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The Shape of Breasts Suspended in Liquid

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Abstract

Philips has designed an optical mammography machine. In this machine the breast is suspended into a cup in which the measurements take place. A special fluid is inserted into the cup to prevent the light from going around the breast instead of going through it but this fluid also weakens the signal. Therefore the cup's shape should be close to the breast's shape.

The aim of this project was to design a device to measure the breast's shape. This device was used to perform a pilot study among 18 women, 36 breasts in total.

There are several possibilities to create 3D images for example MRI, interferometry and triangulation. The method of triangulation is chosen to build a set-up. This set-up contains a video projector to project images into a tank filled with water. Two camera's capture these images. Special software has been written in LabVIEW to create 3D images out of these data.

The maximum height of the breast and the FWHM was measured for all breasts. A correlation was found between bra cup size and the maximum height of the breast. On average the breast was 64 mm high, with a standard deviation of 8.5 mm. No correlation was found between the FWHM and a form of bra size or chest circumference. The average FWHM is 7.6 cm with a standard deviation of 2.5 cm.

Contents

1. Introduction

Of all types of cancer breast cancer is the most prevalent type among women in the Netherlands. 75% of the women aged above 50 who develop cancer develop breast cancer. In the Netherlands about 1 out of every 9 women develops breast cancer and 1 out of every 20 or 25 women eventually dies of breast cancer.[1] A soon diagnosis of breast cancer can improve the mortality rates. Therefore every woman in the Netherlands in the age group of 50 to 75 gets invited once every two years for a breast cancer screening. X-rays of the breasts are produced to search for calcium particles in the breast which might indicate breast cancer. Younger women may get an X-ray breast screening as well when they have another indication for breast cancer.
When abnormalities are detected the women are invited to undergo more diagnostic tests in order to find out if the first screening was correct. The diagnostic tests also determine the type and size of the tumor, its exact location and probable metastasis. These diagnostic tests consist out of MRI, CT, ultrasound and biopts.[2, 3]

In addition to the last mentioned methods optical mammography has been developed. In optical mammography the transmission of (near) infrared light through the breast is measured. Since tumors sometimes contain lots of blood vessels and red light gets reflected by blood very well, this technique can be used to get more information about the tumor. Philips has designed a machine for optical mammography.[4] At the moment this machine is in clinical trial. In first instance it will be used as an additional diagnostical test.
The machine of Philips uses a technique in which a 3D image is obtained from the breast by means of (near) infrared light. The woman lies in a prone position on a table in such a way that a breast is suspended into a ‘hole’ in the table. A cup with measurement equipment is inserted into this ‘hole’.
In order to make a measurement the breast has to fit exactly into this cup. However, this is not possible due to the variety in breast shapes and sizes. Therefore the cavity between the breast and the insert is filled with a fluid with the same optical properties as breast tissue. This fluid is used for three different reasons:

1. It improves the contact between the breast and the optical fibers.
2. It prevents the light going around the breast instead of through the breast.
3. It makes calibrations and reference measurements possible.

A disadvantage is that the fluid absorbs light and thus weakens the signal.

1.1. Purpose of the research

For the last mentioned reason it is of great importance that the cup’s shape and size can be designed in such a way that as little fluid as possible is needed.
The purpose of this research is to measure and describe the shape (contour) of the breast when suspended into a liquid. Depending on the relative density of the fluid compared to water the breast could either be floating or “sinking”. These measurements can be used to determine the optimum shape of the cup. An optimum shape is defined as a shape with which the average volume difference between cup and breast is as small as possible.

1.2. Limitations of the research

The knowledge of the coordinates of the breasts when floating in liquid can be used to improve other parts of the optical mammography system as well. For instance, the time needed for rendering an image can be decreased when the position of the breast can be estimated. This optimization of the rendering process will not be part of this project.

2. Possibilities for shape detection

There are many different ways to determine the shape of an object by scanning, i.e. without physical contact with the object. Most of these methods can be split up into two groups. One group uses reflection of light on an object and the other group uses of projections of shadows.
Methods which might be suitable for this project are described in the following paragraphs. At the end of this chapter the methods will be compared and the best method will be chosen.

2.1. Measurement by reflection

Several techniques are used in which the object’s shape is calculated by using data from reflection on to the object. These techniques are described in the next subparagraphs.

2.1.1. Common, ready to use techniques

First of all there are some very common techniques like MRI. These techniques do not only give information about the surface but can also give information about the inside of the object.
The advantage of using these methods is that the apparatus is already available and no special measurement device needs to be designed from scratch. However, using these techniques is expensive and obtaining one 3D image can take a relatively long time, depending on the technique used.

2.1.2. Optical triangulation

Optical triangulation uses some basic trigonometry rules; when the length of one side of a triangle and two of its angles are known, the lengths of the other sides and positions of the corners can be calculated. This principle is in demonstrated in Figure 1. Instead of using an angle sensor a lens and location sensor (together a CCD camera) can be used as well. The distance in z direction can be calculated when the distance between the lens and the location sensor and the distance measured from the centre of the location sensor to the location of the laser beam projection on the location sensor are known.[5]

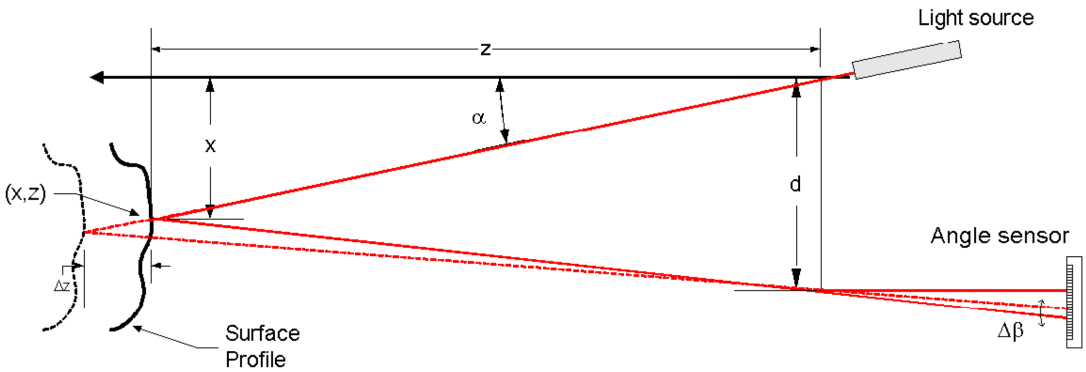

Figure 1: The principle of optical triangulation, when the distance between the light source and the object becomes larger, the angle β becomes smaller.[5]

The relative x and z position can be measured by means of triangulation when the reflection of a spot made by e.g. a laser is used. The whole system has to be moved in the y direction in order to measure at different positions. Another possibility is to use lens to change the laser dot into a laser line in the y direction. All the coordinates in the y direction can be measured at once, by using a detector matrix or by placing several detectors underneath each other.
It is not always possible to detect all of the surface profile when the shape contains a cavity. The reflected beam is fenced off by the object itself.

2.1.3. Time dilatation and interferometers

Another reflection method is by measuring the time it takes a light beam to reflect. The time of reflection depends on the velocity of light through the specific medium. This method needs a very accurate measurement device as changes in time in the order of picoseconds can be measured.
Interferometers can measure the phase shift of a reflected bundle. Thus, this is a very accurate measurement method. However, it is an expensive method and due to the objects size not practical for this experiment.[5, 6]

2.2. Measurement by making use of shadow projections

Shadows produced by or onto an object can give information about the objects shape as well. These procedures as described in the subparagraphs below.

2.2.1. Measurement of the shadow produced by the object

When a light source is projected on the object, there can be measured where the shadow is created, as visualized in Figure 2. By measuring the position of the shadow for light sources all around the object a 3D image of the object can be created. This technique can be compared to the method of CT scans however it uses only black and white and no grey scales.

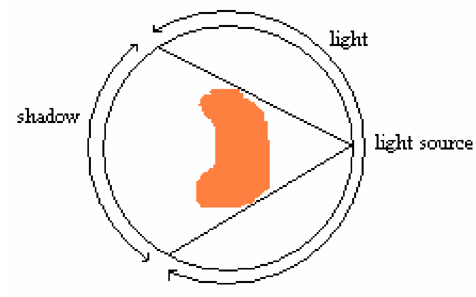

Figure 2: The technique of shadowing. Detection of the locations where the object produces a shadow and where it is does not, using a single diffuse source of light.

Another possibility is to photograph the shadows of the breast from different angles. Techniques in which shadows are used can do the job for spherical objects, however, cavities or crescent shapes can not be detected by this system in a direct way. The relative darkness of a shadow can give some hints on if there is a crescent shape.

Taking a picture from four sides results into an octagon shape. Any shape which touches the 8 sides of the octagon is a possibility. So there is information about the maximum width and depth, but these maximums are not necessarily the case.

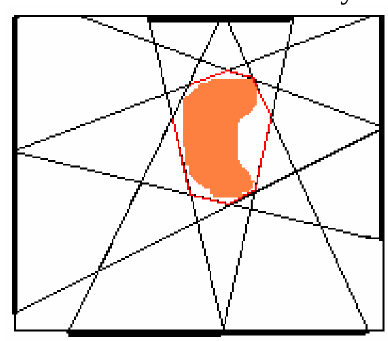

Figure 3: Measuring the shadow produced from four sides results in a certain octagon shape (the red lines). Any object within these red lines which touches at some place each side of the octagon produces these four shadows.

2.2.2. Measurement of a shadow projected onto the object

Not only the shape of the object itself can tell something about the shape of the object, also the shadow of a second straight object can give information about the objects shape. When e.g. the shadow of a rod is projected onto a curved object, the rods shadow will be curved as well.[7, 8]

This technique is very similar to optical triangulation as described in subparagraph 2.1.2, but in this case there is looked at a lack of light (shadow) instead of presence of light (the laser beam). With shadows it is very difficult to image the hollow parts, especially where the object casts a shadow onto itself.

2.3. Stereo photography

A completely different method to determine an objects shape is to take pictures of it from different angles. By using one point of reference on all pictures, it is possible to combine the 2D pictures together to make one 3D image. In this way humans can see 3D by using both eyes.

2.4. Conclusion

Techniques using the shadows of the object are not useful for objects with cavities. The breast suspended in water is expected to be slightly kidney shaped, thus containing cavities.
For the sake of the cups, the exact dimensions of these cavities are not important. A horizontal cross section of the insert will have to be round, so only the maximum radius at each horizontal cross-section is important.

The technique of stereo photography is only useful when each point is visible on both images. For this project it would mean that a grid of dots should be projected onto the breast. Then all the individual dots should be recognized in order to compare their position in both pictures.

Procedures like MRI will take too much time for this project, considering the amount of test persons needed for significant results. Also these techniques are very expensive compared to the other techniques.

The difference in distances measured will probably be too big to measure by means of time dilatation or interferometry. And this technique is also too expensive for this purpose.

Therefore the best method for this project will be triangulation. It is an accurate method which can also detect cavities in some cases; the set-up can easily be made and does not have to be very expensive. An explanation of how the method of triangulation, as shown in Figure 1, is used will be explained in Chapter 5.

In the next chapter the possibilities for a set-up with use of triangulation will be discussed.

3. The measuring device

The method of triangulation can be applied in many different ways. These will be discussed in this chapter.
A moving laser can be used to produce a set of parallel lines. A set of parallel lines will always all have a bigger slope than the breast's contour, therefore most of the breasts shape can be detected. However, if the breast contour tends go inwards close to the chest, this part cannot be detected as can be seen in Figure 4 .

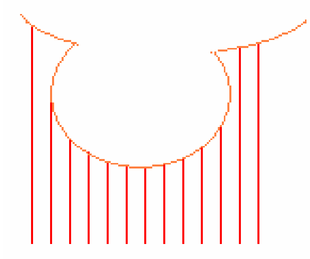

Figure 4: A schematic diagram of parallel lines projected onto the breast and part of the chest in z direction.

There are limitations to the cup's shape too. These cannot go inwards to the top either. Therefore, although not the whole breast might be measurable, the essential parts for the cup can indeed by measured by this method.

Another possibility is to keep the position of the laser still but only to move its direction. This will create a divergent light beam. At places where the slope of the breast's contour is larger than the slope of the line this projection is not visible. Therefore by changing the angle of the light beam not always every part of the breast can be reached as shown in Figure 5. When the laser is positioned relatively further away from the breast, the angles becomes smaller and more of the breast can be measured. At a distance of 1500mm between the light source and the object and an objects width of 250mm, the maximum angle will be

$$\arctan\frac{250/2}{1500} \approx 5^{\circ}$$

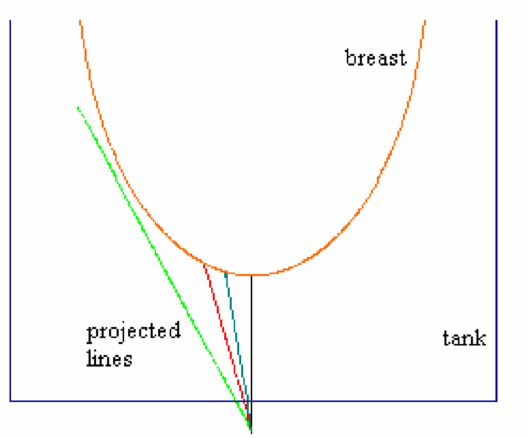

Figure 5: Schematic drawing of a breast in a tank. Underneath the tank a laser beam is diverted and projected onto the breast. Only the blue and the red line will be projected onto the breast. The green line will not hit the breast, therefore the breasts shape can only be measured partially.

There are no specific properties of the laser used, e.g. all light in the same phase. Therefore when choosing to use change in the direction of the angle, the result will be the same as using a diverging light beam, e.g. a video projector. An advantage of using a video projector is that several lines can be projected simultaneously and these lines do not necessarily have to be straight, but they can also be curved in order to adjust to possible deformations of a line due to refractive indices of the different materials. Another advantage of using a video projector is that it does not have any moving parts which need to be calibrated each time the set-up is be used.

3.1. Angle between light source and detection system

Although the example in Figure 1 shows a small angle between the light source and detection system, this does not necessarily have to be the case. The angle can also be about 90˚. This makes it possible to project the lines or spots in z direction and detect in the lines or spots in the x,y direction as shown in Figure 6. The other way around, projections from the side (x, y direction) and detection by a camera from underneath (z direction), is also possible. The direction of the x,y,z coordinates are defined in Appendix A.

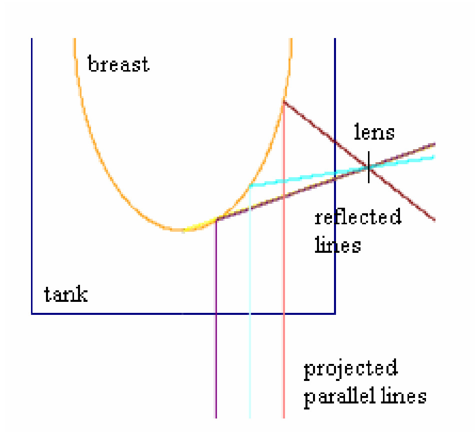

Figure 6: A schematic drawing of parallel lines projected in z direction and their reflection measured in the x direction.

When the angle between the light source and the detector is about 90˚ there will either have to be made use of at least two projection devices or two detection devices. The device in z direction can be single, the device in x,y direction either has to turn around the object or has to be placed at double (at opposite positions) in order to detect the whole breast.

3.2. Shape of the tank

The tank which will be used can either be cylindrical or square shaped. Both shapes have various advantages and disadvantageous which also partially depend on the direction of the light beam.

3.2.1. Cylindrical shaped tank

When the surface of the tank is curved the light source can be moved around the object and thus always produce a light beam which is perpendicular to the surface. But when the beam is projected to the curved surface at an angle, the tank will behave as a lens. The direction of the beam in the water will be difficult to control as it will depend on many factors. The same goes up for the beam detected by the detection device. When it does not go through the curved glass at a perpendicular angle, it will be very hard to estimate the exact origin of the beam.

3.2.2. Square shaped tank

In a set-up with a square tank with flat surfaces the number of directions for perpendicular beams is limited to four. But when light beams hit the surface at an angle, the change in direction can be determined more easily because it only depends on the angle of the beam and the refraction index of the materials.

3.3. Conclusion

A tank with flat walls will be more suitable for this project than tank with curved walls. With flat walls the direction of the light beam can easily be calculated even if the light beam does not get through the wall at a straight angle. A fixed light source can be used as well because not all light beams have to be perpendicular. This means a video projector can be used in stead of a laser. The advantages of a video projector are that the projected lines do not necessarily have to be straight and there are no moving parts needed in the set-up, requiring less calibration.

Whether the video projector or the detection device should be placed in the z direction depends on the properties of these devices, for instance the possible depth of focus and angle of view.

In the next chapter a test set-up is described which was used to test if the method would work properly.

4. A test set-up

Some parts of the set-up had to be tested before the real set-up could be made, which is described in Chapter 5. In this chapter the test set-up will be described including the problems which had to be solved and questions which had to be answered.

4.1. Description of the test-up

At first instance the test-up was made with materials which were ready for use in the lab. There was made use of the following material:

- Old office desk, desktop dimensions 1.60m x 80 cm
- Glass aquarium, length x width x height 30 x 20 x 20 cm^3, filled with tap water
- Video projector, Sharp XR-20X
- PC with firewire connection for the cameras
- 19” TFT screen set at a resolution of 1024x768
- Camera, Marlin F131C, with various lenses and stand
- Mirror, size 15 x 15 cm, golden surface at the back
- Breast phantoms of the mammography machine
- Lined paper, with every mm horizontal and vertical lines

The most important parts of the set-up are shown in Figure 7.

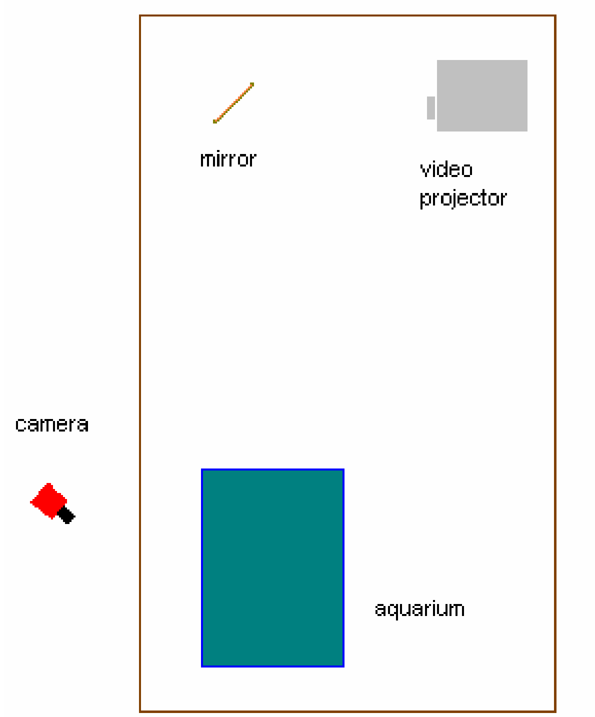

Figure 7: A schematic drawing of the top view of the test set-up

4.1.1. Projected image

The resolution of the video projector was 1024 horizontal and 768 vertical pixels. Therefore the projected image was 1024x768 pixels as well, in this way the image would not be resized by the video projector.
At first an image with horizontal and vertical lines was made. Each line was one pixel thick and the lines were five pixels apart from each other. Most lines were red, every tenth line was yellow, and the horizontal and vertical at the centre of the image were green. The background of the image was black. A red color red was chosen to imitate laser lines. The yellow lines were used to count the number of lines projected onto the image more easily. The centre lines were green, so these lines could be distinguished from the others in order to centre them.

Later this image was turned into an image with all white lines at a black background. This was done to test the possibility for black and white images and to check for the best reflecting color. The lines at the centre were made two pixels thick so they could easily be distinguished from the other lines.

4.2. Testing parts of the set-up seperately

4.2.1. Setting up the projector

Video projectors are designed to project large images (i.e. about 2 meters wide) at distances of about 3.5 m. In this set-up the video projector would stand at a shorter distance and also the image had to be smaller. On forehand it was not certain if it would be possible to project sharp images in this set-up without help of any extra lenses.
Using the mirror it was possible to place the video projector at a distance of about 135 cm to the centre of the aquarium.

The relationship between the focus distance and image dimensions is described in the booklet provided with the video projector. At a distance of 135 cm the image projected would be 68 cm wide and 51 cm high. The video projector projects and image of 1024 pixels wide and 768 pixels high. At the centre of the aquarium each pixel is about 0.66 mm wide.
The aquarium is 30 cm long. At the back and the front of the aquarium the size of the pixels are scaled with the difference in distance from this point to the video projector. Therefore the pixels at the front of the aquarium 0.73 mm wide and at the back 0.59 mm wide.
Due to the refractive index of water the image projected in the tank will be slightly smaller than projected at the same distance outside the tank and so also the pixel sizes must be smaller.
By placing a piece of lined paper in front or directly behind the tank it became visible that the pixels were about 1 x 1 mm, thus slightly larger than calculated. This is because the image was not completely sharp at these places. But also lines of 1 mm wide are still thin enough to create accurate measurements.

The centre of the image is not at the same height as the centre of the lens of the video

projected. The image is tilted upwards 12.9˚. The centre of the image should go through the centre of the aquarium to limit the effect of the different refractive indexes. In this way the maximum angle at which the light enters the tank is as small as possible. Therefore the video projector had to be tilted 12.9˚. This was calculated by information about the distance from the lens centre to the bottom of the image which was mentioned in the booklet of the video projector.
When the projector is tilted the angles of the corners of the projected image are not 90˚, but there is a trapezoidal distortion, as if projected to a slanted wall. The video projector has a sensor so it can automatically adjust for this. The result was that a straight vertical line was not projected straight by the video projector. A column of pixels would half way fade out and the next column would become gradually brighter. This was corrected by using the keystone function of the video projector.

4.2.2. Setting up the camera

For this projected the camera had to be placed relatively close to the object, about 40 cm, so the set-up would fit underneath the table but with a large field of view, about 20 cm wide. The CCD's diagonal is 2/3" (11 mm) and the ratio of the sides is 4:3, so the CCD screen is 8.8 mm wide and 6.6 mm high.
With this information the best optimum lens properties can be calculated. These calculations are shown in Appendix B. The outcome of these calculations, taking the refractive index of water into account is that the lens will net a focus, of 359 mm, a focal length, of 11.8 mm and for a circle of confusion of maximum 0.5 mm the minimum diaphragm, needed is 4.4

Decision on the lens to be used
Lens systems in which the focus and focal length both can be tuned do exist. Theoretically, the exact values needed, can be tuned with these lenses. But very often there is not an exact scale on the lens system, so it is very hard to adjust these lenses to the exact values. It will even be more difficult to adjust two lenses to the exact same values which will be needed for this experiment.
There also exist lenses with a fixed focal length and variable focus. A common focal length is 12 mm, which is very close to the calculated 11.8 mm. If such a lens is chosen the maximum breast height will be 197 mm, keeping all other parameters the same.
The diaphragm does not only change the depth of focus, it also changes the light intensity of the picture. In practice the diaphragm will have to be set to the smallest diameter at which the lines on the picture are still clear. This will also depend on the light intensity of the video projector and the amount of light reflected by the mirror and the skin. The diaphragm will be set during the experiment.

Exact position between camera and video projector
Surfaces which were almost perpendicular to the camera could not be detected by the camera very clearly. Therefore these perpendicular surfaces had to be avoided. A smaller angle between video projector and cameras would give a better view. It would also give an overlap between the two images, allowing checking whether the calibrations went properly. But by changing the angle the sidewalls had to be slanted as well. This would increase the size of the tank and also the weight the sidewalls would have to bear. For these reasons an optimum angle had to be found. This was done by projecting two vertical lines onto a breast phantom, each about one centimeter from the centre and one line

through the centre. When both lines were visible, the camera was considered to be in a good position. This was at angle of 60˚ between the camera and the video projector as shown in the right half of Figure 8.

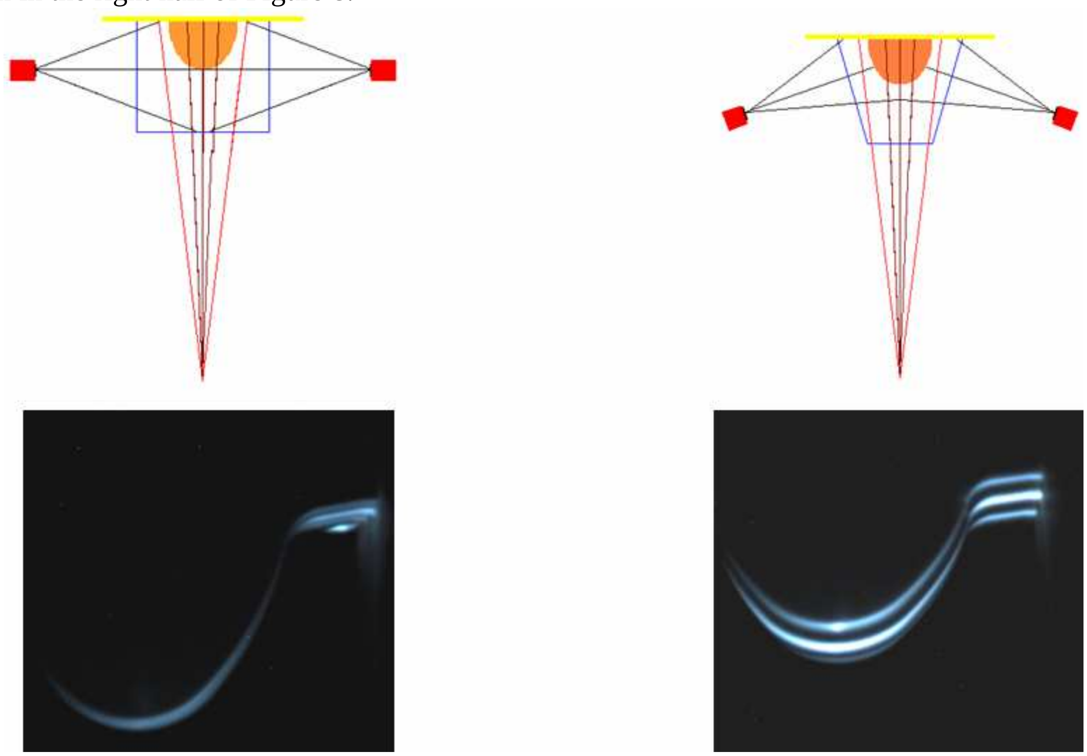

Figure 8: Top: Front view of two possible set-ups for the cameras and the tank. Three lines are shown (brown) which were projected onto the centre of a breast phantom.
Bottom: The three lines projected at the breast phantom. In the left image the angle between the video projector and camera is about 90˚and the lines seems to overlap. In the right image the angle between the cameras and the projector is 60˚ and the 3 lines are visible

4.2.3. The mirror

A mirror was used to increase the path length of the light emitted by the video projector in such a way that the whole set-up would fit underneath the table. At first instance a mirror made of glass with gold at the back was used. It appeared that the front side would produce a double reflection. The back side was tested as well. This did not give a double reflection but the golden surface did not reflect enough light and the aperture of the camera had to be set too big.

Therefore there was decided to have a mirror specially made for this set-up. The mirror was made out of a glass plate, 8 mm thick to make it rigid. The glass was covered with a layer of aluminum which in turn was covered with a thin layer of fused silica (SiO_2). The aluminum was used as the reflecting material, the fused silica was used to protect the aluminum from any damage. To prevent a double reflection due to this layer, the thickness had to be chosen in such a way that there is 1 λ difference in path length. The calculations are shown in Appendix C. The layer of SiO_2 had to be 215 nm.

Another possibility is to make the layer of fused silica very thin so there is hardly any influence of the fused silica. But this layer will be too thin to protect the aluminum properly and will therefore not do its job. It will also be harder to produce a thin layer which is flat than a thick layer which is flat due to its surface tension.

The method of producing this mirror has a 10% error in the thickness of the layer of fused silica. The exact thickness of the layer of SiO_2 can be determined by measuring the interference for different wavelengths or by measuring the interference for one wavelength at different angles. But in practice the angle of the mirror or the color of the light used will not be adjusted according to this knowledge. Therefore it was decided not to check this information.

4.2.4. Use of colors

The color(s) of light which would be used in the images projected by the video projector had to be chosen. A higher maximum intensity is an advantage of white light compared to light of one color. Using white light the aperture of the camera can be smaller and this will increase the depth of focus.
White light is composed of different colors of light which each have a different refractive index for water. But with the camera set perpendicular to the walls of the tank, these effects are limited.
Considering these arguments it would be better to use white light instead of using one color.

4.2.5. Measurement fluid

The matching fluid used in the mammography machine is white and non-transparent. Therefore it can not be used for the measurements of this experiment. The experiment will be performed in tap water. The advantages of tap water are that it is transparent, widely available and extremely cheap.

Whether the breast will either “sink” or float will depend on the breast’s density compared to the density of the used liquid. Thus the density of the matching fluid had to be compared to the density of tap water. The density of the matching fluid was unknown and therefore had to be calculated. The average value for the density of tap water can be found in tables but it was measured as well to find the exact value and to validate the method of calculations.
The procedure and results are shown in Appendix D. The density of matching fluid is about 1% higher than the density of tap water. The density of matching fluid is 1.01 gr/ml.
The difference in density in tap water between 20˚C and 32˚C (the temperature which will be used for the experiment) is less than 0.5%. Assumed is that the difference in density between 20˚C and 32˚C will also be very small for matching fluid.
Because the density difference between tap water and matching fluid are small all measurements will be performed using tap water and no corrections will be made.

The measurements will take place in a static set-up, therefore there is assumed that the viscosity difference between tap water and the matching fluid would not influence the shape of the breasts.

5. The final set-up

When all the separate parts of the set-up had been tested, the final set-up could be designed and put together. The final set-up was designed using AutoCAD and Autodesk Inventor. Two images of the design in Autodesk Inventor are shown in Appendix E. All the separate parts of the tank and were manufactured externally.

The measurement set-up consists roughly out of:

- Bed
- Tank
- Ring
- Gauge
- Video projector
- Cameras
- PC with software

An overall view of the final set-up is shown in Figure 9. All the parts will be described separately in the next paragraphs.

Figure 9: A photograph of the final set-up

5.1. The bed

The used bed is an old office desk with height adjustable stands. The dimensions of the surface of the table are about 1m x 2m. There is a round hole in surface which is about 20 cm diameter so breasts of all sizes will fit through.
The bed is covered with soft foam to make it more comfortable for the test subjects to lie

upon. The foam is covered with plastic so it can be cleaned easily.

5.2. Tank

The tank is positioned directly underneath the hole. The tank is about 26 cm high, 20 cm wide at the bottom and the walls are slanted at an angle of 30˚. These dimensions have been chosen in such a way that all breasts are expected to fit in and the cameras are in an optimum position.
There has to be a water-tight connection between the tank and the bed.

5.3. Ring

There are 3 rings with different sizes which can be placed on top of the hole. These rings will prevent that not only the breast, but also part of the chest will go through the hole.
The rings are designed in such a way that when water is spilled out of the tank the water will automatically be guided away into a bucket.

5.4. Gauge

Pressure might influence the breast's shape. With a simple gauge there can be checked that all breasts are measured under the same conditions.
The gauge will be a high open column which will be connected to the tank. This will also make it possible to add water to the tank when the breast is inserted, if necessary. Under normal conditions the water level in the column should remain the same.

5.5. Video projector

The video projector is located at a distance of about 1 m from the bottom of the tank. It is a standard video projector with a resolution of 1024 x 768. At a distance of 1 m a sharp image projected by the video projector is roughly 63 cm in diameter. Only a part of the image will be used to project onto the tank. At the tank each pixel will be about 1 mm^2, which is accurate enough to perform the measurements. The centre of the image is out-lined with the centre of the tank.
The table is not 1.50 m high, therefore there will be an angle in path of the video projector's light. This will be done with help of the mirror.

5.6. Cameras

The cameras are located perpendicular to two opposite side walls of the tank.
The angle between the video projector and the cameras will be 60˚. This will result in an overlap of the two images which can be used to check the calibration.

5.7. Computer and software

The cameras and video projector are connected to a computer with LabVIEW. The software is described in Chapter 8.

6. Determination of the position of the breast

By use of triangulation the x,y,z coordinates of a certain point can be calculated when the coordinates of the pixel of the video projector and camera are known. A schematic drawing is shown in Figure 10 and below that the calculations are explained.

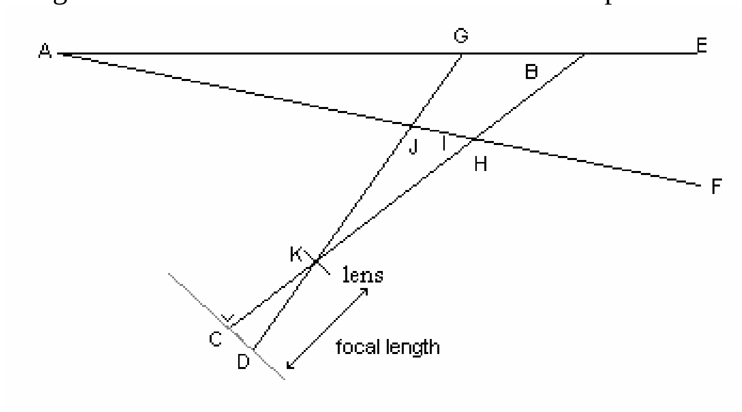

Figure 10: Determination of a position by means of triangulation

Let line AE be the centre of the video projection and let line AF be the projected line onto the object. So the angle of the projected line is A.
B is the angle between the camera and the video projector and the centerline of the image projected onto the CCD is line CB. The object is projected onto the CCD at point D and therefore the object must be on line DG. Thus the object must be at the position of the cross-section of line AF and line DG.

Calculation:
The angle H = 180-A-B and the angle I=180-H=A+B
Distance AH can be determined by: AH= sin(B)* AB/sin(H)
And distance HB can be determined by: HB=sin(A)*AB/sin(H)
The focus distance KB is known and now KH can be calculated as well: KH= KB-HB
K is the angle at which the light enters the camera. This angle can be calculated. Since angle C is 90˚, K=arctan(CD/CK), where CD is the distance at the CCD screen.
Distance HJ can now be calculated:
HJ=sin(K)*KJ/sin(H)
The position of the object on line AF is AH-HJ.
The x and z coordinates of the object are sin(A)*AF and cos(A)*AF respectively.

7. The patterns used for projection

Instead of projecting 1024 images each with a separate line, there are only 10 images projected out of which 1024 separate lines can be subtracted. The width of the lines differs for each image. When comparing the pictures of the 10 patterns there can still be distinguished between 1024 different lines. This is done in the following way:
The images all have vertical lines every next image the width of the lines is halved, so:

- Image 1 has got lines of 512 pixels wide;
- Image 2 has got lines of 256 pixels wide;
- Image 3 has got lines of 128 pixels wide;
- etc…
- Image 10 has got lines of 1 pixel wide.

The first six images are shown in Figure 11.

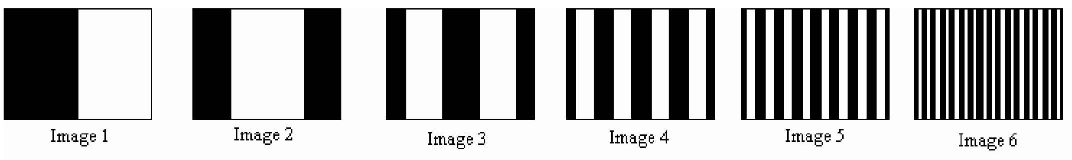

Figure 11: The first six images with lines projected by the video projector.

Each image is an alternating pattern of black and white lines. When these images are placed behind each other into a 3D array, each line in the third dimension will have a unique order of black and white. Black and white can be converted into Boolean values or 0's and 1's as if counting binary.
In Figure 12 two arrays are shown from the side view for a part of 6 images each. The top image in Figure 12 shows an order in which the centre of each black or white block is at the same location for each image. In this way small mistakes (a shift of one position in one picture of the camera) will result in only small errors of location. When one image is shifted one position in the bottom image of Figure 12 it will result in a far bigger error for the calculated position. Therefore the top pattern was used, in which the start of each line is shifted half a phase each time.
The advantage of the bottom image in Figure 12 is that the order of black and one is exactly the same as the order of 1's and 0's while counting binary. Therefore when the images obtained with the order shown in the top of Figure 12 are placed into an array these have to be converted into the order of the bottom image. In this way consecutive lines will have consecutive numbers.

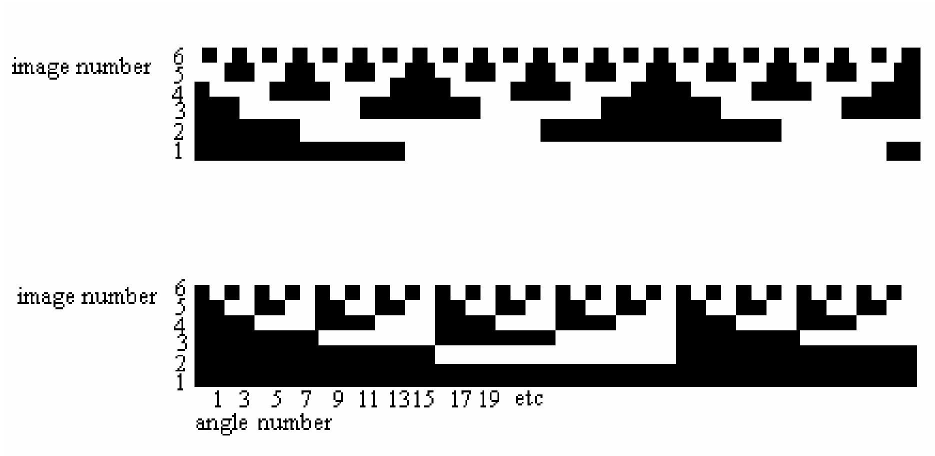

Figure 12: The binary pattern of the 10 images, top image ordered in such a way that no big errors can be made, bottom image in such a way that binary counting can be done easier.

Also a completely black and a completely white image were created. These were used to normalize all the images so errors like dead pixels in the CCD and dark spots on the skin are taken out automatically. The image used for calculating the height profile therefore was:

$$\frac{original\_image - black\_image}{white\_image - black\_image}$$

In this way also the contrast of the image was increased an example is shown in Figure 13. In the normalized image also the lines projected at the surface of the water are visible.

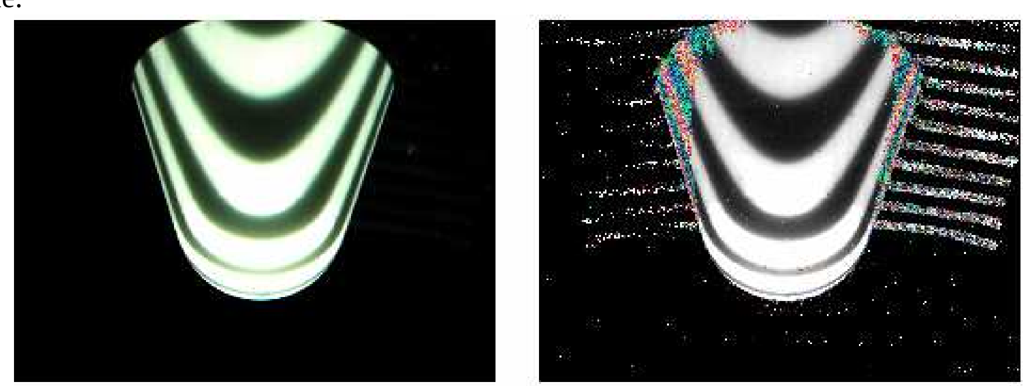

Figure 13: An example of the original image (left) and the normalized image (right) of a phantom. In the right image the projected pattern is also visible as a reflection of the water surface.

The cameras created full color images of the projected lines. A histogram could specify which color, red, green or blue was reflected best. Green resulted in having the best contrast, probably because of the best reflection by the skin. Another reason could be that each pixel has got 2 green subpixels and only subpixel for red and blue. This was tested by taking images of the skin of an elbow inserted into the tank. Therefore the threshold to determine which pixel would become black and which pixel would become white was determined by the amount of green in the image. All pixels with a higher value than 50% of the maximum value for green would become white, all other pixels would become black.

8. The Software

The software has been written in LabVIEW. It was decided to use LabVIEW instead of any other programming language because the expertise was available and the created software can be used easily.
A separate program has been made to project the patterns by the video projector and to capture the images by the camera.
Two other LabVIEW programs have been written to create height profiles out of the images taken. One LabVIEW program creates a calibration file to calculate the height at each point. The other LabVIEW program uses this file to calculate the height profile. Both VI's consist of several subvi's. One of these subvi's is inserted into both programs.

The LabVIEW program "create calibration file.vi" consists out of the following subvi's:
Create calibration file.vi
- PNG to Boolean.vi
- Directory file selector.vi
- To 24 bit subvi.vi
- Split RGB subvi.vi
- Normalization subvi.vi
- 3DScan_calibration.vi
- 3dScan_image_pattern_to_angle_number.vi

The "main.vi" LabVIEW program contains the following subvi's:
Main.vi
- Read calibration file.vi
- PNG to Boolean.vi
  - Directory file selector.vi
  - To 24 bit subvi.vi
  - Split RGB subvi.vi
  - Normalization subvi.vi
  - 3Dscan_depth_recon.vi
    - 3dscan_image_pattern_to_angle_number.vi
  - Height filter.vi

All the LabVIEW VI's and the subvi's will be explained in the next paragraphs. In Figure 14 a block diagram is shown of the most important parts of the programs to convert the images of patterns into a height profile.

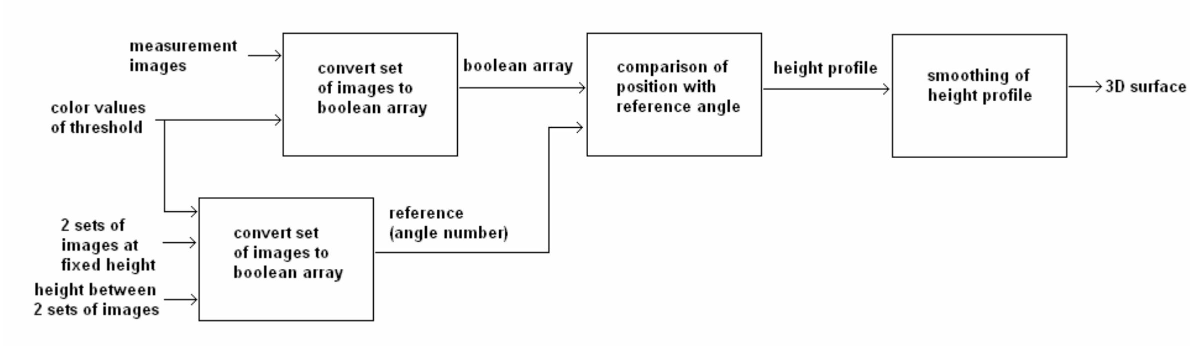

Figure 14: Block diagram of LabVIEW programs

A final separate vi has been written to analyze the data. This program is named data analysis.vi. This program will be explained in the last paragraph of this chapter.

8.1. Program to capture images

The BMP images which will be used to project onto the breast should all be placed into a certain folder before the LabVIEW program is opened. At the front panel of the LabVIEW program the images which should be projected can be selected. Also the order of projection of the images can be chosen.
While running the program the images are projected in sequence. A picture is captured with each camera, this does not happen simultaneously but in sequence. Using two cameras and twelve images the whole program lasts about 10 seconds. The captured images are displayed as thumbnails at the front panel.
As a default option the captured images are saved but this can be turned off. These images are saved in a certain folder which can be selected at the front panel. The images are saved as “name of projected image.bmp.cam#.png”.

8.2. Create calibration file.vi

Using two sets of images of horizontal planes this LabVIEW program calculates the angle gain and reference position calculated by 3DScan_calibration.vi. The values are saved as a .txt file which is used by the other LabVIEW program.

8.2.1. 3DScan_calibration.vi

The subVI 3DScan_calibration.vi creates a cluster of angle gain and reference positions out of the arrays of number of the two reference heights. These arrays of numbers are created by the subVI 3Dscan_image_pattern_to_angle_number.vi. The Boolean output of the PNG to Boolean.vi is used as an input for this subVI. In the first loop the used binary code is converted into “normal” binary numbers so consecutive lines get consecutive numbers. The second loop converts these numbers into digital numbers.

8.3. Main program

The main program creates the actual height profile of the object. The output of the main program is a 2D array of the height profile. This array is also shown in a 3D graph and can be saved as a text file.

8.3.1. Read calibration file.vi

The subVI opens the txt file created by the program crate calibration file.vi and converts the information into a cluster of angles and position.

8.3.2. 3dscan_depth_recon.vi

The subVI 3dscan_depth_recon.vi compares the angle numbers of the reference with the angle numbers of the image of the scanned object. With this information it calculates the height of the height of the scanned object. The angle numbers are created by the 3DScan_image_pattern_to_angle_number.vi subVI in the same way as it is done for the create calibration file.vi.

8.4. Height filter

The program height filter reduces the amount of errors in the height. Without this filter there are lots of errors at steep edges. This is because the lines come very close together at steep edges.
This subVI compares the value of one position, P(n), with the values of the positions directly before and after it, P(n-1) and P(n+1) respectively. P(n) should have a value which is at least the minimum value of P(n-1) and P(n+1) minus the difference between P(n-1) and P(n+1). The maximum value of P(n) should be the maximum value of P(n-1) and P(n+1) the difference between P(n-1) and P(n+1). When this is not the case the value of P(n) is replaced by the average value of P(n-1) and P(n+1).

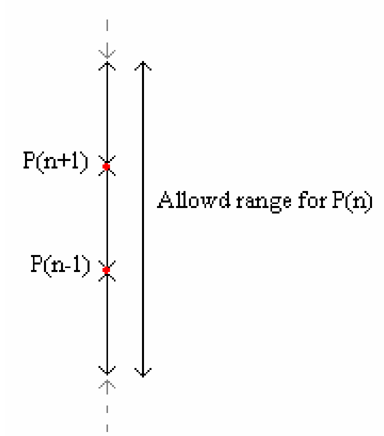

Figure 15: Schematic diagram showing the range to which the value of P(n) should belong.

The height filter is used in both x and y direction. This is done by first filtering in one direction, then transposing the array, filtering it in the other direction and afterwards transposing the array back again.

8.5. PNG_to_Boolean.vi

The subVI PNG to Boolean creates a 3D Boolean array of the selected images. The images are selected by the directory file selector.vi. PNG to Boolean.vi turns a pixel 1 when one of the thresholds is exceeded. The thresholds can be set separately for the values of the red, green and blue.

8.5.1. Directory file selector.vi

The subVI Directory file selector uses the dialog function which asks to select a certain folder. This folder should only contain the images of the lines projected onto the image.

8.5.2. To 24 bit.vi

The subVI to 24 bit.vi turns all selected images into a 24 bit image. In this way all images can be processed further in the same way.

8.5.3. Split RGB subvi.vi

The subVI Split RGB subvi.vi splits the signal of the color into its read, green and blue components using the split number function. In this way a separate threshold can be set for each of the three color components.

8.5.4. Normalization.vi

The subVI normalization.vi normalizes the values of the color. This is done by subtracting the measured value from the value of a total white image and dividing this value by the difference between of values of a white and black image. Thus, the outcome is the relative color intensity.

8.6. Data analysis.vi

The text file produced as an additional output in the program main.vi is used as an input for the program data analysis.vi. The same intensity graph as in main.vi is shown at the front panel of this program. A waveform graph is also visible at the front panel. This waveform graph shows a cross section of the intensity graph. Cursor lines are located on both graphs. The x, y and z position of a point can be determined with help of these cursors.

9. Calibration of the set-up

In order to get data with absolute values the set-up has to be calibrated. The height was defined from the top of the hole, the width and depth were defined from the camera's perspective. The cameras were not positioned at right angles to the top of the tank. Thus, this was a non-orthogonal system.

9.1. Calibration of height

The height was calibrated using two flat parallel planes. The patterns were projected onto these planes. Due to the divergent light of the video projector, the position of each light of white and block will be different at both planes. For each line of pixels the offset is calculated and the angle of the line between the two planes.

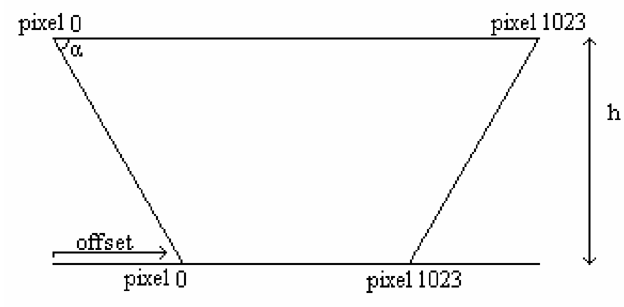

Figure 16: Schematic drawing of the two planes with the outer two pixel columns.

10. Test subjects

There was chosen to do a pilot study among about 50 volunteers. After this study there can be chosen to expand the test population and to perform a trial.

10.1. Acquisition

For a pilot study acquisition of test subjects was performed among the female employees of the High Tech Campus in Eindhoven. This was done by writing an e-mail to the female employees of the department and by hanging up notes at coffee machines and an invitation on the electronic bulletin board. This is an impersonal way so no social pressure is placed on the potential test subjects. This will ensure the participation on voluntary basis.
This population might give a bias because the working population is on average much younger than the population which will be screened on the mammography machine. But this pilot study will give an impression on the order of magnitude of the variety of breast shapes. Also a trend line in age might be visible. In a later study trial also (older) women from outside the High Tech Campus can be measured.

10.2. Inclusion and exclusion criteria

The aim of this project was to get an overall view of women's breasts. Therefore almost all women will be included in this experiment.
Additional information about the test subjects was collected via a questionnaire. During data analysis there could be decided whether or not certain criteria influence the breast shape significantly and should have been excluded from the experiment.

Inclusion criterion:

- Females with at least one breast

Exclusion criteria:
Women with the following criteria are excluded from the experiment:

- Age younger than 18
- Age older than 75
- Incapacitated
- Wounds and/or contagious diseases of the skin at the breast surface
- Pregnant
- Pain in back or neck

11. Method

After the set-up had been developed and tested with small objects and the test subjects had been recruited, the real experiment could start.
The experiment was performed according to the protocol described in Appendix E. The informed consent, shown in Appendix G, was discussed with the test subjects before performing the experiment and the test subjects were asked to sign it. Then the test subjects were asked to answer the questions of the questionnaire, a copy is shown in Appendix H.
After that the test subjects would lay down on the measurement bed and the actual measurements would be performed.

Most test subjects were only measured once. Some test subjects were measured several times in order to test the reproducibility of the measurement and to test the intrasubject variance.

12. Performed statistics

12.1. Measurement of bra cup size

The bra cup size was measured by measuring the chest circumference directly underneath the breast, which indicates the number of the bra size, and measuring the band size (that is the maximum chest circumference) usually at nipple height, as shown in Figure 17. This was done while the volunteers stood up straight. The letter of the bra size, (cup size) was calculated by the difference between the band size and chest size. A difference of 12 indicated a size A, a difference of 14 indicated a size B and so on. To compare measured circumference differences with the cup sizes of the worn bra's, the worn bra cup size is also expressed as a number in the graphs shown in chapter 13.

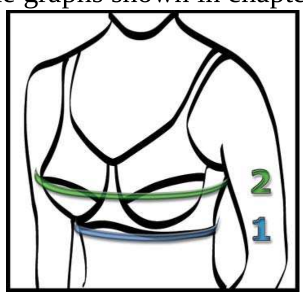

Figure 17: The size (1, blue) and maximum circumference (2, green).[9]

12.2. Measuring breast dimensions

Breast dimensions were measured using the LabVIEW program data analysis.vi. The height map created in the program main.vi was used as an input for this program. A waveform graph with cursors was used to measure the height at each position. This had to be done manually because not all measurement errors (noise) had been filtered out. Taking the maximum height value for the height of the breast, would result in indicating to an error. A screenshot of a waveform graph is shown in Figure 18. In the shape of the waveform graph it could easily be seen what was an error and where the real maximum of the graph was located.

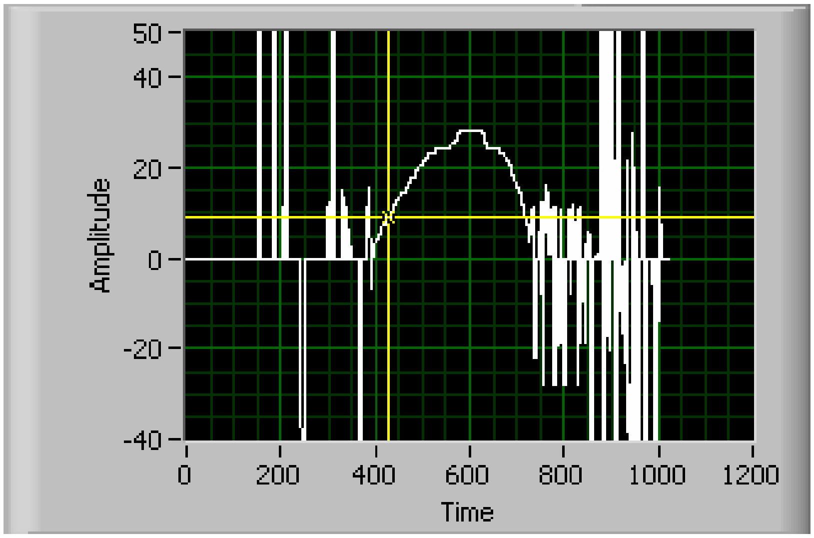

Figure 18: A waveform graph which shows a cross-section of the measured breast. Clearly visible are the nipple and the noise at the sides of the breast.

12.2.1. Full width half maximum

The full width half maximum (FWHM) is the width of a graph at the amplitude of ½ f_{max} as shown in Figure 19. This number can indicate for the curvature of the graph when the height is the same and the width at ground level is either hard to determine or the same for all objects as well.

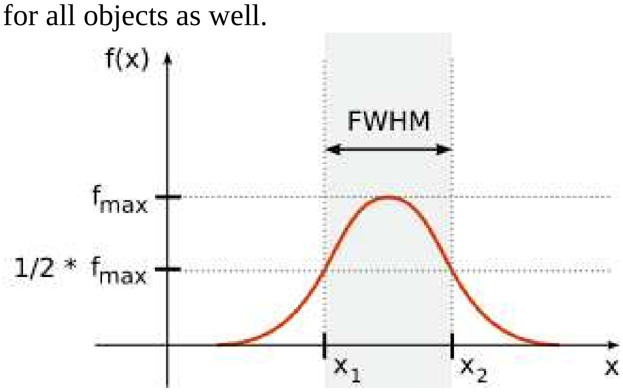

Figure 19: The full width half maximum of a curve.[10]

For these calculations the base level of the graph should be defined. In this experiment this base level was defined as 43 mm above the highest calibration height. This height is located at about the top of the table.

12.2.2. Aspect ratio

The aspect ratio is the ratio between the height and the width of an object. The width at the base was very hard to estimate due to the shape. Therefore the aspect ratio between the height and the FWHM was calculated.

13. Results

13.1. Description of the tested population

In total 18 test subjects have been measured. Three of the test subjects have been measured three times in two days to test the reproducibility of the measurement.
The characteristics of the population are described in Table 1. For all characteristics the data of all volunteers were used, except for the measurements of the % in periodic cycle, this was only known for 13 women. The maximum for periodic cycle is higher than 100% because one volunteer continued with a second strip of contraceptive pills directly after having finished a first strip of contraceptive pills.

Characteristic	Minimum	Maximum	Average	Standard deviation	Median
Age (years)	23	48	30	7	29
BMI (kg/m^2)	17.5	26.8	21.4	2.2	21.8
Bra size letter	A	D	NA	NA	B
Bra size number	70	85	NA	NA	75
Measured chest circumference (cm)	71	84	77	4.8	77
Measured band circumference (cm)	78	98	88	7.2	89
Circumference difference (cm)	6	17	11	11	3.4
Volume measured (ml)	195	540	392	129	440
% of cycle	14%	114%	52.3%	35.3%	41.1%

Table 1: The main characteristics of the tested population.

Fifteen volunteers described themselves as being Caucasian, one being a mix of Caucasian/East-Asian, one as East-Asian and one as a mix of Caucasian and Suriname.
None of the volunteers had reached menopause yet, though one volunteer had an irregular hormonal values due to removed ovaries after cervical cancer. None of the volunteers has had any kind of breast surgery. Five volunteers have been pregnant, all five have also nursed. They have nursed for 7 to 16 months (cumulative). None of the women who have been pregnant used hormonal medicine at the time of the measurements. Of the other 13 women 9 used a form of contraceptive pills and one woman used Livial, a tibolone containing drug. The three other women did not use any type of hormonal medicine.

13.2. Used bra size versus measured bra size

The calculated correlation between chest circumference and bra number seems to be low, R^2=0.45. But when the theoretical bra number (i.e. the correct bra number for ones chest circumference) is used, the correlation is R^2=0.52. Because the correlation could not have been bigger than this, the correlation between measured chest circumference and bra number could be considered high. In fact that out of all 18 volunteers 10 wore a bra with a theoretically correct circumference, 5 wore a bra which was theoretically too small and 3 wore a bra which was theoretically too big.

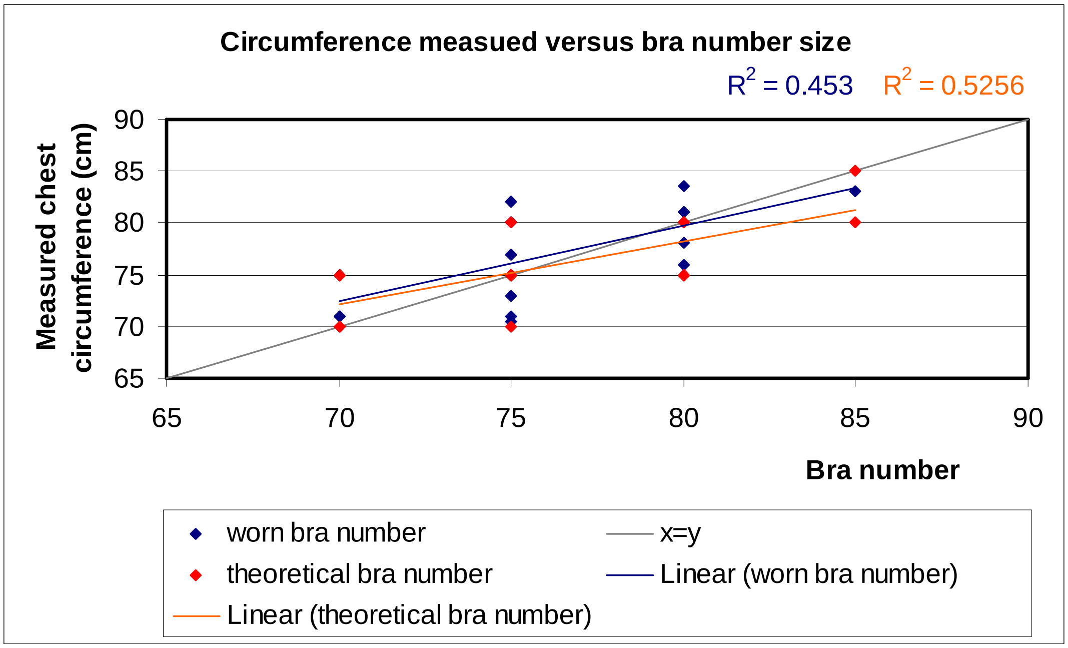

Figure 20: The correlation between the measured bra number size and the actual bra number size

The bra letter is derived from the difference between chest and band circumference. But there is hardly any correlation measurable between these two values as R^2=0.08.
Almost all women wore a bra with a theoretically too big cup size. When a linear equation between the worn cup size and the actual circumference difference is compared to the equation of the theoretical cup size and the actual circumference difference there is a difference in outcome which varies from 22-25%, depending on the actual cup size. This means there is a stable difference between these two measurements.

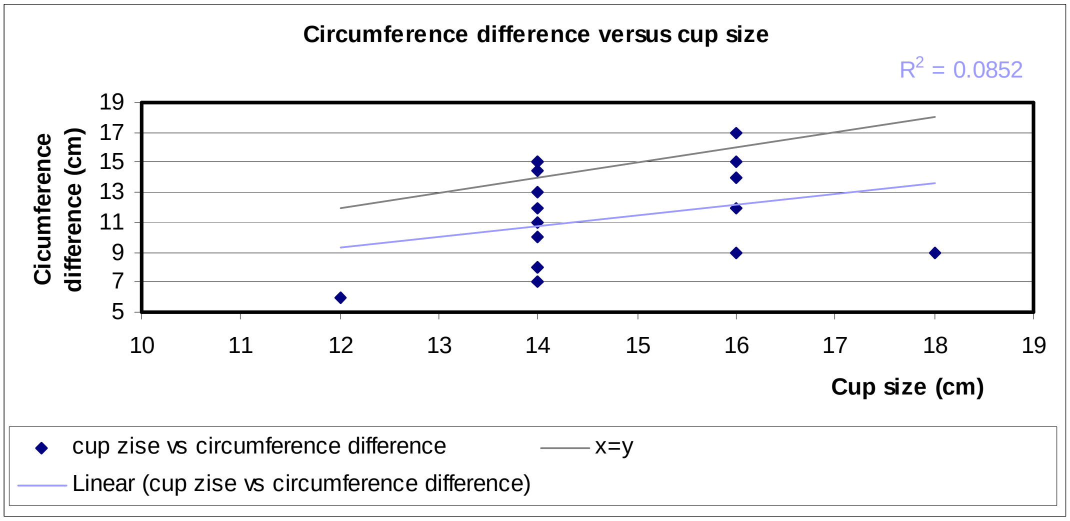

Figure 21: The correlation between the measured cup size and the actual cup size.

13.2.1. Breast volume

Some of the water poured out of the tank while the breast was suspended into the tank. This water was collected was to get an indication of the breast volume. The volume of the breast can also be estimated when the bra size is known. In this case a size 75C equals 80B and 85A. Bra size 70 C equals 75 B and 80 A and so on. The correlation between the measured amount of water and the bra size is shown in Figure 22.

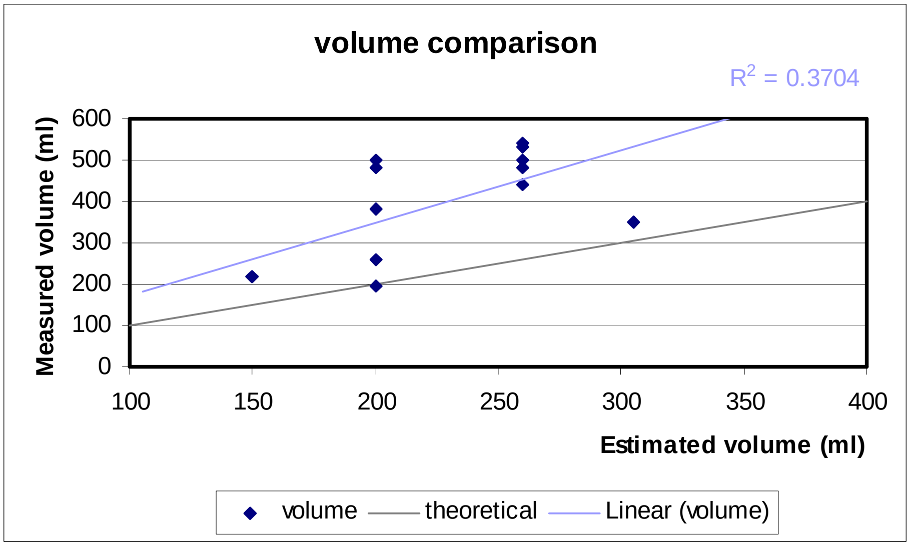

Figure 22: The measured volume which floated out of the tank during measurements versus the estimated breast volume according to the bra size.

In all but 1 case the measured volume was larger than the expected volume.

13.3. Breast dimensions

13.3.1. Height of the breast

The height of the breast was determined including the nipple. In most cases the nipple was fully erected but not in all cases. There was not distinguished between these variations. In Figure 23 the measured height is compared with the cup size and the measured circumference differences, i.e. the theoretical cup size. The cup size being described by a number as explained in paragraph 12.1.

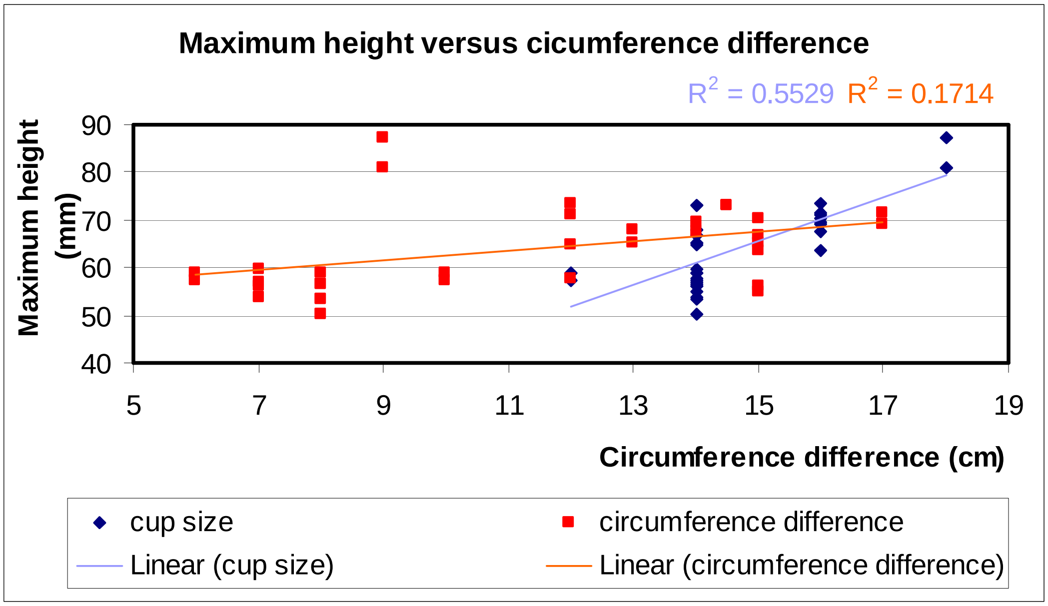

Figure 23: The maximum height as function of the cup size (blue) and measured circumference difference (red).

The graphs in Figure 23 show a higher correlation between the given bra size and measured height (blue) than between the measured circumference difference and height (red). The averages and standard deviations of the breast's height per cup size and for the total tested population are shown in Table 2.

Cup	Number of breasts measured	Average height (mm)	Maximum height (mm)	Minimum height (mm)	Standard deviation (mm)	Mean (mm)
A	2	58.1	58.8	57.3	1.1	58.0
B	22	60.3	73.1	50.3	6.5	60.0
C	10	69.5	73.3	63.8	2.9	69.5
D	2	84.0	87.1	80.8	4.5	59.3

Table 2: The averages and standard deviations of the height measurement.

The maximum height was also plotted versus the bra number and measured chest circumference as shown in Figure 24. In this case the correlation was higher with the measured circumference than with the given bra size.

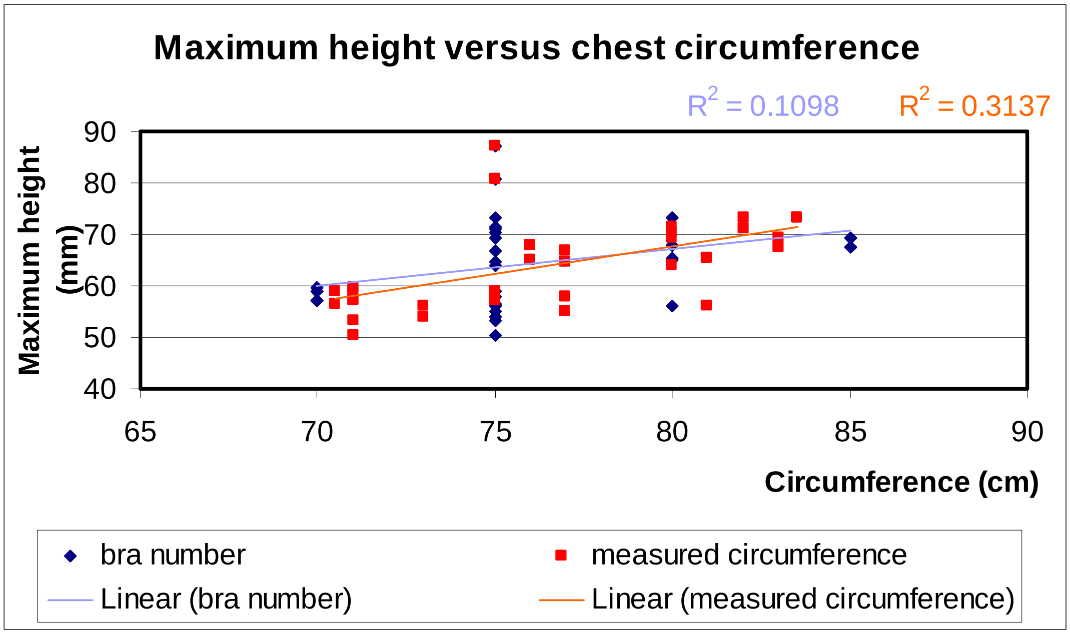

Figure 24: The maximum height as function of the bra number (blue) and measured chest circumference (red).

Third, the correlation between the expected breast volume and the maximum height was determined. The breast's volume was estimated by a combination of the bra letter and number. This is shown in Figure 25.

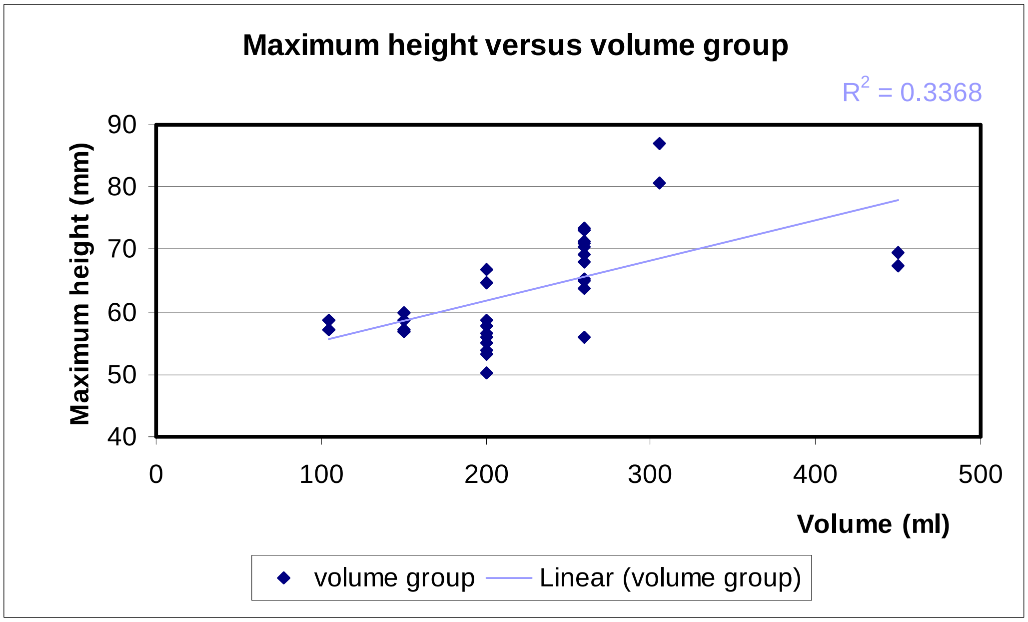

Figure 25: The maximum height as function of the expected volume of the breast.

13.3.2. Full width half maximum

The FWHM was plotted against the bra cup size, bra number size and estimated breast volume, as shown in the graphs in Appendix I, to determine which parameter would give the best indication for the FWHM. These graphs were made for the left and the right breast separately. The left breast was measured form the lateral side, whereas the right breast was measured from the medial side. None of the parameters showed a clear correlation, bra cup size showed least low correlation with FWHM.
No real statistics could be performed on cup sizes A and D since only one left breast of cup size A and D were measured and one right breast of cup size A and D were measured. Size A and D are included in the tables to make up for the totals.
The averages and standard deviations per cup size are shown in Table 3 and Table 4.

Cup size	Number of breasts measured	Average FWHM (mm)	Max FWHM (mm)	Minimum FWHM (mm)	Standard deviation (mm)	Mean FWHM (mm)
A	1	74.7	74.7	74.7	NA	74.7
B	10	77.3	103.8	61.3	14.3	76.1
C	4	64.8	79.5	33.2	21.8	61.3
D	1	105.4	105.4	105.4	NA	105.4
Total	16	75.8	105.4	33.2	17.6	73.5

Table 3: The averages and standard deviations of the FWHM measurement of the left breasts.

Cup size	Number of breasts measured	Average FWHM (mm)	Max FWHM (mm)	Minimum FWHM (mm)	Standard deviation (mm)	Mean FWHM (mm)
A	1	76.2	76.2	76.2	NA	76.2
B	9	65.4	88.9	5.3	26.3	53.5
C	4	84.8	96.2	70.9	11.2	84.2
D	1	111.1	111.1	111.1	NA	111.1
total	15	74.3	111.1	5.3	24.5	64.9

Table 4: The averages and standard deviations of the FWHM measurement of the right breasts.

13.3.3. Aspect ratio

The FWHM was analyzed for the left and the right breast separately. Therefore the aspect ratio had to be calculated for the left and right breast separately as well. The average and standard deviations of the aspect ratio per cup size and in total are shown in Table 5 and Table 6.

Cup size	Number of breasts measured	Average aspect ratio (mm)	Maximum aspect ratio (mm)	Minimum aspect ratio (mm)	Standard deviation (mm)	Mean aspect ratio (mm)
A	2	1.271	1.271	1.271	NA	1.271
B	10	1.303	1.600	0.942	0.235	1.283
C	4	0.965	1.247	0.467	0.352	0.903
D	1	1.304	1.304	1.304	NA	1.304
total	16	1.216	1.600	0.467	0.284	1.176

Table 5: The calculated averages and standard deviation of the aspect ratio between height and FWHM of the left breasts.

Cup size	Number of breasts measured	Average aspect ratio (mm)	Maximum aspect ratio (mm)	Minimum aspect ratio (mm)	Standard deviation (mm)	Mean aspect ratio (mm)
A	1	1.330	1.330	1.330	NA	1.330
B	9	1.085	1.517	0.089	0.430	0.893
C	4	1.195	1.368	0.993	0.175	1.185
D	1	1.275	1.275	1.275	NA	1.275
total	14	1.143	1.517	0.089	0.345	1.013

Table 6: The calculated averages and standard deviation of the aspect ratio between height and FWHM of the right breasts.

13.4. Reproducibility

The reproducibility was tested by measuring 3 volunteers three times in total. The first time they were measured only once. The second time these volunteers were measured twice, both trials directly after each other. That is, the left breast was measured, the women repositioned to have the right breast measured and then directly afterwards the left and right breast were measured again, without the volunteer leaving the bed in between the measurements.
Paired T-tests were performed to compare these three sets of measurements. The outcomes of the T-tests are shown in Table 7. The higher the number, the greater the chance that the two sets of data are the same.

	Trial 1-Trial 2	Trial 1- Trial 3	Trial 2-Trial 3
Height	0.24	0.35	0.96
FWHM	0.80	0.71	0.31
Aspect ratio	0.75	0.73	0.38

Table 7: The outcome of T-tests when the three trials with three test subjects (6 breasts in total) are compared. Trial 1 was performed 10 days before trial 2 and 3.

Comparing the outcome of the comparisons for height, it looks like the test is reproducible when measured directly after each other. But the tests are not reproducible when comparing two different days.
The combination of trial 2 and 3 is the combination with least similarities for the FWHM. As trial 2 and 3 are supposed to be most similar data sets, this could mean that the FWHM is very hard to reproduce.

14. Discussion

14.1. Calculating the bra size

Tables of how to measure bra size can be found on websites of bra selling or producing companies. The chest circumference measured directly underneath the breasts should correspond with the bra number. The difference between the maximum chest circumference (also called band width, found at about nipple height) and the prior defined chest circumference should indicate the bra letter. A difference of 12 cm equals size A, 14 cm equals size B and so on. These circumferences should be measured while wearing the best fit bra. The band width should be measured while keeping the tape line quite loose.
These instructions are hard to reproduce. Therefore an alternative way of checking the bra size was used. Instead of a loose tape line a tape line with automatic tensioning was used. But this results in a compression of the breast, which might be different for women with relatively more fat or glandular tissue.
Some breasts also tend to be suspended more when they are not supported by a bra than other breasts. This could also influence the measurement of the band width. Instead of predicting a maximum height using cup size there could be looked if the maximum height can be predicted by measuring the height of the breast when the woman bends forward.

14.2. Difference between right and left breast

A T-test has shown that the height of the left breast could not be compared with the height of the right breast. In 13 out of 18 cases the height of the right breast was bigger than that of the left breast. Thus there was a clear asymmetry in the results. In future experiments the right- or left handedness of the subject might be noted, to test if this height difference is caused by an asymmetrical development of the m. pectoralis major.
Another reason for this asymmetry could be that the data of only one camera were used. Although the maximum height measured should be the same seen from both cameras.

14.3. Reproducability

In the reproducibility tests it turned out that the height was reproducible on the same day. But the tests showed they were not reproducible at different days. The FWHM was however not reproducible on the same day. This could indicate that right positioning of the test subject is very important.

14.4. Volume measurement

The volume of the breast was measured indirectly. It was measured by measuring the overflow of water when the test subject would lie on the bed. This flow was not measured in between the measurement of both breasts, but only at the end of the whole experiment. Therefore, only the maximum breast volume of each test subject was measured.
But the measured volume was more than the theoretical estimated volume. It could be

that more water was spilled out of the tank than the volume of the breast. But this should have been visible on the pictures. It could also be that the used table for estimation of breast volume according to bra size was not correct. This could be checked by estimating the total breast volume from the pictures.

14.5. Possible future research

While performing the research many different questions were raised. Some of these questions can be answered in the future by performing more experiments. These questions will be discussed in the following paragraphs.

14.5.1. Influence of breathing

Small fluctuations in water level in the gauge were visible during each measurement. These frequency of these fluctuations corresponded to the frequency of breath. This indicates a volume change during each measurement. The test subjects were not asked to hold there breaths during the measurement because during a real mammography test it will be impossible to hold ones breathe as the measurement takes about 15 minutes. Thus, these fluctuations will also take place in reality.
In the future there could be tested how much the difference in volume is. This could be done by comparing measurements with of completely breathed in and completely breathed out, while subjects held there breathe during the complete measurement.

14.5.2. Influence of time

Since a real mammography measurement takes about 15 minutes, time might influence the shape of the breast as well. It could be possible that the shape of the breast changes when the breast is suspended for 15 minutes. This could happen when gravitational forces have influence on the amount of blood in the breast since the venous valves are absent in veins in the ventral body cavity.
Therefore the shape of the breast should also be measured when it has been suspended for 15 minutes. Also intermediate times could be measured and compared.
For this follow-up experiment it might be better to improve the fluid in which is measured. The fluid should match the fluid which is used in the mammography machine in more ways. For example not only the density but also the viscosity might influence the shape of the breast.

14.5.3. Extra calculations on size

Instead of measuring only full width half maximum also the width at other height percentages (e.g. quarter height) can be measured.
The FWHM was now measured at the cross-section halfway the cup. When the shape of the breast was not symmetrical or when the breast was not positioned exactly in the middle of the hole, the measured FWHM would not have been the true FWHM.

14.5.4. Use of bigger insert rings

The measured chest circumference ranged between 71 and 84. When assumed that the chest has got an anterior posterior mirror image in transverse plane, the base of the two breasts is spread out over a distance of less than 36 to 42 cm. For each breast this would mean a maximum possible base width ranging from 18 to 21 cm. This is much bigger than the diameter of the used insert, which was 12.5 cm. Therefore tests should be performed using bigger rings as well. To see if the breast can be inserted deeper into the hole but still with a limited amount of movement freedom, so the positioning is reproducible.

15. Conclusion

A measurement device has been build with which the 3D shape of objects in water can be measured. The objects' maximum size can be about 20x20x25 cm^3 and the actual measurements can be performed within 10 seconds.
A set of 36 breasts, 18 volunteers, has been successfully measured. There is a high correlation between the bra cup size and the height of the breast. On average the breasts are suspended 64 mm into the hole. Breasts of a cup D size are suspended about 2 cm deeper into the water than breasts of a cup A size.
All measured breasts fitted into a ring of 12.5 cm diameter. No correlation could be found between the FWHM and form of bra or chest circumference measurement. The average FWHM is 7.6 cm, its standard deviation being 2.2 cm.
Having given birth or having nursed babies does not seem to have an influence on the breast's shape. Also using contraceptive medicine does not seem to have influence on the breast's shape.

References

1. www.kwfkankerbestrijding.nl
2. D.B. Kopans, J.E. Meyer, and N Sadowsky, “Breast imaging”, Volume 310 (1984) 960-967
3. www.borstkanker.net
4. Nielsen et.al. “Image reconstruction and evaluation of system performance for optical fluorescence tomography”, Proc. SPIE 6431 Multimodal Biomedical Imaging II, Fred S. Azar, Ed., 643108 (Feb. 7, 2007)
5. Beraldin et. Al. “Active 3D sensing”, Modelli E Metodi per lo studio e la conservazione dell’architettura storica, 10 (2000) 22-46
6. Besl Paul, “Active, Optical Range Image sensors” Machine Vision and Applications 1 (1988) 127-152
7. J.Y. Bouguet and P. Perona “3D photography on your desk” Computer vision (1998) 43-50
8. J.Y. Bouguet “3D Photography Using Shadows” proceedings ISCAS98 Monterey, California June 3rd, 1998
9. www.blooberry.com
10. http://en.wikipedia.org/wiki/FWHM
11. Pedrotti et al “Introduction to Optics” Prentice Hall Inc. 1993 Upper Saddle River, NJ, USA
12. Melles Griot Optics Zevenaar, The Netherlands1995/1996
13. http://www.simetric.co.uk/si_water.htm
14. http://www.sciencebyjones.com/Laboratory%20Glassware%202004.htm
15. E. N. Marieb, “Human Anatomy & Physiology” Addison Wesley Longman 1999

A Definition of the x,y,z coordinates

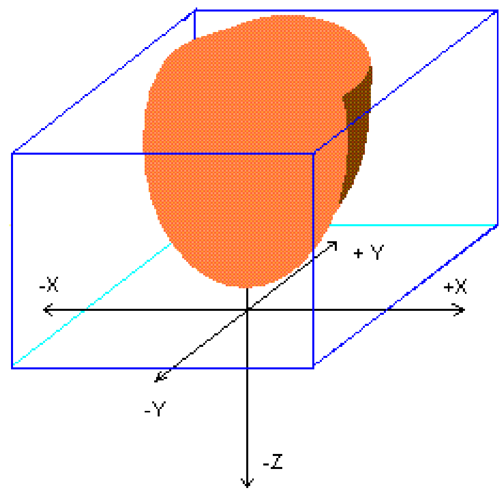

Figure 26: The tank with breast suspended and the used x,y,z coordinate system. The centre of the bottom of the tank is the origin of the coordinate system. All three directions are at perpendicular angles.

B Calculation on the lens system

When the size of the CCD screen, the width of the object (at focal length) and the minimum and maximum depth of focus are known, the required focus and focal length of the objective lens can be determined. By either choosing the diaphragm or circle of confusion the other one can be determined as well.[11]

When:

C	circle of confusion
D_n	minimum focal length
D_f	maximum focal length
f	average focal length
N	diaphragm
S	focus

The focus is determined by:

$$S = \frac{2 * D_n * D_f}{D_n * D_f}$$

The focal length is determined by:

$$f = \frac{width\_CCD\_screen * S}{object\_width}$$

The diaphragm needed for the appropriate depth of focus can be calculated by:

$$N = \frac{f}{A}$$

With A being the diameter of the diaphragm which is proportional with C, D_n and S:

$$C = A * \frac{abs(D_n - S)}{D_n}$$

Combining these equations leads to:

$$N = \frac{f}{\dfrac{C}{abs(D_n - S)/D_n}} = \frac{f * abs(D_n - S)}{D_n * C}$$

With a fixed diaphragm, the circle of confusion can be determined as well:

$$C = \frac{f}{N} * \frac{abs(D_n - S)}{D_n}$$

The above mentioned formulas are correct when the light beam travels through one medium, for instance air. When the light beam travels through air and water, the direction of the light beam is changed. This causes that another focus and focus length are needed and thus changes the circle of confusion as well. To determine the appropriate values the formulas have to be changed in order to take in account the distance traveled in each medium and the refraction index of the medium. This would lead into the following adjustments of the formulas.

The path of light traveled through water has to be adjusted by the refractive index of water.
When:
l_{air} the part of the distance to D_n or D_f in air
n refractive index of water

Then the D_n and the D_f which have to be used for calculations will be:

$$D_n = \frac{(D_n - l_{air})}{n} + l_{air}$$

and

$$D_f = \frac{(D_f - l_{air})}{n} + l_{air}$$

With these new values of D_n and D_f the appropriate focus can be calculated and with this new value for S also the new focal length can be calculated.
Also the circle of confusion is changed by the refractive index of water. Therefore, the circle of confusion has to be divided by the refractive index in order to get the right circle of confusion to calculate the diaphragm needed.

In this case the original D_n and D_f are 329 mm and 465 mm. The distance from the tank to the camera will be 264 mm.
There is made use of a camera with a 2/3” CCD screen, which means the screen is 6.6 mm high and 8.8 mm wide. The breasts which will be measured are expected to be maximum 200 mm high and 250 mm wide. The CCD does not have the height to width ratio as the expected height to width ratio of the breast. When for the calculations the height is used, the width is expected to fit automatically as well.
In this case the lens will need a focus, S, of 359 mm, a focal length, f, of 11.8 mm and the minimum diaphragm, N, needed is 4.4 when the circle of confusion is 0.5 mm.

C Calculation of the optimum thickness of the layer of fused silica

The aluminum coating of the mirror has to be protected by a layer of fused silica (SiO_2). But this layer reflects the images as well. Therefore the thickness of the layer has to be chosen in such a way that there is 1 λ difference in path length. In this way the there will be constructive interference.

The thickness and the variables are displayed in Figure 27.

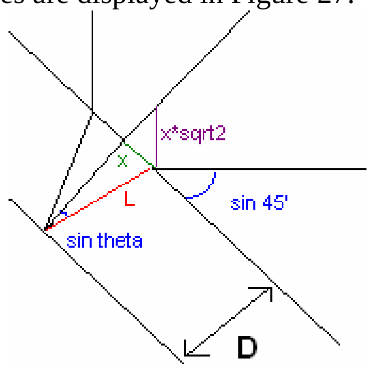

Figure 27: Schematic drawing of the pathway of a light beam through the layer of fused silica. Mentioned are the angles and distances required to determine to required thickness of the fused silica.

The light hits the mirror at an angle of 45˚. Figure 27 makes clear that:

$$\sin 45 = \frac{1}{2}\sqrt{2} = n \sin\theta$$

$$\cos\theta = \frac{D}{l}$$

$$\sin\theta = \frac{x}{l}$$

$$l_{air} = x\sqrt{2}$$

$$\lambda = 2nl - l_{air}$$

From the formulas above there can be derived that:

$$\lambda = D\left(\frac{2n}{\cos\theta} - \sqrt{2}\tan\theta\right)$$

And

$$\theta = \arcsin\left(\frac{\sqrt{2}}{2n}\right)$$

Together this is:

$$D = \frac{\lambda}{\frac{2n}{\cos\left(\arcsin\left(\frac{\sqrt{2}}{2n}\right)\right)} - \sqrt{2}\tan\left(\arcsin\left(\frac{\sqrt{2}}{2n}\right)\right)}$$

The refractive index of fused silica is 1.46. The wavelength used is 550 nm.[12] This is the average wave length of the visible spectrum. Therefore the thickness of the layer of fused silica should be 215 nm.

D Procedure and results of calculation of the density of matching fluid

D.1 Procedure

Several items of volume measuring equipment were weighed empty and filled with different volumes of the matching fluid. The items used were:

- Vol flasks, brands: Hirschmann, Fortune and Winzer
- Syringe 60 ml
- Graduated cylinder 250 ml
- Beakers 80 ml, brands: Fischer and Schott

Each vol flask was filled and weighed twice. The syringe was filled completely, than the air was taken out and the weighed was measured at 12 volumes. The graduated cylinder was filled 5 times and weighed. The graduated cylinder was also three times filled up to 200 gr and the volume was read afterwards. The beakers were filled twice with volumes of 20 ml, 40 ml, 60 ml and 80 ml.
The procedure was repeated for tap water as well. This was to check the validity of the procedure by comparing the calculated density to the density mentioned in tables.
All measurements were performed at 20,8˚C.

D.2 Results

The measured density for tap water was closest to the literature values[13,14] for the measurements in the vol flasks. The least accurate measurements were performed with the beakers.

	density (gr/ml)		relative density	
	water	**matching fluid**	**matching fluid/water**	**water compared to theoretic value**
vol flask 25 ml				
Hirschmann	0.9961	1.0072	101.12%	99.81%
Fortune	0.9951	1.0095	101.44%	99.71%
Winzer	0.9980	1.0080	101.00%	100.00%
Syringe				
range 15-20 ml	1.0253	1.0270	100.16%	102.74%
range 35-40 ml	1.0041	1.0043	100.02%	100.61%
all measurements	1.0147	1.0156	100.09%	101.67%
Graduated cylinder 250 ml				
Fixed volume	0.9910	0.9988	100.78%	99.30%
Fixed weighed	1.0260	1.0219	99.60%	102.81%
Beaker				
Fischer	0.9548	0.9488	99.38%	95.67%
Schott	0.9163	0.8617	94.04%	91.81%

Table 8: The measured density and relative density for the different measurements.

D.3 Discussion

The meniscus of the matching fluid is not visible due to the non transparency of the fluid. Therefore the volume measurements of the matching fluid must have been less accurate than the volume measurements of water. The diameter of the cylinder and beakers is larger than the diameter of the vol flasks, thus creating a bigger meniscus. This is another reason why the vol flasks would have given the most accurate measurements.

The more accurate the measuring equipment, the higher the relative density of matching fluid compared to water.

E Design of the set-up in Autodesk Inventor

Figure 28: Top view of the set-up as designed in Autodesk Inventor. The ring around the opening is clearly visible. Also some extra lines (yellow and red) are shown which show the centre of the field of vision of the video projector and the cameras. These lines were needed to calculate distances between separate parts of the set-up.

Figure 29: Bottom view of the set-up as designed in Autodesk Inventor. Notice the extra beams underneath the table to strengthen it. In this picture is also visible how the video projector is connected to the table and the tank.

F Protocol

Test number	
Title	The shape of breasts suspended in water
Date of experiment	15-06-2007 – 15-07-2007
Investigators	Selma de Kleijn, Wouter Rensen
Observer	t.b.d.
Project	Diffuse Optical Tomography
Number of subjects	Up to 50
Test persons	Employees at the High Tech Campus
Frequency	1 measurement (some test subjects measured more often)
Time needed per session	About 15 minutes
Pre treatment	None
Compensation	None

Aim of the test

Primary Objective: The purpose of this research is to measure and describe the shape (contour) of the breast when suspended in a liquid (water). Depending on the relative density of the fluid and the breast, the breast could either be floating or "sinking". These measurements can be used to determine the optimum shape of the inserts for the Philips optical mammography system.[1]

Secondary Objective: The knowledge of the coordinates of the breasts when suspended into a liquid can be used to improve other parts of the optical mammography system as well. For instance, the time needed for rendering an image can be decreased when the position of the breast can be estimated.

Compliance

The study will be conducted in compliance with this protocol, in the spirit of Good Clinical Practice, and applicable regulatory requirement(s).

Benefits and Risks

The results from this study may help improve the sensitivity of the optical mammography system being developed by Philips.

There are no direct benefits for the volunteers participating in this study.

There are no specific risks associated with this study.

Existing knowledge

There are no published studies of the shape of breast in fluids. There are several studies[2, 3] published in which 3D images are created by using a video projector and one or several cameras. Some of these methods have also been used to create 3D images of parts of the human body.

Selection test subjects
All healthy women aged between 18 and 75 may participate in this study. The test subjects will be recruited at the High Tech Campus in Eindhoven, The Netherlands.

Inclusion criteria: Female with at least one breast

Exclusion criteria:
- Age younger than 18
- Age older than 75
- Incapacitated persons
- Wounds and/or contagious diseases of the skin at the breast surface
- Pregnancy
- Pain in back or neck

Measurement positions
In upright position: measurement of chest circumference
In prone position on “bed”: breast surface

Measurement session
The subject will be given a questionnaire (see Appendix) with short questions about the possible confounders.
Chest circumference will be measured at two different heights.
During the study the test subject will lie on a “bed” with a hole in the mattress, one of her breasts suspended in a transparent tank filled with lukewarm water. 12 different black and white line patterns are projected onto the breast and will be photographed by two cameras. This will be repeated for the other breast as well.
An observer will be sitting in the room where the experiment is performed.

Equipment
“Bed” with a hole in the mattress. Below the hole is a transparent tank filled with lukewarm water. A projector connected to a pc is positioned underneath the bed to project patterns on the breast that is suspended in the water tank. Also underneath the bed are two video cameras connected to a pc that can record images of the patterns projected on the breast.
Measuring band for measuring chest circumference

Randomization
Each test subject is given a unique, random subject number to connect the measurements and the questionnaire.
A list of names and contact addresses of all test subjects together with their subject number is stored on a separate file. In this way the subjects can be traced back if necessary. This information will be kept in a locked cabinet and only the researchers will have access to this cabinet.
The raw data will be stored with the subject numbers on a pc with a back-up on another pc. The pc's are secured by a password and the files with data are protected by a password as well. Only the researchers know these passwords.

Ethics
The study will be conducted in accordance with the ethical principles that have their origin in the ICH-GCP Guidelines of 17 January 1997.

Analysis
The study design will be a cross-sectional observational study. In principle all test subjects are measured once and they are all measured in the same way.
A few test subjects will be measured several times to examine the reproducibility of the study.
All test subjects will be measured within a period of one month.

In first instance the height of the breast and the radius perpendicular to the height are measured. Average values and standard deviations will be calculated.

Univariate analysis
Correlation of the parameters below with 3D size and shape of breasts:

- Bra cup size
- Bra circumference size
- Estimated volume (a combination of cup and circumference sizes)
- Measured circumference size
- Calculated bra cup size (calculated out of two measured circumferences)
- Calculated estimated volume

Multivariate analysis
No multivariate analysis will be performed due to the limited amount of test subjects.

Insurance
Philips has a world-wide liability insurance that covers compensation for trial related injuries or property damage for experiments for which the company is legally responsible. Contact person: Jeroen Pax, tel. 040-2784505

References

1. Nielsen et. al. "Image reconstruction and evaluation of system performance for optical fluorescence tomography", Proc. SPIE 6431 Multimodal Biomedical Imaging II, Fred S. Azar, Ed., 643108 (Feb. 7, 2007)
2. Sinlapeecheewa C, Takamasu K. 3D profile measurement using color multi-line. Integrated Computer-Aided Engineering;12-2005:333–341.
3. Valkenburg RJ, McIvor AM. Accurate 3D measurement using a structured light system. Image and Vision Computing;16-1998:99-110.

G Informed conscent

Consent form for participation in a research study of the

Biomedical Photonics group, Philips Research

The shape of breasts suspended in water

Description of the research and your participation
You are invited to participate in a research study conducted by Wouter Rensen en Selma de Kleijn. The purpose of this research is to determine the shape of breasts suspended in water.

Your participation will involve answering a questionnaire (see Appendix) with short questions about the possible facts which might influence the results of the study.
Your chest circumference will be measured at two different heights.
During the study you will lie on a “bed” with a hole in the mattress through which one of your breasts is suspended into a glass tank filled with lukewarm water. Halfway the study you will change position in such a way that your other breast is suspended into the hole. 12 different black and white patterns will be projected onto your breasts. Pictures of these patterns will be taken by two cameras. The deformation of the pattern on the breast will be used to calculate the 3D shape of the breast.

The amount of time required for your participation will be approximately 15 minutes.

Risks and discomforts
There are no health risks or discomforts related to this experiment.

Potential benefits
There are no benefits for the test subjects. Results from this research will help us to improve the new mammography machine.

Protection of confidentiality
We will do everything we can to protect your privacy. For example, we will make data anonymous, store it in closed filing cabinets, destroy data (such as images or video tapes) that are not useful, etc. Your identity will not be revealed in any publication that might result from this study.

Insurance
Philips has adequate insurance covering liability for health impairment and property damage occurring as a result of participation in the study.

Qualified Physician

The Philips Research Company doctor is available to provide medical care related to clinical trial results and health impairments occurring as a result from participation.

Name: Dhr. Engels

Telephone number: 040 – 2742390

Cost/Payment

There will be no cost to you to take part in this study, other than your time. You will not be paid to participate in this study.

Voluntary participation

Your participation in this research study is voluntary. You may choose not to participate and you may withdraw your consent to participate at any time. You will not be penalized in any way should you decide not to participate or to withdraw from this study.

Contact information

If you have any questions or concerns about this study or if any problems arise, please contact Selma de Kleijn (investigator, Biomedical Photonics group) at tel. 040 – 2747813, Wouter Rensen (investigator, Biomedical Photonics group) at tel. 040-2747576, or Nijs van der Vaart (head of the Biomedical Photonics group), tel. 040 – 2747667.

Consent

I have read this consent form and have been given the opportunity to ask questions.
I give my consent to participate in this study.

Participant's name: ………………………………………….

Date of Birth: …………………………………………………

Participant's signature: ______________________________ Date: _____________

I have discussed the above mentioned information with the above mentioned participant.

Name: ………………………………………….

Function: …………………………………………………

Signature: _______________________________________ Date: _____________

A copy of this consent form should be given to you.

H Questionnaire to be answered by test subjects

This questionnaire is to find out if certain features have a correlation with the shape of the breast. This information can later be used to predict the breast's shape.

Do you meet any of exclusion criteria below?

- Age younger than 18
- Age older than 75
- Incapacitated
- Wounds and/or contagious diseases of the skin at the breast surface
- Pregnant
- Pain in back or neck

0 Yes
0 No

1) Age (years)
0 ___________
0 No answer

2) Length (cm)
0 ____________
0 No answer

3) Weight (kg)
0 ____________
0 No answer

4) Some features of the human body (e.g. blood group, hair structure) correlate to where a person(s family) originally comes from (race). To which race do you consider yourself? *(More than one answer is possible)*
0 Caucasian (European)
0 African (South of Sahara)
0 Indian
0 East-Asian
0 Other: _________________________
0 No answer

5) What is your bra size? (Number and letter)
0 numbers: letter:
0 No answer

6) Do you buy your bras in the Netherlands? *(If not, indicate country)*
0Yes
0 No, _______________________
0 No answer

7) Do you use any medicine with hormones (e.g. contraceptive pill, medicine against climacteric symptoms *Dutch: overgangsverschijnselen*)?
0Yes, ________________________
0 No
0 No answer

8) Have you had your menopause? *(If so indicate how many years ago.)*
0 Yes, ________________________ *(skip questions 9&10)*
0 No
0 No answer

9) What date did your last period start? *(Date)*
0 ____-____-_____
0 No answer

10) How many days does one period cycle last (on average)?
0 ___________
0 No answer

11) Have you ever been pregnant?
0Yes
0 No
0 No answer

12) Have you nursed babies or do you nurse at the moment?
0 Have nursed, for … months.
0 Nursing at the moment, for … months.
0 Have never nursed
0 No answer

13) Do you have any breast implants or have had any other breast surgery? *(If so, please indicate.)*
0 Yes, _________________________
0 No

I Correlation between FWHM and bra size

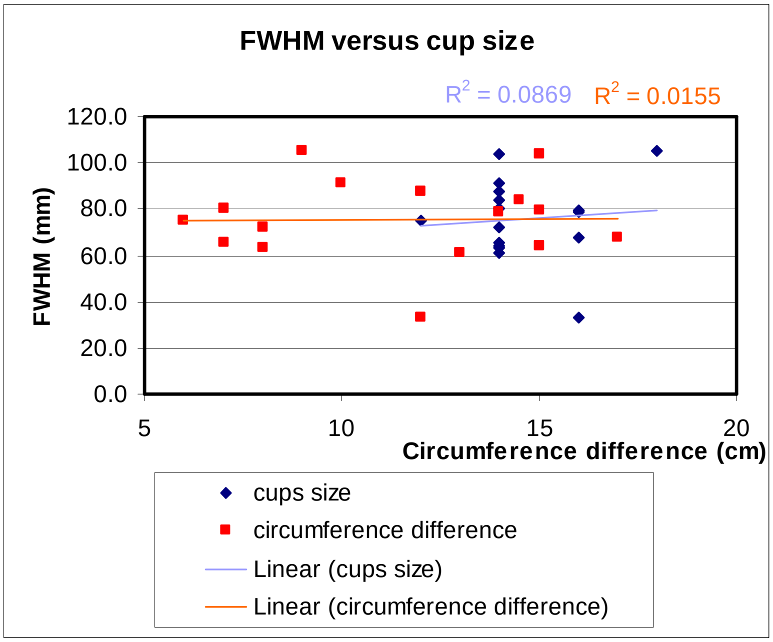

Table 9: The measurements of FWHM versus circumference difference for the left breast.

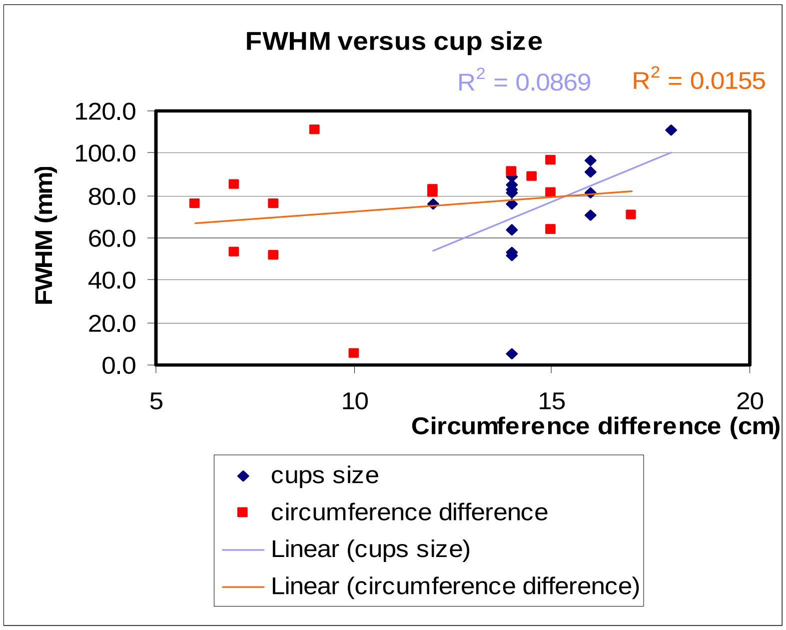

Table 10: The measurements of FWHM versus circumference difference for the right breast.

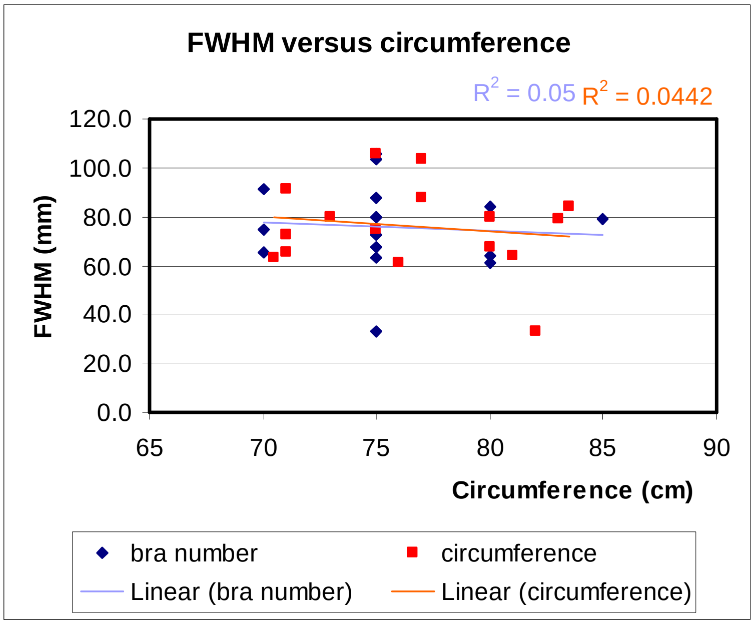

Table 11: The measurements of FWHM versus chest circumference for the left breast.

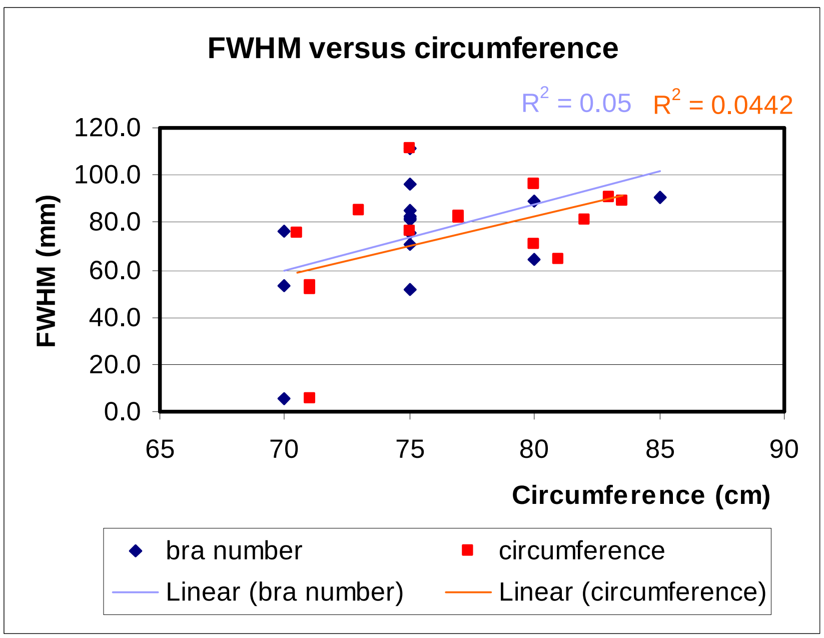

Table 12: The measurements of FWHM versus chest circumference for the right breast.

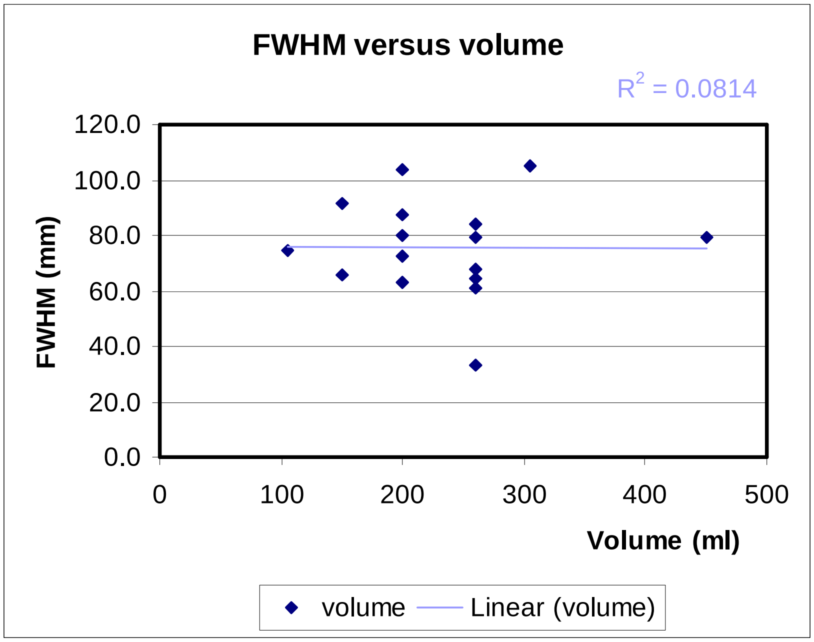

Table 13: The measurements of FWHM versus estimated breast volume for the left breast.

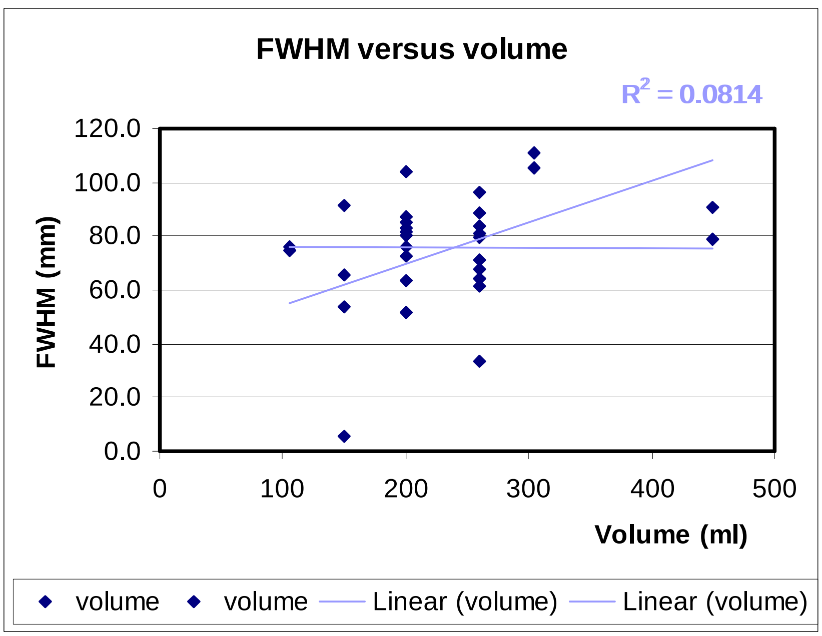

Table 14: The measurements of FWHM versus estimated breast volume for the right breast.