed.

There are a lot of test soils on the market with different quality. For this study, test soils to validate the cleaning process of surgical instruments, mentioned in the ISO-standards, were considered. Also test soils on the advice of experts in the field of cleaning medical instruments are taken into consideration. From interviews with the CSSD department of the Erasmus MC, Browne test soil is often used in Dutch hospitals to assess the cleaning efficiency of the washing machines. The test soils mentioned in the ISO-standards are (heparinzed- or defibrinated) sheep blood, egg yolk, Semolina mixture, Bovine haemoglobin, artificial soil consisting of albumin, haemoglobin, fibrinogen and thrombin or an citrated

cattle blood coagulated with calcium chlorid.

Heparinzed or defibrinated sheep blood is an interesting test soil, since it is able to demonstrate the ability to remove hemoglobin. Hemoglobin on the medical devices is often encountered after surgeries. Heparin is added to sheep blood to prevent the blood from coagulation. A more common way of preventing blood from clotting is defibrination. Defibrinated sheep cells are aseptically collected whole sheep blood that has been processed to remove fibrin. Next to hemoglobin, red blood cells is enclosed in a thin membrane, which consists of chemically complex proteins, and carbohydrates. **Egg yolk** is a test soil that is able to mimic the carbohydrates and protein that could be found on instrument surfaces. Another soil that is used for protein and carbohydrates deposition on the instruments is a **mixture of semolina**. This contains skimmed milk powder, butter, sugar, semolina (durum wheat meal) and tap water. Another test soil used, is **bovine haemoglobin in combination with a TMB solution**. The TMB solution consists of 0,1 % tetramethyl benzidine (TMB) in 5 % acetic acid;, and 3 % hydrogen peroxide solution. 1 ml TMB solution with 4 drops of 3% hydrogen peroxide solution could be used to detect blood residues. When blood residues are present the residues colors blue. In hariharan et al. (2018) [8], an **artificial soil** was selected to investigate the cleaning performance. This soil consisted of two solutions. Solution A consisted of albumin, hemoglobin, fibrinogen and a 0.4% NaCl solution. Solution A consisted of albumin, hemoglobin, thrombin and a 0.4% NaCl solution and $CaCl_2$ solution. Furthermore, **citrated cattle blood** could be used with calcium chlorid. This was applied to coagulate the blood after which is can be disposed on the test soil. The test soil used by the Erasmus MC and is also in by most of the Dutch hospital is the **Browne Washer Disinfector Test Soil**. This is an commercially available test soil of which the ingredients are unknown.

Design of the test tube

The important factors of the design that influences the cleaning performance of hollow medical instruments are the lumen length, material, surface roughness and complex geometry. In this study different manufacturing methods are considered and a list of interesting complex geometries to be investigated was listed.

Manufacturing Most of the surgical devices consists of stainless steel. Stainless steel has been the material for hollow medical instruments for decades. Stainless steel was not only chosen for its strength and resistance to corrosion. Stainless steel is also easier to clean and makes it ideal for environments where hygiene is a priority. However, stainless steel comes with different surfaces roughnesses.

The surface roughness of medical devices was measures using a profilometer. The medical device was cut open to measure the roughness of the inner surface. Then a diamond stylus moved laterally across the device with a specified force and for a certain distance. With this movement, small surface variations were measured. In this case, a contact profilometer is used, since optical profilometers can end up measuring the surface contaminants, that still remained on the surgical instruments, instead of the surface itself. Those measurements resulted in a surface roughness of 0.3 µm- 0.45 µm.

Different manufacturing technologies, such as turning, milling, coating and 5-axis CNC milling, where investigated to make test tubes with a inner surface roughness of 0.3 µm- 0.45 µm. Furthermore, the option to use precision tubes was also included.

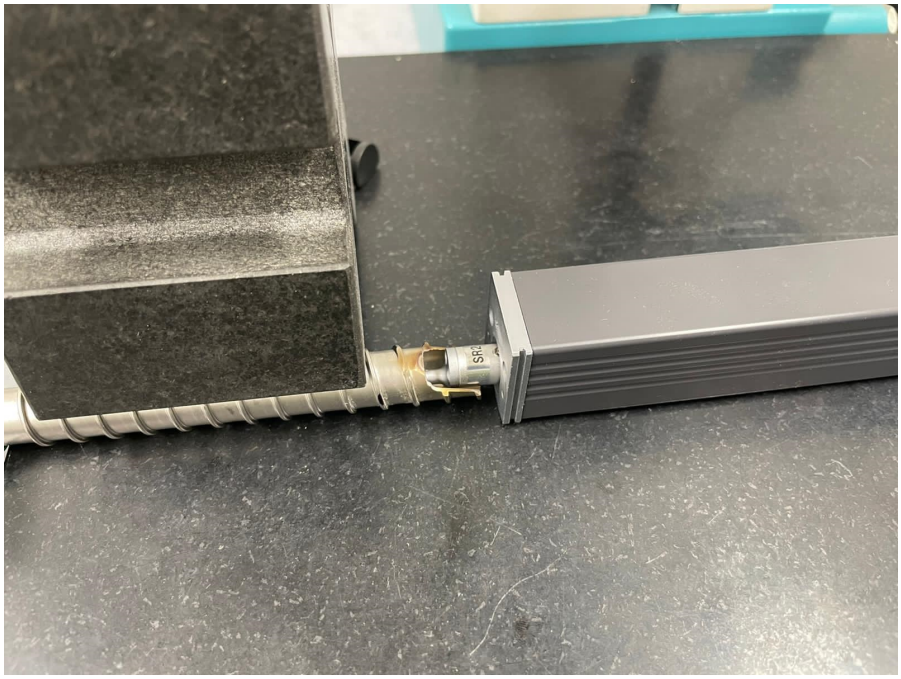
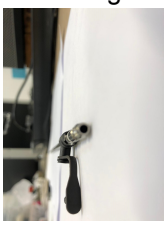


Figure B.4: Profilometer used for measuring the surface roughness

Complex geometries

In practice, different types of geometries can be found. A set of medical instruments were listed and common complexities were investigated, based on literature and instruments that are available at the university.

Table B.2: Overview of complex geometries

Tubes with thread	Tubes with cut-out	Tube with blockage	Tubes L-S	Tubes L-S-L	Tubes with insufflation
					
					
					

Measuring cleaning performance

Qualitative measurement A way to express the cleaning performance of several cleaning parameters is by describing the amount of remaining test soil that is visible on the test tubes. One big disadvantage of this method is that not all the contamination are clearly visible. Furthermore, this method is also sensitive for variations in layer thickness. This makes this type of measurements less robust.

Quantitative measurement A more objective measurement of the remaining test soil is by weighting the residuals on the test tube. This method is less sensitive for human perceptions. Furthermore, it also takes to invisible contamination into account.

B.2.2. Concept selection

In this section the concept selection is explained and presented in figure B.5 The figure provides an overview of the criteria whereupon the concepts were judged with the score per concept. Each subfunction of the experimental setup was individually assessed.

5	4	3	2	1

Flow induction	Centrifugal pump	Positive-displacement pumps	Axial-flow pump
Flow rate between 0-10 LPM.	3	5	3
Constant flow	5	5	5
Measurements of the flow rate is possible	5	5	5
Pulsating flow	0	5	0
Total	**13**	**20**	**13**

Design of test tube	Turning and milling	Turning and milling, with coating	5–axis CNC milling	Precision tube
Surface roughness	0	3	4	5
Diameter of hollow instrument	2	2	4	5
Length of hollow instrument	2	2	2	4
Material representative for medical devices	5	5	5	5
No undesired effect on the flow regime	2	2	2	3
Soil applicable and removable	5	5	5	5
Total	**16**	**18**	**22**	**27**

Test soil	Heparinzed / defibrinated sheep blood	Egg yolk	Mixture of semolina	Bovine haemoglobin (with a TMB solution)	Artificial soil (Hariharan et al. (2018)	Citrated cattle blood	Browne Washer Disinfector
Soil appears in ISO/TS 15883 5:2005	5	5	5	5	5	5	0
Common in the Netherlands /recommended by the CSSD.	4	4	3	4	4	3	5
Disposable as non-hazardous, non-clinical waste	2	4	4	2	2	2	2
Realistic contamination after surgery	3	4	4	3	4	3	2
Visible and/or its weight is measurable	4	3	3	4	4	4	4
Total	**18**	**20**	**19**	**18**	**19**	**17**	**13**

Measuring cleaning performance	Optical observation of residuals	Measuring weight of residuals
The total experimental set up allows qualitative or quantitative measurement of remaining residuals	3	5
Measurement of residuals can safely be performed without risks of infections	5	4
The way of measuring must be repeatable	4	4
Total	**12**	**13**

Figure B.5: Harris profile

For the pump selection, a positive displacement was chosen based on the ability of generating pulsating flow patters, which a the desired criteria. Furthermore, the flow rates that could be generated with those pumps was ideal for the purposes in this thesis.

Several manufacturing procedures were investigated and the ability of precision tubes to design test tubes with a roughness of 0,34 μm - 0,37μm was decisive. Since other technology were not able to reach this surface roughness, the test tubes were manufactured from precision tubes.

In Hariharan et al. [8] (2018), artificial test soil showed to be hard to eliminate. A big disadvantage of this soil is that is not constant. In the Erasmus MC and most of the other hospitals in the Netherlands, use the Browne test soil. According to the experts in the Erasmus MC. It is too easy to eliminate

the Browne test soil, since a lot of soil was already before using any detergent and by only using the machine cleaning process. According to them, it is doubtful if the Browne Test soil offers enough challenge. Egg yolk is a cheap, easy to prepare and several studies showed that egg yolk was not easily removed.

Weighting the residual contamination was chosen, because with this a more objective measures of the removed contamination could be obtained. Especially when the layer thickness is not always constant on every test tube.

B.3. Embodiment design

The final experimental setup is shown in figure B.6. The setup consists of a gear pump, a flow sensor and the test tube which debouches into a tray. In this section each part of the setup is described.

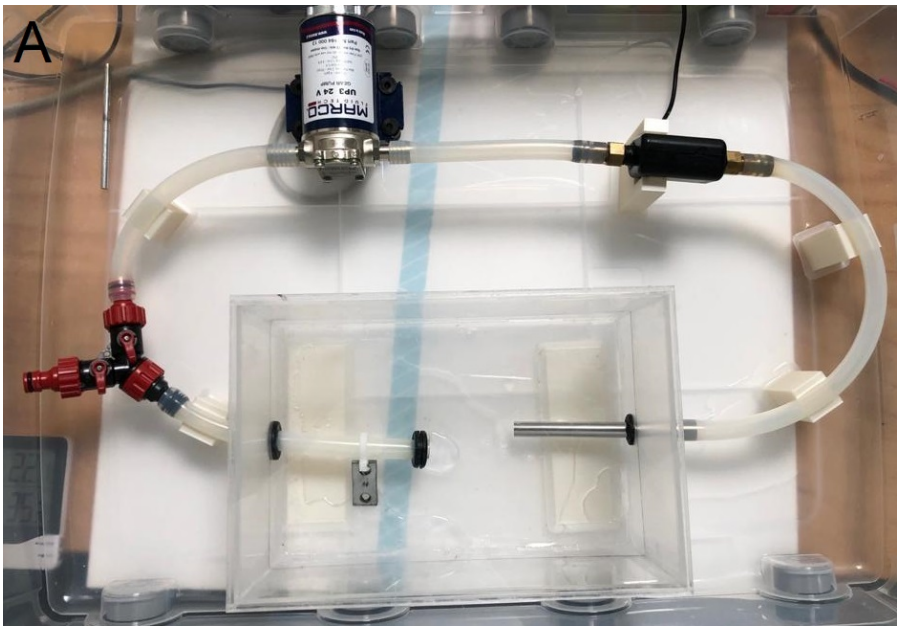


Figure B.6: Final experimental setup

B.3.1. The gear pump

The pump chosen for this study is the self-priming gear pump. This pump was fabricated in Brecia in Italy. A self-priming pump means that the pump is able to to use liquid stored in its housing to generate a vacuum on the suction line. The pump has the ability to generate a flow up to 15 L/min for 0 bar pressure and 11 L/min for a pressure of 2.5 bar. The pump was connected to a power source, via a micro-controller. The pump is amperage controlled and a maximum of 3 A can be applied to the pump. Three parameters can be adapted to define the flow pattern you need. The first parameter is the current frequency. This is the rate at at which the current changes per second. The second parameter is the current. This parameter defines the desired flow rate you would like to apply on the test tubes. The last parameter is the amplitude. The pump is able to generate a constant flow, as well as pulsating flow patterns. For pulsating flows an amplitude can be indicated so the current flow will wave around a constant current with a certain amplitude. Those parameters can be controlled using a user interface via LabVIEW (Version 18.0, National Instruments, United States) (see appendix ...)

B.3.2. Flow sensor

The pump is only able to move the fluid, so no information of the flow rate was provided by the pump. Therefore, a flowmeter is needed to measure the flow rate through the tube. In the experimental setup a NETIX flowmeter (110 series, United Kingdom) was used. The flow meter is able to measure flow rates between 0.2 and 25 L/min. The flowmeter makes use of up- and downstream transmitted sound. If there is no flow through, it will take the same time for up- and downstream travel between transducers. For higher flow rates, the upstream transmitted sound will travel slower and take more time than the

downstream wave. The differences between the up- and downstream sound travel time is a benchmark for the flow rate. The difference in time is converted into an output signal (A) by a micro-controller. Now, the flow rate can be calculates, since the output signal is proportional to the flow rate. An output of 20 mA as output corresponds to a flow rate of 25 L/min.

B.3.3. Tube design

The standard diameter of the design was chosen to be 9 mm and the length of the test tubes are 150 mm. For investigating different surface roughnesses, the diameter and length are important, since other mechanical technologies are not able to change the surface roughness of pipes larger than 150 mm for 9 diameter pipes. Furthermore, it is expected that there will be a difference between laminar flow and turbulent flow through the pipe on the cleaning performance. For diameters smaller than, laminar flow will already occur for flow rate ≤1.0 L/min.

The test tubes consists of two inner parts, the reason for this is that the position of the complex geometry is important and with those two parts the position of the complex geometry can be shifted. An example of this is shown in figure B.7.

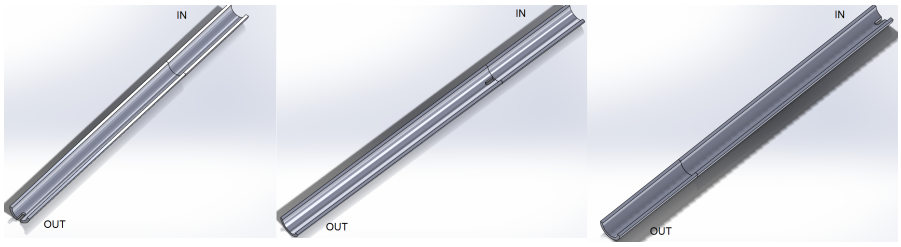
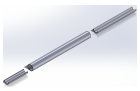
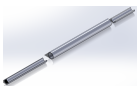
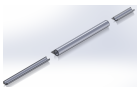
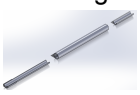
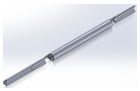
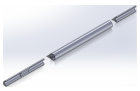
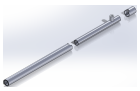


Figure B.7: Position complex geometry

In table B.3 all 3d drawings of the complex geometries are shown.

Table B.3: Overview of CAD model complex geometries

Normal tube	Tubes with thread	Tubes with cut-out	Tube with blockage	Tubes L-S	Tubes L-S-L	Tubes with insufflation
						

B.3.4. Tray

The test tubes debouches into a tray. This rectangular acrylic tray was made to simulate the pressure drops in washer-desinfector since flow through medical device in the washing machines also ends directly in an open space. The size of the tray is 30 cm x 20 cm x 15 cm. To keep the pressure on the test tubes constant, the amount of water in the tray needs to be equal during experiments. The tray is connected to the circuit, using pvc grommets. At both short sides of the tray, two holes have been made (25 mm and 22 mm). In the 25 mm hole, a pvc grommet, with inner diameter of 16 mm was placed which fits tightly on the tube. In the 22 mm hole, a pvc grommets was placed, with inner diameter of 13 mm, so the test tubes fits perfectly in the grommet and prevents the setup from leakage. Furthermore, there is a lid placed on the tray to prevent contamination flushing out of the tray. The tray is shown in figure B.8.

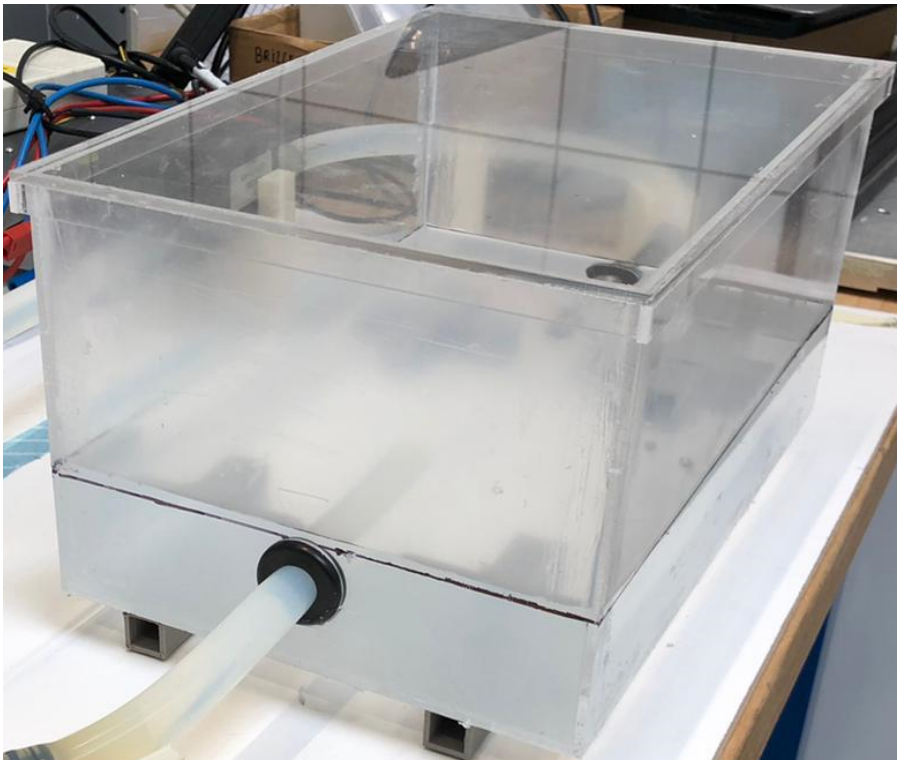


Figure B.8: Tray

C

Abbreviations in ANOVA-table and Tukey HSD table

The abbreviation used in the ANOVA table is explained below. In this table, the df stands for the ”the degrees of freedom”, SS is the ”sum of squares”. MS is the ”mean sum of squares”. F is the ”F-statistic”. The F static can be calculated by equation C.1, with $\mathrm{MSB} = \frac{SSB}{k-1}$ and $\mathrm{MSE} = \frac{\mathrm{MSE}}{N-k}$. Here, MSB = Mean Squares (MS) between groups MSE = Mean Squares within group, k = the number of treatments per groups and N = total number of observations. The P-value is the probability of observing a $F_{critical}$-value as big as the F-value

$$F = \frac{\mathrm{MSB}}{\mathrm{MSE}} \tag{C.1}$$

For the Tukey HSD table, the critical value was calculated using equation C.2. In this formula the q is a constant value and can be looked up in the ”Studentized Range q Table”. the MS_w, is the mean square within subjects and was obtained by the ANOVA analysis. The n.obv is the number of observations per group.

$$HSD = q\sqrt{\frac{MS_w}{n.obv}} \tag{C.2}$$

The ’k’ and ’Combination’ corresponds to the number of groups and the amount of possible combinations without repetition, respectively.

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