Determining the flow of breastmilk using echo PIV

Building a setup

Puck van de Beek

Committee:
Dr. Ir. N. Bosschaart
Ir. D. Thompson
Dr. G. Lajoinie

BMPI
14-07-2022

UNIVERSITY OF TWENTE.

Acknowledgements

I want to thank the BMPI group for their hospitality during this bachelor assignment. In particular, I want to thank David Thompson for his daily support these past few weeks. I also want to thank the "Mothermilk Meeting" group within BMPI, for the weekly meetings and feedback, in particular Nienke Bosschaart. Ashkan Ghanbarzadeh-Dagheyan, thanks for helping me use the Echo PIV MATLAB scripts and taking the time for helping me understand them. Thanks to Tim Boers for showing me how to pour and work with polyacrylamide. And thanks to Hadi Mirgolbabaee for supplying the microbubbles used in my setup.
I also want to thank the committee (Dr. Ir. N. Bosschaart, Ir. D. Thompson, Dr. G. Lajoinie) for taking their time to read and judge this thesis.

Abstract (English)

The importance of breastfeeding is recognised, as there is extensive evidence of the beneficial qualities for mother and child. But only around 41% of babies younger than 6 months is breastfed exclusively. The combination of perceived lactation insufficiency (lack of volume) and the nutritional issues (lack of calories) are the main reasons mother stop breastfeeding. There are no current techniques that research both real-time. That is why an idea has been proposed, to create a measuring device in the form of a nipple shield with photonic-based measuring methods in one of the channels. As getting more insight into the actual lactation and nutrional values will result in higher confidence for mothers and more understanding in breastfeeding problems. In this thesis, a setup is made to measure the flow of breastmilk through a channel using echo Particle Image Velocimetry (echo PIV).

The experimental setup consists of three main parts and several connecting parts. The three main parts are the breast pump, the ultrasound transducer and the channels within a block of polyacrylamide (PAA). To connect the parts, thin tubes and 3D printed coupling pieces are used. Different concentrations are tried when making the PAA. The flow is calculated by measuring the mean velocity perpendicular to the channel and multiplying it by the cross sectional area of the channel. The flow of the circular shaped channel is 0,0057 ml/s and of the square shaped channel is 0,0068 ml/s.

A working experimental setup was made in which successfully a liquid flow through a channel was measured using echo PIV.

Abstract (Nederlands)

Het belang van borstvoeding wordt erkend, aangezien er uitgebreid bewijs is van de gunstige eigenschappen voor moeder en kind. Maar slechts 41% van de baby's jonger dan 6 maanden krijgt uitsluitend borstvoeding. De combinatie van waargenomen lactatie-insufficiëntie (gebrek aan volume) en voedingsproblemen (gebrek aan calorieën) zijn de belangrijkste redenen waarom moeders stoppen met borstvoeding. Er zijn geen huidige technieken die beide realtime onderzoeken. Daarom is het idee geopperd om een meetinstrument in de vorm van een tepelhoedje te maken met fotonische meetmethoden in één van de kanalen. Omdat meer inzicht in de actuele lactatie- en voedingswaarden zal leiden tot meer vertrouwen voor moeders en meer begrip voor borstvoedingsproblemen. In deze thesis wordt een opstelling gemaakt om de stroom van moedermelk door een kanaal te meten met behulp van echo Particle Image Velocimetry (echo PIV). De experimentele opstelling bestaat uit drie hoofddelen en verschillende verbindende delen. De drie belangrijkste onderdelen zijn de borstkolf, de ultrasound transducer en de kanalen in een blok polyacrylamide (PAA). Om de onderdelen met elkaar te verbinden, worden dunne buisjes en een 3D-geprinte koppelstuk gebruikt. Bij het maken van de PAA worden verschillende concentraties uitgeprobeerd. De stroom wordt berekend door de gemiddelde snelheid loodrecht op het kanaal te meten en te vermenigvuldigen met de dwarsdoorsnede van het kanaal. De stroom van het cirkelvormige kanaal is 0,0057 ml/s en van het vierkante kanaal is 0,0068 ml/s.
Er is een werkend experimentele opstelling gemaakt waarin met succes een vloeistofstroom door een kanaal werd gemeten met behulp van echo PIV.

Contents

Chapter 1

Introduction

Worldwide, the importance of breastfeeding is recognised but still only around 41% of babies younger than 6 months are breastfed exclusively [1], despite of extensive evidence that this is beneficial for the mother as well as for the child. Benefits for the short- and long term protection for the infant include; reduction in occurrence of diarrhoea, respiratory infection and sudden infant death syndrome. Breastfeeding also reduces the chance of ovarian cancer for the mothers [1]. Eventhough it is known to be healthy and benefical, mothers stop breastfeeding within the first 6 months. One of the reasons for mothers stopping breastfeeding is the perception that their child was not satisfied by breast milk alone [2]. The perception of lactation insufficiency and nutrition issues were cited as the reason to stop breastfeeding. But the percentage of actual lactation insufficiency is 10-15% compared to the perceived lactation insufficiency of 40-50%. The gap between the actual and perceived lactation insufficiency is substantial and at present there aren't many ways to research and support the lactation. For most mothers it is not clear if the reason that their baby is not satisfied by breast milk alone, comes from problems with their breast milk volume or from nutritional issues. This can result in lack of confidence and misunderstanding breastfeeding problems, which can lead to misdiagnoses.

The main macronutrients in breastmilk are overall fat, protein and carbohydrate (lactose) [3]. The composition of breastmilk changes over time during a breast feed as the fat content increases. The milk starts out more thirst quenching and as the fat content increases, becomes more filling for the infant. Most of the calories come from the fat content ($\sim$55%), followed by lactose ($\sim$37%) and protein ($\sim$8%). Lactation insufficiency can be related to suboptimal energy intake of the infant [4], that is why it is interesting to monitor the fat concentration as well. Knowing the volume and calorie intake of a breast feed, gives information about the lactation and possible nutritional issues.

1.1 Current techniques

Currently the main method to measure the volume of breast milk a baby has drunk, is to weigh the baby before and after feeding [5]. This indirect method can be unreliable as the instrument accuracy and evaporative water loss have to be taken into account. This method can also be sensitive to errors. There are no real-time techniques available that do not interfere with the breastfeeding pattern.
Weighing the baby only gives insight in the milk volume that is taken in, but yields no information on the milk composition. Current methods used to research the composition use labour intensive analytical methods or near/mid-infrared spectroscopy [6][7]. In the dairy industry near infrared specroscopy is used, yielding good estimates for the fat, protein and lactose concentrations. The equipment used however is relatively costly. [8]. These methods are also only able to measure offline via a sample of the milk. It is also interesting to measure the breast

milk composition real-time, as the composition of the breast milk changes during a breastfeed. A study from 1982 has researched the possibilties of measuring the milk intake of breast-fed babies real-time using a nipple shield [6]. A miniature Doppler ultrasound flow transducer was used, located in the tip of the nipple shield which was able to record the instantaneous milk flow and through integration over time, the cumulative intake. This nipple shield however was quite bulky and did not research the composition.

1.2 Nipple shield

If a mother would have real-time information on the quality of lactation, her perception and self confidence in breast feeding would be greatly enhanced which can be expected to have a significant positive impact on the number of mothers that continue breast feeding. Getting more insight of milk supply has proven to result in higher breastfeeding confidence [9]. The idea has been proposed to create a measuring device in the form of a nipple shield based on photonic-based method in one of the channels [10], see figure 1.1. The methods proposed are optical and ultrasound based. If successful, the nipple shield would allow the mother to breast feed while in a non intrusive way vital information on the quality of the lactation is made available real-time.

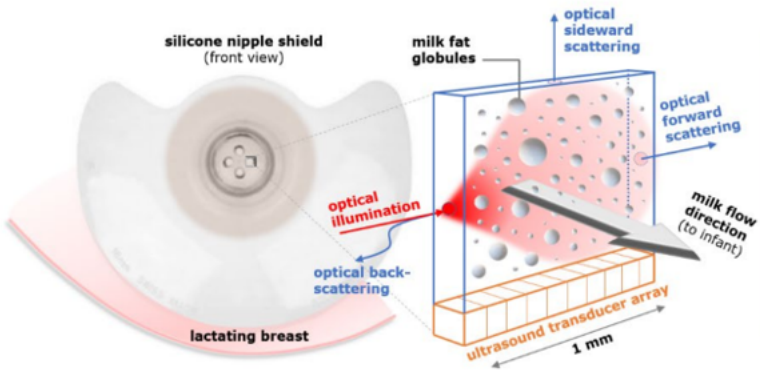


Figure 1.1: Proposed design nipple shield

1.3 Experimental setup

In this thesis, an experimental setup to measure the flow of breast milk under realistic conditions using ultrasound will be built and tested. A breast pump to simulate the drinking movement of a baby is used to pump the liquid into the setup. The setup itself is made of polyacrylamide (PAA) and connecting tubes. A transducer is used to perform high-speed ultrasound imaging from which the flow can be measured using echo particle image velocimetry (echo PIV). The flow will be measured using a channel with a square cross section as well one with a circular cross section. The square shape is researched as the ultrasound transducer will need a flat interface to measure the flow as this gives a direct measurement of the channel. And the circular shape is researched because it is expected to give better laminar flow profiles. Using laminar flow profiles will reduce the marginal error when calculating the flow. This setup and the usage of echo PIV, will also be used to validate further flow research using laser Doppler.
The research question that will be answered in this thesis is: can the flow of breastmilk through a channel be determined using echo PIV?

Chapter 2

Methods and Materials

The experimental setup consists of three main parts and several connecting parts. The three main parts are the breast pump, the ultrasound transducer and the channels within a block of polyacrylamide. To connect the parts, thin tubes and 3D printed coupling pieces are used. A schematic image of the whole setup is given below, see figure 2.1.

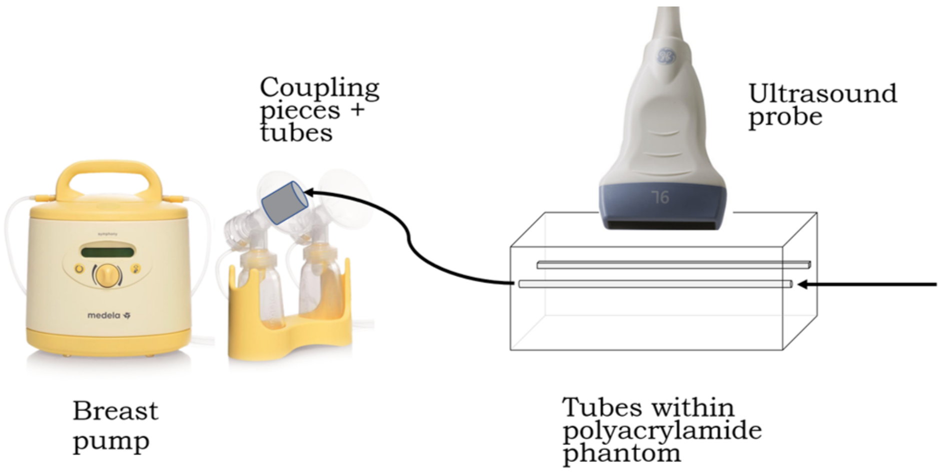


Figure 2.1: Schemetic overview of setup (not to scale)

2.1 Breast pump

The milk is pumped and fed through the setup using a breast pump. The breast pump used is a Medela Symphony [11], see figure 2.1. This breast pump has several different pumping options, the one used is a function that can imitate the way babies drink. This is done by changing the speed and pressure of the suction flow. It has two fases, firstly the *initiate* fase [12]. This fase consists of fast and low pressure pumps (125 cycles per minute), just as babies do when drinking. This is to stimulate the milk flow. The breast pump has after this fase, the *sustain* fase, where the pressure is higher and with longer intervals (54-78 cycles per minute). This will create a pulsating flow in the setup. The maximum vaccuum that can be generated by the Medela Symphony is 270 mm Hg. But research shows that the the maximum comfortable vaccuum lies around 190 mm Hg [12] and that the use of the mother's personal maximum pressure enhances the milk flow and milk volume pumped. The average milk flow measured in this study was 0,13 ±0,03 ml/s (118.5 ±11.4 ml per 15 minutes).

2.1.1 Coupling piece

The breast pump consists of a couple of different parts, the pump is normally attached to the breast by a breast shield, a connector, tubing and the membrane cap [11]. In this setup, the breast shield is replaced with a custom-designed 3D-printed connecting piece as it has to attach to a tube with a diameter of 1 mm. The difference bridged between the connector and the channel is from 30 mm to 1 mm. Different sizes coupling pieces are tried to get the best vacuum. The coupling part is attached on the connector using tape to create a seal. The channel is sealed in the coupling part by using vaseline. A picture of the connector, coupling piece and tube can be seen in figure 2.2. The inside diameter of the coupling tubes are 1 mm and the outside diameter is 1,3 mm. These sizes fit nicely within the PAA phantom channels and no leakages are observed.

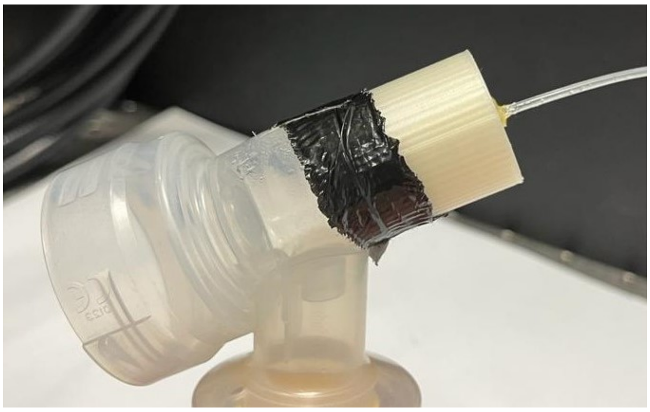


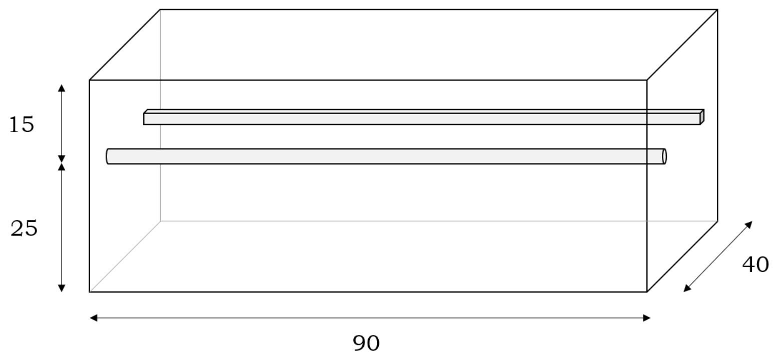
Figure 2.2: Picture of the 3D-printed coupling piece connected to the connector using tape and the tube

2.2 Polyacrylamide

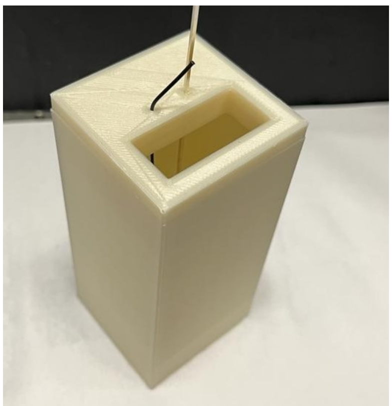
Polyacrylamide (PAA) is a polymer having acoustic qualities similar to the acoustic properties of soft tissue and water. Speed of sound is around 1500 m/s [13], compared to the speed of sound of water which is 1480 m/s and soft tissue contains mainly water. PAA is clear, which means it would be suitable for optics as well as for ultrasound. PAA consists of demineralized water, acrylamide, ammonium persulfate (APS) and tetramethylethylenediamine (TEMED). Acrylamide is polymerized by APS and this process is catalyzed by TEMED. The phantom can be made more or less stiff by changing the percentage of acrylamide and APS. Other substances could be added as well, for instance to change the acoustic qualities [13]. The process of making PAA is relativly simple, which is one of the reasons why it is used in this setup [14]. It is as simple as combining the components and homogenizing through mixing. When setting, the phantom heats up a little bit but this is perceived as warm to the touch, around ∼10-15 degrees celsius. The phantom also cools down again when completely set. The phantom is typically quite durable, when stored airtight. Using gloves when handling the phantom is advised, as unpolymerized acrylamide is considered toxic [13] and it is possible that not all the acrylamide is completely polymerized.

2.2.1 Phantom mold

The phantom was created in a 3D-printed mold, figure 2.3b. This mold is able to withstand temperatures without deforming up to 60 degrees celsius [15]. This is why it is used to create the phantom. Using 3D-printing techniques also makes it possible to create the mold perfectly for the setup and meet the requirements. Two wires were used to create the channel within the phantom when removed. A circular shaped iron wire with a diameter of 1 mm and length of 150 mm and a square silver wire with dimensions of 1 x 1 x 150 mm were used. The materials of the wires were not relevant when choosing the wires, as finding the correct shape and dimensions was the first priority. The measurements of the phantom are 90 x 40 x 40 mm. The channels lie 15 mm deep in the phantom as the focus point of the transducer lies that deep, see figure 2.3a. A lid with holes was also 3D-printed to ensure that the wires stay in place while pouring. On the bottom of the mold, two slots are created to ensure that the wires stay in place throughout the mold. Some vaseline was added to the sides of the square wire for easier and better removal as the wire was troublesome to remove during the first couple attempts. When removing, the wire created a uneven channel surface which made the cbannel unusable. The orientation of the final phantom is horizontal, but because of the channels the phantom is poured in a vertical orientation. This way, the wires that create the channel can be pulled out easily out of the mold without any leakage.



(a) Polyacrylamide phantom dimensions (mm) with circular shaped channel (diameter 1,0 mm) and square shaped channel (1,0 x 1,0 mm)



(b) Picture of 3D printed mold

Figure 2.3: Dimensions of phantom and a picture of the mold used

2.2.2 PAA proportions

To find a suitable composition for the PAA, eight samples with different concentrations were made. A couple of different ratios were tried, starting with 17,50% acrylamide, 0,14% APS, 0,28% TEMED and 82,08% demi water [13]. After a couple of attempts, it became clear that too much TEMED was used, as the PAA set too quickly and already solidified in the beaker while pouring. The phantom itself was also not stiff enough, the diameter of the channel changed with the pulsation of the flow. By increasing the acrylamide and the APS, this effect was reduced. Increasing the acrylamide and the APS will increase the amount of crosslinking within the PAA and which results in a more rigid block. An overview of all the PAA pouring attemps is given in table 2.1. The diameter of the circular shaped channel of attempt 2 changed to ∼60% of its original diameter whereas the latest attempt (attempt 8), the diameter of the circular shaped channel changed to ∼80% of its original diameter. This shows that the relative amount of acrylamide and APS helps make the PAA phantom more stiff.

Table 2.1: PAA componentes and proportions (v/v Volume concentration volume/volume, w/v Weight concentration weight/volume)

Components	Volume (ml)	Demi water (v/v)	Acrylamide (v/v)	APS (w/v)	TEMED (v/v)
Attempt 1 (%)	158	82,08	17,50	0,14	0,28
Attempt 2 (%)	158	82,14	17,50	0,14	0,22
Attempt 3 (%)	60	81,92	17,50	0,30	0,28
Attempt 4 (%)	50	81,92	17,50	0,45	0,42
Attempt 5 (%)	50	73,13	26,00	0,45	0,42
Attempt 6 (%)	50	73,17	26,00	0,45	0,38
Attempt 7 (%)	160	73,17	26,00	0,45	0,38
Attempt 8 (%)	160	73,30	26,00	0,45	0,25

2.3 Echo PIV

2.3.1 Ultrasound

To measure the flow of the breast milk, ultrasound and a technique called echo Particle Image Velocimetry (PIV) are used. An ultrasound transducer is used to image the particles in the medium. A transducer sends out a short electrical pulse through the piezo electric parts of the transducer which then produce a soundwave [16]. The soundwaves reflect each time they reache an interface with a different acoustic density and these echos are detected again by the transducer. The piezo elements can translate the deformation by the soundwave back into an electric field. The different intensities and the time between signals then can be translated into an image. The frequencies used clinically vary between 2 and 12 MHz [17], but for higher resolution images, frequencies up to 20 MHz can be used. In this setup, the center frequency is around 15 MHz with a bandwidth between 8 and 22 MHz. The frame rate is of 1000 frames per second. For moving structures, having a high frame rate is important. The higher the frame rate, the more images per second can be scanned which gives a higher temporal resolution. The transducer used in this setup is the Kolo L22-8v in combination with a Verasonics Vantage 256 System [18].

2.3.2 PIV

To determine the flow, echo PIV is used. Echo PIV is based on the cross correlating of backscatter measured by the ultrasound transducer [19]. The difference in acoustic density of the particles/fatglobules/bubbles and the phantom will result in an echo. These images with a high frame rate will be saved to be reconstructed later again, using MATLAB. These reconstructed images can then be analyzed using echo PIV. The MATLAB script used are written by colleagues in the Multimodel Medical Imaging (M3i) group, the latest version used was written by Ashkan Ghanbarzadeh-Dagheyan. Echo PIV will ask for a mask of the part of the frames needed to be analyzed. It will then compare 2 frames and cross correlate the particles visible in the frames. The difference in position will be translated into a vector representing velocity and direction. A figure to illustrate this can be seen in figure 2.4.

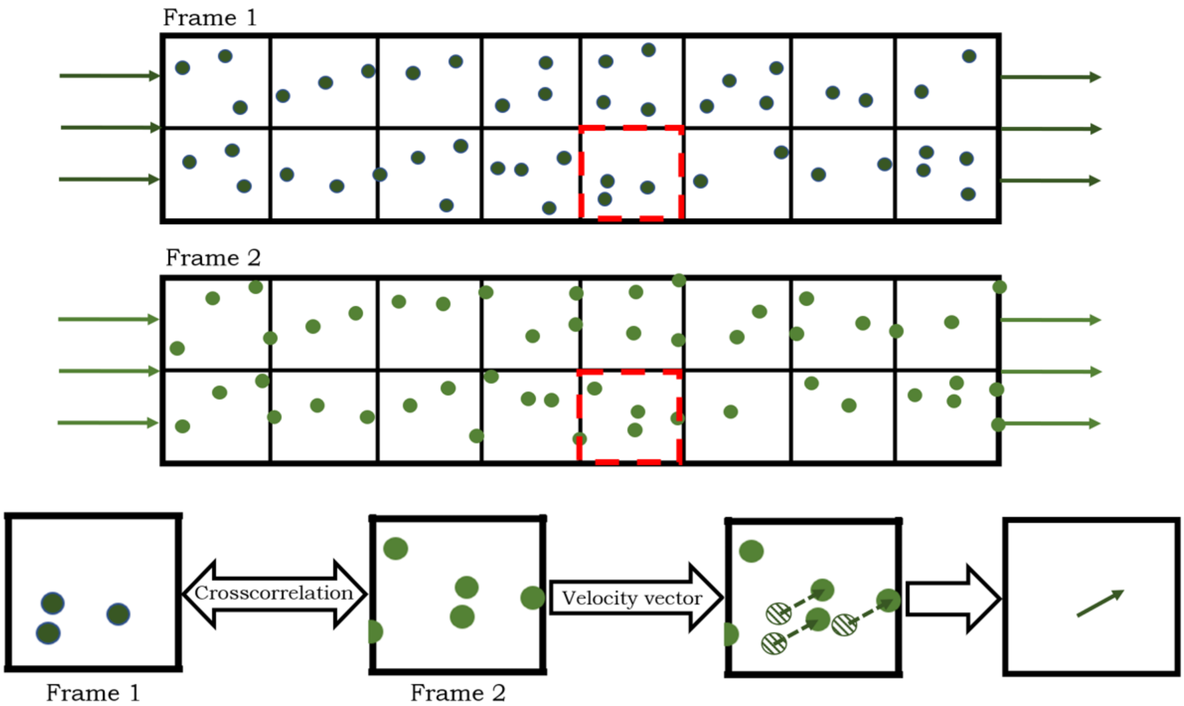


Figure 2.4: Schematic explanations of the principles of echo PIV where two successive frames are cross correlated and visualized in a mean vector.

2.3.3 Flow

To calculate the flow of the setup, the mean velocity is used. The average flow of the frames is given in one figure and a line perpendicular to the channel is drawn. See figure 2.5. The mean velocity on this line is given in a graph. To get the correct flow within the channel, not the maximum velocity is used, but the integrated velocity. The area under the graph is calculated by taking the integral of the graph. Knowing the mean velocity (m/s) and cross sectional area (m^2), the flow can be calculated (m^3/s).

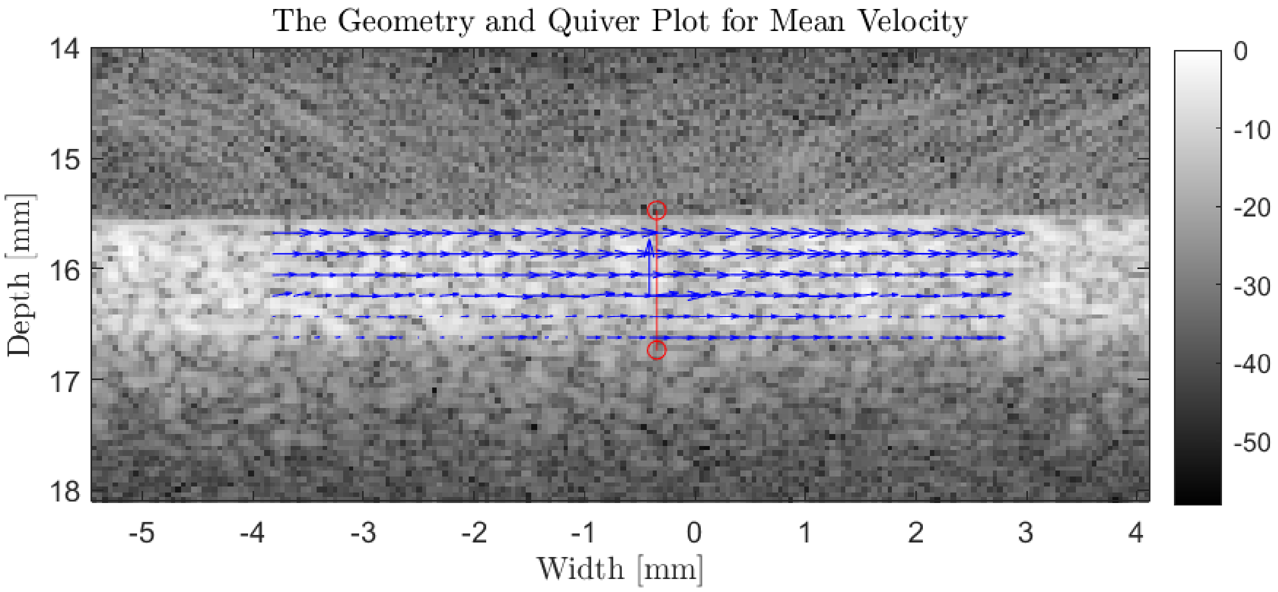


Figure 2.5: Cross section of flow to determine the mean velocity (circular shaped channel)

2.3.4 Particles

To test the setup, lipid-coated microbubbles are used instead of breast milk. The microbubbles are made at the Physics of Fluids group at the University of Twente by Hadi Mirgolbabaee. The diameter of the microbubbles is 6,5 µm, which is bigger than the diameter of human milk fat globules. The diameter of human milk fat globules lie between 1 and 5 µm [20]. 1 ml of microbubble solution is diluted in 30 ml phosphate-buffered saline (PBS) and this liquid acted as the contrast agent in the setup.

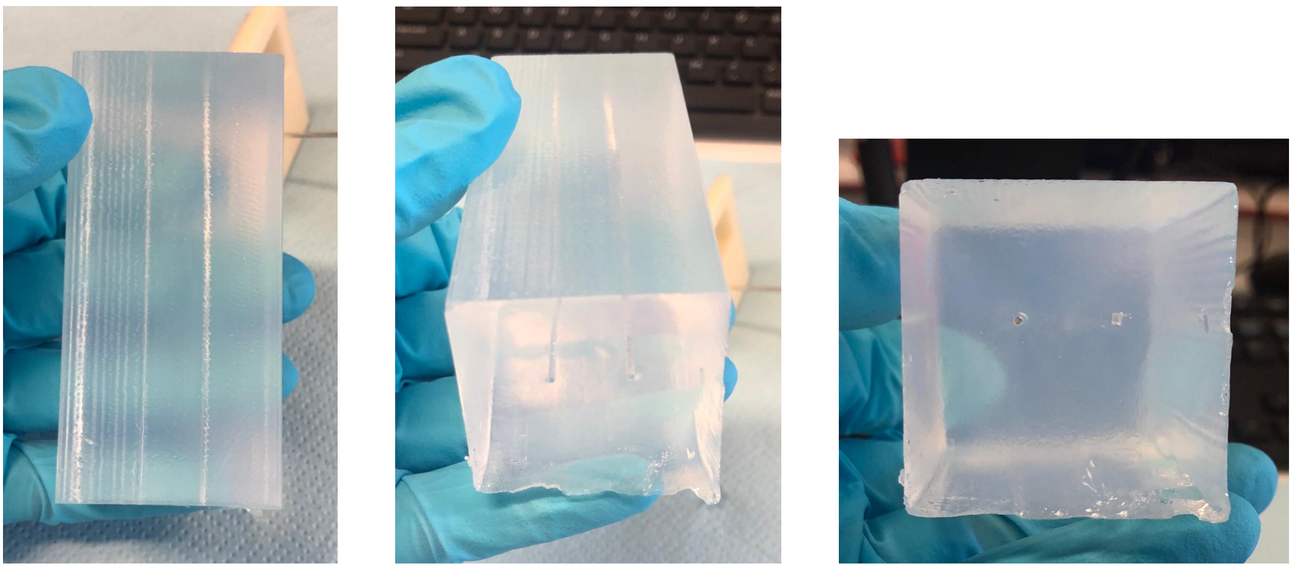
Chapter 3

Results

The results of the how the PAA phantom turned out and the reconstruction of echo PIV are given here. The mean flow is calculated. A picture of the final setup made is given in the appendix (chapter 6).

3.1 PAA phantom

A total of eight attempts of pouring the PAA are tried and six phantoms are made. Two attempts did not complete the pouring or got damaged during the removal from the mold. Attempt number 8 had the best stiffness of all the attemps and is used in the setup. The percentages used are 26,00% acrylamide, 0,45% APS, 0,25% TEMED and 73,30% demineralized water. The volume made and poured was 160,0 ml. The channel within the phantom shrunk to about 80% of its original width. A picture of the used phantom is given below, figure 3.1. The square and circular shaped wires were removed cleanly, creating the two channels within the phantom. The shape of the two channels can be seen in figure 3.1c, with the circular shape on the left and the square shape on the right. The squared shaped wire was misplaced on the bottom of the mold by 1 mm, so the squared channel has a slight horizontal decline. This can be seen slightly in the echo PIV results, see figure 3.2b.



(a) Top view of the PAA phantom, the 2 tubes can be seen vertically in the photo

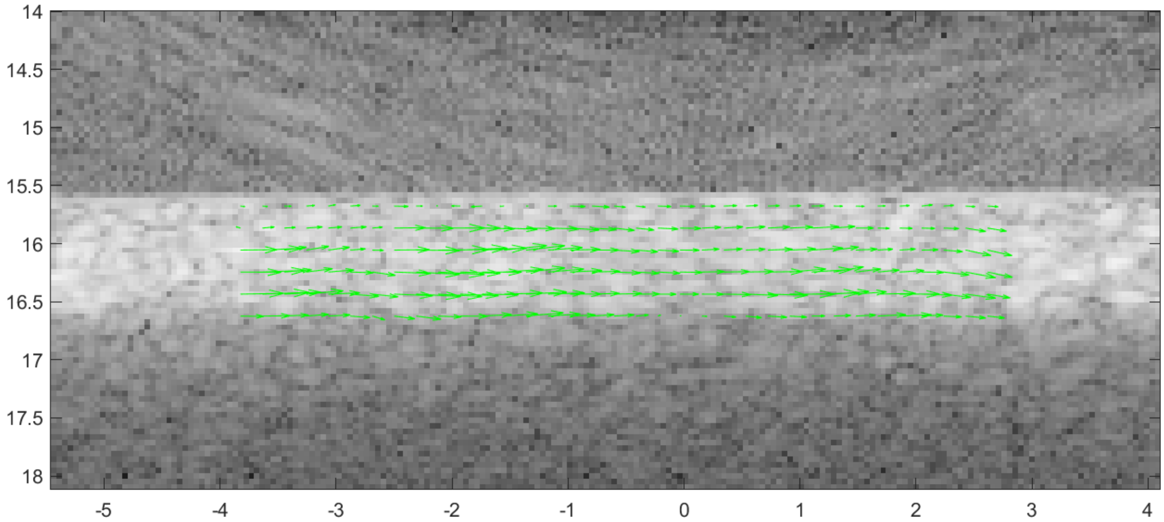
(b) Top and cross section view of the PAA phantom

(c) Cross section of the phantom, the left tube is circular shaped and the right tube is squared shaped

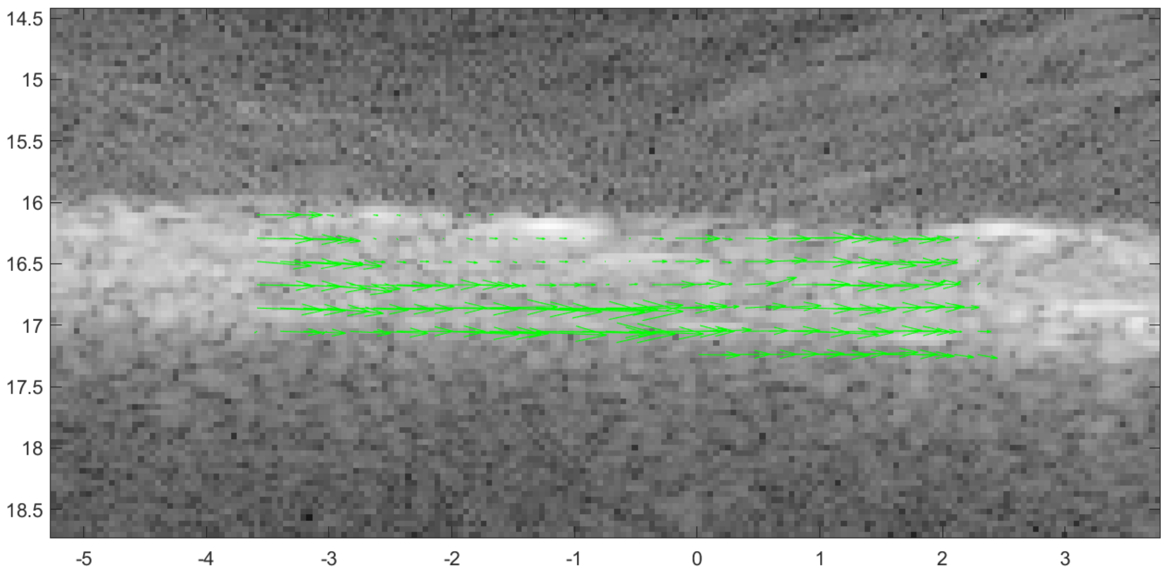
Figure 3.1: Three views of PAA phantom attempt 8. The tube on the left is circular shaped and on the right is squared shaped.

3.2 Echo PIV

Each frame is cross correlated and can be analyzed frame by frame. A total of 996 frames are analyzed using the echo PIV MATLAB script. The vector fields of the circular and squared shape tube are given in figure 3.2. Here the vectors representing the flow are shown during similar frames within the loop. The flow moves from left to right, as the vectors are showing. The squared shape channel shows a part of the tube which has a low flow, on every frame. Earlier measurements showed some irregularties within the squared channel already which did not move with the flow and pressure.



(a) Echo PIV circular tube (mm)



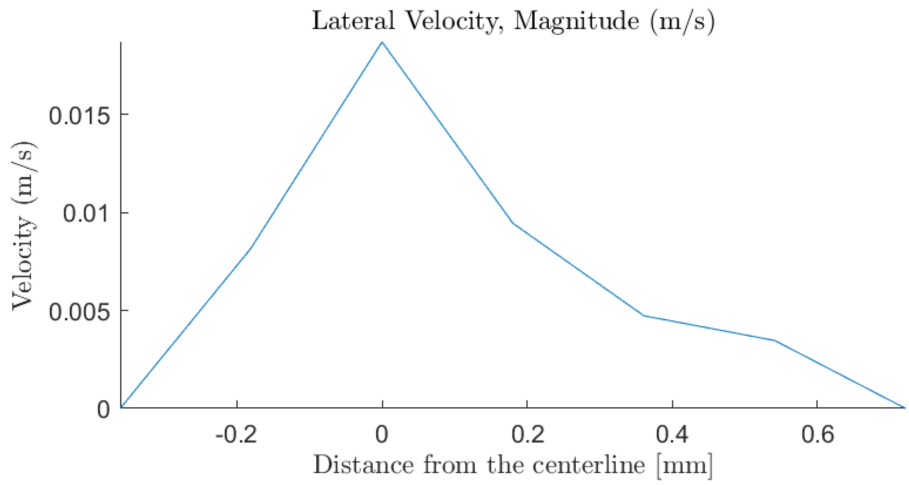
(b) Echo PIV square tube (mm)

Figure 3.2: Echo PIV result, circular and squared shape compared

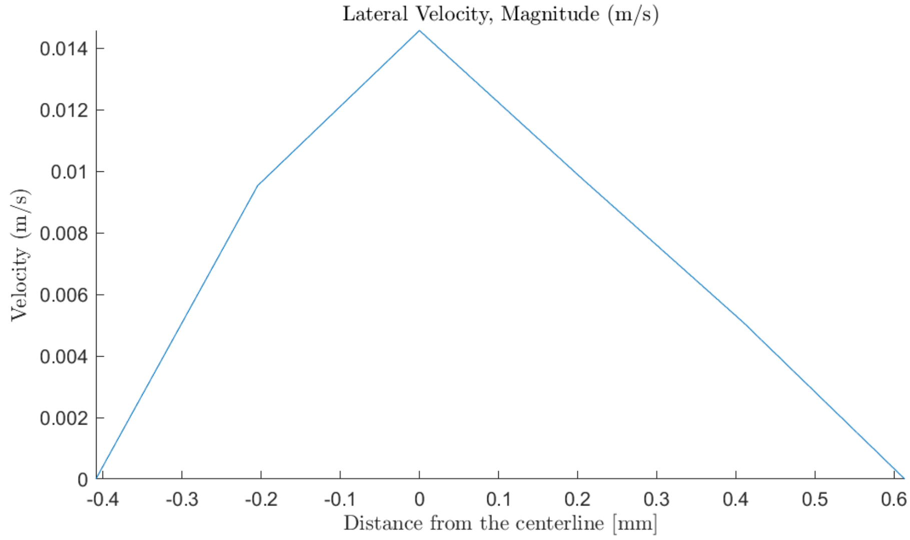
Not all frames give reliable vectors. There are frames where the vectors jump and give hard to explain results. This can result in an incorrect mean velocity. It is not clear within this research if the vectors calculated are accurate.

3.2.1 Flow

The flow is calculated as mentioned in 2.3 using the velocity profiles are given in figure 3.3. The average velocity calculated in the circular shaped tube is 7,3 mm/s and the area of the circular cross section is 0,785 mm^2. The calculated flow of the circular shaped tube is 5,7 mm^3/s (0,0057 ml/s). The same can be calculated for the square shaped tube. The flow calculated of the square shaped tube is 6,8 mm/s and the area of the circular cross section is 1 mm^2. The calculated flow of the circular shaped tube is 6,8 mm^3/s (0,0068 ml/s).



(a) Velocity (m/s) perpendicular to the circular tube



(b) Velocity (m/s)perpendicular to the square tube

Figure 3.3: Velocity (m/s) measured perpendicular to the tube

Chapter 4

Discussion and Recommendation

In this chapter, the discussion will be presented. The discussion is divided into three sections, similar to Methods and Materials and the Results. Corresponding recommendations will also be given.

4.1 Breast pump

Flow The pulsated flow created by the breast pump had some backflow. This was visible in the echo PIV data. The mean velocity is not compensated for this, the backflow is also included with the mean. For the next setup it might be wise to start with a constant flow, so less variables are created. This may result in smaller error margins as well. Having a constant flow would also mean a constant cross sectional area, which would take the cross sectional area variation out of the equation.

Breast milk The ultimate goal is to test the setup using breast or cow milk. This has not been done yet due to lack of convenient access to raw cow milk or human breast milk. Instead, a solution of lipid-coated microbubbles is used. The diameter of the globules used is larger than the fat globules found in human breast milk. For the next setup, it is recommended to test on real milk as well to get a setup which can be better compared to reality and to see if it is really possible to measure the flow of breast milk using echo PIV.

Expected flow There was only one source found which stated something about the flow created by the Medela Symphony breast pump. In this article, the volume and total duration of expression were given, and the expected flow was calculated using this source. The flow calculated in the article (0,13 ml/s), is higher than the flow calculated using this setup and echo PIV (0,0057 ml/s). But conclusions are hard to make, as the time measured is vastly different. The expected flow [12] was measured over a time period of 15 minutes and the flow measured using this setup was measured over a time period of 2 seconds. The whole setup of measuring the flow is also vastly different.
The flow in this setup is also not validated due to time. It is recommended to validate the flow by measuring the volume before and after during a given amount of time. The weight of the volume pumped through the setup should be compared to flowrate integrated over time.

4.2 Polyacrylamide

Phantom In this setup, the diameter of the channels within the PAA phantom change. The pressure of the breast pump causes the diameter of the channels to shrink to 80 percent of its original diameter. In this thesis, the change of the cross sectional area is not taken into consideration when calculating the mean flow. The original cross section area is used in the calculations. But to give a rough estimation, the cross section area of the circular shaped channel would change from 0,785 mm^2 to 0,503 mm^2 when shrunk to 80 percent of its original diameter. Combining this with the velocity (7,3 mm/s) gives a flow of 0,0036 ml/s. It can be estimated that the most accurate calculation of flow would be when the diameter is smaller. This because the vaccuum is the highest when the diameter shrinks.

It is recommended to increase the amount of acrylamide and relatively the amount of APS. This will create a more stiff phantom, which would decrease the need to compensate the flow calculations when processing the data.

Square tube The PAA phantom used in the setup, had a slight horizontal decline as the wire was placed 1 mm next to the assigned slot. It is not clear how this decline of the channel affects the flow. The decline itself is visible in the echo reconstruction, but no clear flow changes are observed because of the decline.
Irregularities within the square shaped channel can be seen in the echo PIV, see figure 3.2b. This might be some vaseline residue left over after removing the square wire coated in vaseline. The lipid-coated microbubbles could also be sticking to the vaseline and appear as irregularities. It could also be the result of removing the wire not smooth enough. Which might have created some damages within the channel. What the cause of the irregularities within the square chaped channel actually are, has not been determined in this thesis.
Because of the slight decline and the irregularities within the square shaped tube, it is recommended to remake the PAA phantom for the next setup to ensure the best quality of channel and corresponding echo PIV images.

There can't be conclusions made about the difference of channel shape. The mean flow is similar and the velocity profiles don't have enough data points and difference to make for a conclusion.

4.3 Echo PIV

Vectors The vectors given when the flowrate is high, do not give consistent results. At high flowrates, the vectors jump around a bit sometimes. Instead of following the expected flow profile, the vectors sometimes go into a different directions and with a different size, see figure 4.1. This happens only when the flow rate is relatively high. At low flow rates, the vectors seem to move within the expected direction of the flow.
Reflections and speckles can also influence the vectors calculated. The amount of contrast can be one of the sources of extra reflections. These artefacts can bring difficulties regarding cross correlation. When cross correlating the frames, it is possible that the software compares speckle instead of the contrasting particles. This, in combination with perhaps a high flow rate, can result in the inconsistent vectors.

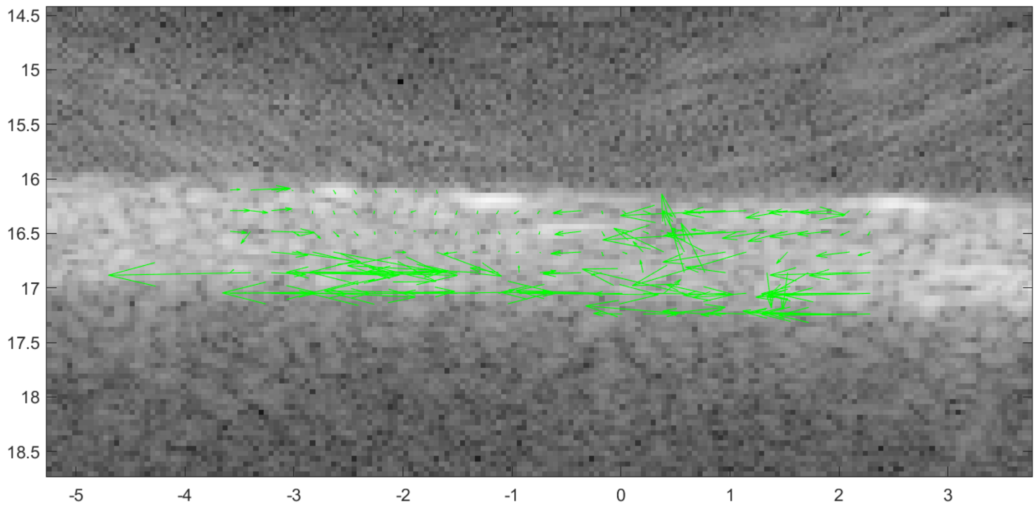


Figure 4.1: Turbulent flow, high flowrate in the square shaped channel.

Lateral velocity The shape of the graph of the lateral velocity is piramide shaped. The expected velocity profile of laminar flow is a parabolic shape [21]. The piramide shape could be explained by the limited amount of datapoints. The graph has 6 or 7 datapoints only, which come from the 6 or 7 vectors found on the cross section.

Chapter 5

Conclusion

A first working version of an experimental setup was build in which successfully a liquid flow through a channel was measured using echo PIV.
Breast milk A solution of lipid-coated microbubbles proved to be suitable as a subsitute for breast milk, yielding usable echo images.
Phantom Channels within a phantom were contructed using polyacrylamide (PAA), for which a working composition was developed. The phantom was successfully connected to a Medela Symphony breast pump via tubes and a 3D printed coupling piece.
Echo PIV Ultrasound proved to be successful in imaging the contrast liquid and from the echo images, the velocity vectors could successfully be calculated using a MATLAB script. The mean velocity could then be intergrated over the cross sectional area of the channels in the phantom to yield a flow.

Based on the first limited number of measurements, it can be concluded that this experimental setup provides a good basis for further research.

Bibliography

[1] Cesar G Victora et al. "Breastfeeding in the 21st century: epidemiology, mechanisms, and lifelong effect". In: *The lancet* 387.10017 (2016), pp. 475–490.

[2] Ruowei Li et al. "Why mothers stop breastfeeding: mothers' self-reported reasons for stopping during the first year". In: *Pediatrics* 122.Supplement_2 (2008), S69–S76.

[3] Wei Wei, Qingzhe Jin, and Xingguo Wang. "Human milk fat substitutes: Past achievements and current trends". In: *Progress in lipid research* 74 (2019), pp. 69–86.

[4] Olivia Ballard and Ardythe L Morrow. "Human milk composition: nutrients and bioactive factors". In: *Pediatric Clinics* 60.1 (2013), pp. 49–74.

[5] PG Arthur, PE Hartmann, and M Smith. "Measurement of the milk intake of breast-fed infants." In: *Journal of pediatric gastroenterology and nutrition* 6.5 (1987), pp. 758–763.

[6] MW Woolridge et al. "The continuous measurement of milk intake at a feed in breast-fed babies". In: *Early human development* 6.4 (1982), pp. 365–373.

[7] Gerhard Fusch et al. "Rapid measurement of macronutrients in breast milk: How reliable are infrared milk analyzers?" In: *Clinical Nutrition* 34.3 (2015), pp. 465–476.

[8] Ben Aernouts et al. "Visible and near-infrared spectroscopic analysis of raw milk for cow health monitoring: reflectance or transmittance?" In: *Journal of Dairy Science* 94.11 (2011), pp. 5315–5329.

[9] Jacqueline C Kent et al. "Impact of measuring milk production by test weighing on breastfeeding confidence in mothers of term infants". In: *Breastfeeding Medicine* 10.6 (2015), pp. 318–325.

[10] Nienke Bosschaart. "LactIns-and-outs". In: *Research proposal* (2021).

[11] AG Medela. *Symphony - medela.nl.* 2007. URL: `https://www.medela.nl/dam/medela-com/breastfeeding-consumer/documents/products/symphony.pdf/symphony-borstkolf-gebruiksaanwijzing-thuisgebruik.pdf?uuid=jcr:806b1bbb-8647-443f-b170-3824fa343ba4`.

[12] Jacqueline C Kent et al. "Importance of vacuum for breastmilk expression". In: *Breastfeeding Medicine* 3.1 (2008), pp. 11–19.

[13] T Boers et al. "Matrix 3D ultrasound-assisted thyroid nodule volume estimation and radiofrequency ablation: a phantom study". In: *European radiology experimental* 5.1 (2021), pp. 1–10.

[14] Karin Zell et al. "Acoustical properties of selected tissue phantom materials for ultrasound imaging". In: *Physics in Medicine & Biology* 52.20 (2007), N475.

[15] S Solarski, M Ferreira, and E Devaux. "Characterization of the thermal properties of PLA fibers by modulated differential scanning calorimetry". In: *Polymer* 46.25 (2005), pp. 11187–11192.

[16] John E Aldrich. “Basic physics of ultrasound imaging”. In: *Critical care medicine* 35.5 (2007), S131–S137.

[17] Valentina S Lucas et al. “Utility of high-frequency ultrasound: moving beyond the surface to detect changes in skin integrity”. In: *Plastic surgical nursing: official journal of the American Society of Plastic and Reconstructive Surgical Nurses* 34.1 (2014), p. 34.

[18] *CMUT transducers*. 2022. URL: https://verasonics.com/cmut-hf-transducers/.

[19] Hyoung-Bum Kim, Jean R Hertzberg, and Robin Shandas. “Development and validation of echo PIV”. In: *Experiments in fluids* 36.3 (2004), pp. 455–462.

[20] Wendi Jiang et al. “Variation of fat globule size and fatty acids in human milk in the first 30 days of lactation”. In: *International Dairy Journal* 100 (2020), p. 104567.

[21] Hua-Shu Dou. “Energy gradient theory of hydrodynamic instability”. In: *arXiv preprint nlin/0501049* (2005).

Chapter 6

Appendix

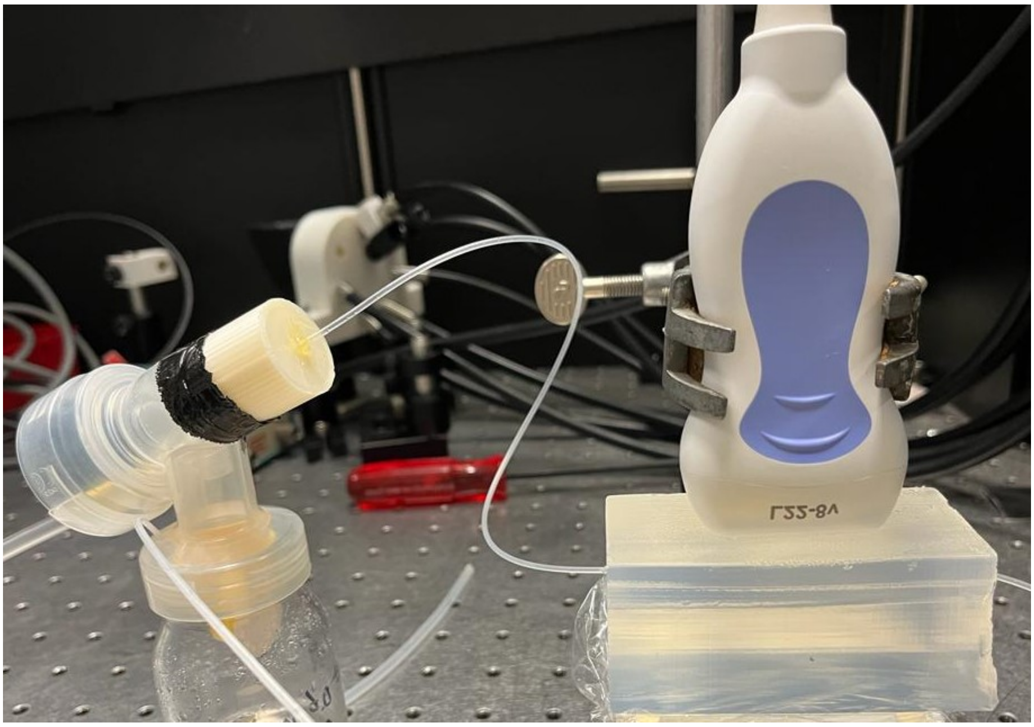


Figure 6.1: Picture of the final setup made, including the PAA phantom, ultrasound transducer and coupling pieces and tubes. The breast pump is not included in the picture.