Ultrasound Artefacts

Marcus Jönsson

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Electrical Measurements
Faculty of Engineering, LTH
Department of Biomedical Engineering
Supervisor: Monica Almqvist

Abstract

Image artefacts in diagnostic ultrasound partly occur due to a number of assumptions made concerning how sound and tissue interact and of the acoustic properties of tissue. Ultrasound artefacts in B-mode imaging and the underlying physics that cause them is a well-documented subject. These artefacts and the causes behind them have been studied with the goal of designing a number of ultrasound phantoms containing objects that produce ultrasound images resembling the artefacts.

The reason behind wanting these phantoms is to make the teaching about ultrasound artefacts and phantoms in the course ‘*Ultrasound physics and technology*’ (given at the Department of Biomedical Engineering, at the Faculty of Engineering, LTH, Lund) more interactive. The idea is to integrate the finished artefact phantoms into a laboratory exercise for students. The phantoms have been designed to display some of the most common B-mode artefacts.

For the purpose of creating long-lasting phantoms a new background material was tested. This material was a commercial candle gel material. Compared to other available options the candle gel proved to have the best ability to last long. The acoustic properties of the gel were measured and estimated to ensure it was a good fit. The gels acoustic properties combined with its physical properties of being reversible and clear in color made it a good fit.

A large amount of materials and objects were tested for the purpose of reproducing the wanted artefacts and once suitable materials and objects had been found three phantoms were designed and constructed. The overall results were satisfying.

Keywords: Ultrasound, Artefacts, Phantoms

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1. Introduction

1.1 Background

Many associate the word ultrasound with grayscale images of a fetus in the womb of a pregnant woman, but ultrasound is used in a wide variety of applications in medicine besides obstetrics. Ultrasound as an imaging technique has a lot of advantages and is in many places used as a first line of investigation. [1] [2] Compared to other imaging techniques there are no ionizing radiation or strong magnetic fields only sound waves and the images are updated in real time with minimum delay [3]. Examinations can be made where the patient is, bedside, without any preparations, there is no need to move a patient as there is with other imaging techniques. The image construction in the ultrasound machine is partially based on few false assumptions about how sound propagates through and how it is attenuated by human tissue. These assumptions are part of the cause for the occurrence of image artefacts in ultrasound images. An image artefact is any irregularity or distortion in the image caused by either false assumptions about sound propagation or by the presence of irregularities in the investigated subject. [4] [5] Recognizing the artefacts when they occur is an important part of diagnostics and while some artefacts may be a sign of sickness and can be used to make a correct diagnosis other give false information and can in some cases be removed from the image by simply moving the transducer. Understanding the physics behind sound waves and their propagation through human tissue and other materials is of great importance to understand how the artefacts occur. [6] With the same knowledge it is possible to artificially reproduce the artefacts in a tissue phantom. Choosing the right tissue-mimicking material is important when constructing phantoms since there are many different materials with varying properties to choose from. [7] Experience with encountering artefacts is among the best ways to recognize and in some cases avoid the occurrence of these artefacts.

1.2 Brief history of ultrasound in medicine

The history of ultrasound applications for medical use only dates back to the late 1940’s and early 1950’s. What drove the development was the poor performance of available imaging techniques or the lack of such techniques. During the world wars techniques using sound to detect enemy submarines (SONAR) and airplanes (RADAR) had been developed. The question was if the technique could be used to form images of the human body and its internal structures. [8]

In the United States some of the most important and earliest pioneers were John Wild, George Ludwig and Douglas Howry. In their early work they tried to develop a technique to visualize the abdominal area with ultrasound. Their work included developments of B-mode equipment and techniques to visualize gallstones and breast tumors. [9] In Lund, Sweden, the biggest and most important pioneers were Inge Edler and Hellmuth Hertz. Inge Edler was a cardiologist and Hellmuth Hertz a physicist and together they revolutionized the field of echocardiography in 1953. [10] Edler wanted to look for signs of mitral stenosis and try to diagnose mitral regurgitation and with Hertz help they were able to produce an M-mode (M for motion, see more under Ultrasound modes) diagram that showed how the position of the structures of the heart changed during a cardiac cycle (i.e. during one heartbeat) [11].

During the first few years the work of Edler and Hertz was not recognized as being as groundbreaking as it is today. Their work still inspired others to develop techniques in other areas. As the understanding and spreading of ultrasound imaging techniques grew the work of Edler and other pioneers was recognized and the techniques were starting to get used and developed even further. [11] During the second half of the 1950’s and the 1960’s advancements were made in the areas of gynecology, obstetrics, neurology and much more. During the 1960’s the first Doppler techniques were developed with the purpose of visualizing blood flow in the heart and in different blood vessels. In the 1970’s further Doppler techniques were developed and during the 80’s the first three-dimensional techniques were developed. The performance of existing techniques has been steadily improved and making the ultrasound systems more sophisticated and improving image quality has been a big part of the development since the 70’s and 80’s. [12] With the digital revolution in the 90’s the development of ultrasound machines with analogue to digital converters was started. The digitalization of the machines meant significant improvements in the whole signal processing chain and image quality was possible. [13] New applications are constantly being developed and among the recent innovations are hand-held devices [14].

1.3 Purpose and Goal

A section of the course ‘*Ultrasound physics and Technology’* (course code: EEMN15) is dedicated to the subject of ultrasound artefacts. Up until now the explanation and experience with artefacts have been limited to the theoretical explanation using two fake images, one of a phantom and one of a sonogram of that phantom. These two images can be seen in figure 22. For the purpose of making the teaching about ultrasound artefacts more interactive the idea is to design and produce one or a few ultrasound phantoms containing similar objects and show the same artefacts, or as close to these as possible, that can be seen in figure 22. The following questions will lay the ground for the literature and laboratory studies.

1. What is an ultrasound artefact and what are the physical properties that cause them?
2. How can the artefacts be visualized in phantoms?
3. How can artefact-phantoms be integrated into a laboratory exercise for students?

The main goal is to produce phantoms and integrate them into a laboratory exercise for the students taking the course. So in addition to producing the phantoms instructions for how to investigate them, as a part of the laboratory exercise, will be written.

1.4 Choice of Method

To be able to re-create artefacts in a phantom it is important to understand why and how they occur. For this purpose a literature study will be performed on the subjects of basic ultrasound physics, systems and artefacts. A literature study on ultrasound phantoms and phantom materials will also be performed.

Based on the knowledge from the literature study different background materials and their properties will be tested. An estimation of the attenuation and the speed of sound in different background materials will be tested. The difficulty and time needed to create a phantom using the different background materials will also be tested and compared. Different objects will be tested with the goal to achieve ultrasound images resembling the goal picture as closely as possible, see figure 22. The tests will be done using water as background material in the first step and in the second step objects will be molded into the chosen background material in smaller test phantoms. When all materials and objects have been chosen the phantoms will be molded in the final phantom containers. These containers will be built in the department’s workshop, that offers the opportunity to mill and cut Plexiglas pieces that can be used to construct the containers. The workshop also offers the opportunity to 3D-print details and this may be used to create some objects or parts for objects.

2. Theory

The purpose of this chapter is to explain the origin of sound waves and how sound waves propagate through different materials and what the important properties of sound are. This will continue into an explanation of how the basic B-mode ultrasound system works and creates images. Next the occurrence of ultrasound artefacts will be explained based on the knowledge of the ultrasound system and the properties of sound waves.

2.1 Sound waves and Ultrasound

Understanding how sound waves are created and how they propagate through materials is important for the understanding of the basic principles of diagnostic ultrasound. Sound is created by vibrations in a material that causes the particles in the material to oscillate. These vibrations can be transferred to adjacent materials, such as air, causing the same oscillations in this material. This creates a sound wave that continues to travel until the energy is gone. The number of oscillations per second i.e. the frequency [Hz] is one of the most important properties of the sound wave. The human ear has the ability to detect sounds that range from 20 Hz up to 20 000 Hz, all frequencies above 20 000 Hz are considered as ultrasound. [1]

The oscillating particles can motion either in the direction of travel of the sound wave, longitudinal wave, or perpendicular to the direction of travel, transverse wave. The ultrasound waves used in medical imaging are of the former type. The propagation of the wave through a material causes oscillations of the particles in the material and by doing so particles in one area will move towards each other causing a region of compression (increased pressure) and in another area the particles will have moved away from each other causing a region of rarefaction (reduced pressure). [1]

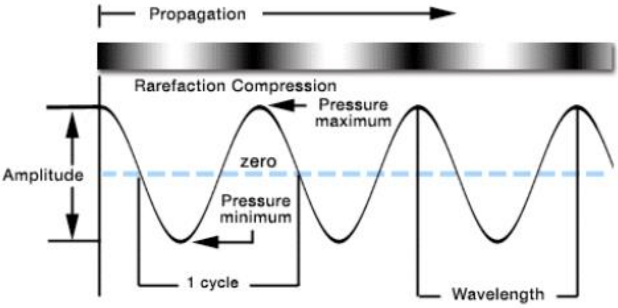

Figure 1 Schematic picture of a longitudinal wave, showing amplitude, wavelength frequency (cycles/second) and rarefaction/compression **[15]**

The propagation speed of a wave is dependent on the material or medium it is propagating through. The speed of sound, c, in a material is given by equation (1):

$$c = \sqrt{\frac{1}{\rho\kappa}} \tag{1}$$

Where ρ is the density of the medium and κ is the adiabatic compressibility of the medium. For a longitudinal plane wave the particle velocity, u, and the acoustic pressure, p, is related through equation (2):

$$u = \frac{p}{Z} \tag{2}$$

The specific acoustic impedance, Z, is defined as the ratio between particle speed and acoustic pressure at one point in the medium. For a propagating plane wave in non-viscous liquids it is defined as material constant and is called the characteristic acoustic impedance*:*

$$Z = \rho c \tag{3}$$

In table 1 the characteristic acoustic impedance for some tissues and liquids is listed. [1]

Table 1 Characteristic acoustic impedance for some tissues and liquids

Material	**Z(kg/m^{2}s)**
Liver	1.66x10^6
Kidney	1.64 x10^6
Blood	1.67 x10^6
Fat	1.33 x10^6
Water	1.48 x10^6
Air	430
Bone	6.47 x10^6

The acoustic pressure is defined as a function in three dimensions and time, *p(x,y,z,t)*. This function is zero when there is no wave and it has to satisfy the wave equation:

$$\left(\frac{\delta^2}{\delta x^2}+\frac{\delta^2}{\delta y^2}+\frac{\delta^2}{\delta z^2}\right)p(x,y,z,t)=\frac{1}{c^2}\frac{\delta^2 p(x,y,z,t)}{\delta t^2} \tag{4}$$

A plane wave traveling in one direction reduces equation (4) to:

$$\frac{\delta^2 p(z,t)}{\delta z^2}=\frac{1}{c^2}\frac{\delta^2 p(z,t)}{\delta t^2} \tag{5}$$

This general one dimensional wave equation has a number of different particular solutions depending on initial and boundary conditions. One of these solutions can be written as:

$$p(z,t)=p_0 e^{(j(\omega t-kz))}$$

Where k is the wave number and ω is the angular frequency of the wave. The following relations apply to the wave number and angular frequency:

$$k=\frac{2\pi}{\lambda}\ ,k=\frac{\omega}{c},\omega=2\pi f\ \Rightarrow k=\frac{2\pi f}{c}=\frac{2\pi}{\lambda}\ \Rightarrow f=\frac{c}{\lambda} \tag{6}$$

The wavelength, λ, of a wave is, as shown in figure 1, the distance between two equal points on the wave or the length of one cycle and the unit used for wavelength is usually meters. The number of cycles per second is the frequency of the wave and frequency has the unit per second or Hertz [Hz].

In diagnostic ultrasound applications the frequencies used range from 2 MHz to 15 MHz. [1] [16] [17]

As mentioned above the speed of sound varies from material to material and human tissue is no different. The speed of sound in human tissues and some other materials are listed in Table 2. [1] [7]

Table 2 Speed of sound in human tissues and fluids

Material	c (m/s)
Liver	1570-1595
Kidney	1560
Fat	1430-1480
Blood	1584
Water	1480
Air	330-340
Bone	3200-3400
Average Tissue	1540

2.1.1 Reflection, Transmission and Refraction

The law of reflection states that a wave incident on a large surface interface will be reflected at an angle equal to the angle of incident, see figure 2A [18], [1]. If the angle of incident is zero i.e. the wave is traveling along the normal perpendicular to the surface, the wave will be reflected back in the same direction it came from. At tissue to tissue interfaces one part of the wave will be reflected back into the first tissue and the other part will be transmitted into the second tissue. At normal incident, as said above, both reflection and transmitted waves will continue to travel along the normal but at other angles of incident the reflected wave travel in a direction as explain above and the transmitted wave may be refracted. How much of the wave that is reflected and how much that is transmitted depend on the difference in acoustic impedance between the two tissues, there has to be a difference for the reflection to occur. [1]

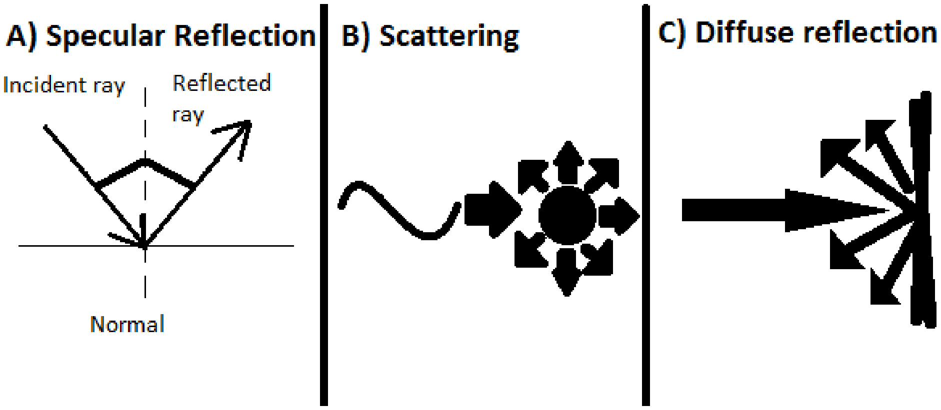

Figure 2 A) Specular reflection at large smooth interface, the angle of reflection is the same as the angle of incident, B) Scattering of the ultrasound wave against a very small object, C) Diffuse reflection against a rough surface, the wave is reflected in many directions **[1]**

The (characteristic) acoustic impedance was defined in equation (3) and for reflection at a large surface interface at an oblique angle of incidence the pressure reflection coefficient is defined as: [16]

$$R_a = \frac{Z_2 \cos\theta_i - Z_1 \cos\theta_t}{Z_2 \cos\theta_i + Z_1 \cos\theta_t} = \frac{p_r}{p_i} \tag{7}$$

At normal incident this is reduced to:

$$R_a = \frac{Z_2 - Z_1}{Z_2 + Z_1} \tag{8}$$

The part of the wave that is not reflected is transmitted and the pressure transmission coefficient is defined as:

$$T_a = \frac{2Z_2 \cos\theta_i}{Z_2 \cos\theta_i + Z_1 \cos\theta_t} = \frac{p_t}{p_i} \tag{9}$$

This is reduced to the following at normal incident:

$$T_a = \frac{2Z_2}{Z_2 + Z_1} \tag{10}$$

The reflection and transmission coefficients can also be expressed in terms of intensity reflection, R_i, respectively transmission, T_i, coefficients. It can be shown that the intensity is proportional to the square of the pressure:

$$I = \frac{p^2}{2Z} \tag{11}$$

This combined with (7) and (9) gives the following for reflection:

$$R_i = R_a^2 = \left(\frac{Z_2 \cos\theta_i - Z_1 \cos\theta_t}{Z_2 \cos\theta_i + Z_1 \cos\theta_t}\right)^2 \tag{12}$$

And for transmission:

$$T_i = T_a^2 \frac{Z_1}{Z_2} = \frac{Z_1}{Z_2}\left(\frac{2Z_2 \cos\theta_i}{Z_2 \cos\theta_i + Z_1 \cos\theta_t}\right)^2 = \frac{4Z_1 Z_2 \cos\theta_i}{(Z_2 \cos\theta_i + Z_1 \cos\theta_t)^2} \tag{13}$$

At normal incident these are reduced to:

$$R_i = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2 \text{ and } T_i = \frac{4Z_1 Z_2}{(Z_2 + Z_1)^2} \tag{14}$$

The angles in equation (7) and (9), the angle of incident θ_i and transmission angle θ_t are related by Snell's law, equation (15). [19] [1] [16] This law is also sometimes called the law of refraction as it determines how much the angle of the transmitted wave will change at a large interface if the incident angle is non-perpendicular to the interface and if the speed of sound is different on each side of the interface.

$$\frac{c_1}{c_2} = \frac{\sin\theta_i}{\sin\theta_t} \tag{15}$$

The refraction of an incident wave can be explained as it is shown in figure 3. The first tissue have a speed of sound c_1 and the second tissue have a speed of sound c_2 ($c_2 > c_1$).

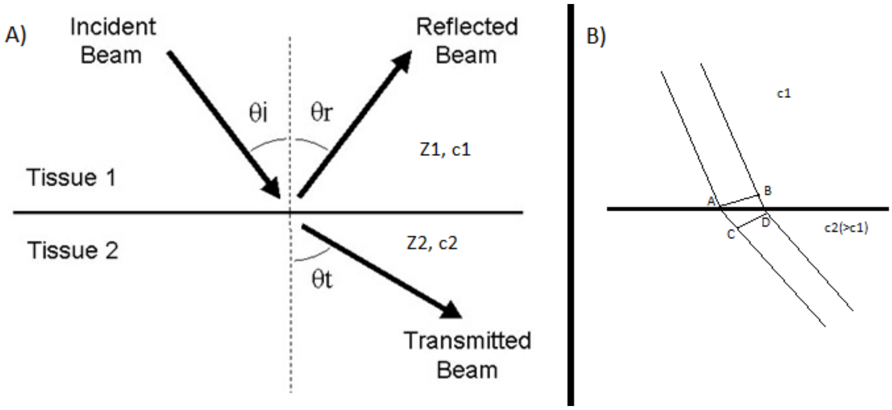

Figure 3 Refraction. A) Shows refraction of the transmitted beam and the angles related to the incident, reflected resp. the transmitted wave **[20]** B) The wave front AB travels through tissue 1, point A reaches the interface to tissue 2 before point B and thus travels further into tissue 2 before point B enters tissue 2. The wave is refracted and a new wave front, CD, is created **[1]**

A wave front stretching from point A to point B approaching the boundary between two tissues at an angle will have the edge of the wave at point A entering the tissue before the edge at point B , see figure 3B. At point A the wave will travel faster than the wave at point B and will travel a distance to the point C before the wave edge at point B enters the second tissue at point D. At this point a new wave front stretching point C to point D is formed. The new wave front will have been deviated away from the normal. The new angle towards the normal is the angle of transmission θ_t. When the speed of sound increases across an interface, the angle to the normal increases for the passing wave. [1]

2.1.2 Scattering and Diffuse reflection

Scattering occurs when the ultrasound wave encounters objects comparable in size to the wavelength of the wave or smaller than the wavelength. Scattering means that the part of the incident wave that is reflected will be spread or scattered over a large range of angles (see figure 2B). The energy of the wave will spread over a large range of angles and less energy is left in the propagating wave to create echoes from deeper laying structures. If the targets size, *d*, is much smaller than the wavelength ($d \ll \lambda$) the wave can be scattered uniformly in all directions but for targets of the same size order as one wavelength ($d \approx \lambda$) the scattering will not be uniform in all directions. In the latter case the scattering can still be over a large range of angles. Comparing echo signals from a small scatterer to that from a large surface interface the power or amplitude of these echoes is much lower and will appear much weaker in the ultrasound image. The scattered power depends strongly on two parameters, the size, d, of the scattering object and the wavelength, λ, of the incident wave. The frequency dependence of the scattering is referred to as Rayleigh scattering and it can be shown that the scattered power is inversely proportional to the fourth power of the wavelength and proportional to the sixth power of the size of the scattering object. [1]

$$W_S \propto \frac{d^6}{\lambda^4} \propto d^6 f^4 \tag{16}$$

Since the small objects scatter the ultrasound over a large range of angles (uniformly if the object is very small) there will not be a significant change of appearance in the image when the angle of incidence is changed. For the case of large surface interfaces the angle of incident of the ultrasound beam does play an important role for the appearance in the image. [1]

In chapter 2.1.1 reflection against large interfaces was described. The surface of these interfaces was assumed to be smooth and perfectly flat but tissue to tissue interfaces in the human body can in some cases be slightly rough. If the roughness is on the scale of the wavelength of the incident wave the sound will be reflected over a range of angles, see figure 2C. The effect resembles the scattering from small targets and is known as diffuse reflection. [1]

2.1.3 Attenuation

Attenuation is the process through which the ultrasound wave loses its energy to the tissue it is propagating through. There are two main processes that accounts for the attenuation, scattering and absorption. Scattering, as described above in chapter 2.1.2, causes the energy of the wave to be spread over a large amount of angles and if the scatterer is very small the sound can be spread uniformly in all directions. Scattering only accounts for a small part of the attenuation in tissue, absorption is the dominant processes accounting for anywhere between 75-95% of the attenuation. Absorption means the energy of the wave is converted into thermal energy. This conversion into thermal energy is due to several different mechanisms such as heat conduction, viscous loss and losses due to molecular energy exchange processes. [21] The composition of human tissue is very complex and this makes it hard to derive simple mathematical models that can be used to describe how the attenuation depends on the frequency [16]. The most common way is to make a simple phenomenological model to describe the frequency dependence of the attenuation. [17]

As described earlier, as the ultrasound wave propagates through a medium, in this case tissue, the particles of the medium move back and forth as a response to the pressure of the wave. The particles have a limited freedom to move within the medium and cannot move instantaneously. At high frequencies it is likely that the rapid fluctuations of pressure will cause the particles of the medium to be unable to move in step with the passing wave and the energy will not effectively be passed back to the wave. This means that a part of the energy of the passing wave is retained by the medium and converted into heat. At lower frequencies it is more likely that the particles will be able to move in step with the passing pressure wave and more of the energy can effectively be passed back to the wave as it moves through the medium. [1] This only explains a small part of the absorption phenomenon and the description in total is still imperfect [16].

In a phenomenological model it is common to assume a linear dependence between attenuation and frequency and distance travelled. This kind of model agrees well with practical observations but in terms of theory it is not as easily supported. [16] The attenuation in tissue can be described as a fractional decrease for each unit length traveled. If the pulse is attenuated by 20% after traveling 1 cm, i.e. the intensity is 0.8 of the initial value, the pulse will have been attenuated 20% of that value after traveling another centimeter, i.e. the intensity after 2 cm is 0.64 (0.8*0.8) of the initial value. [1] In medical applications it is most common to express the rate of attenuation in dB/[cm*MHz] (decibels per centimeter and megahertz). Decibel (dB) is used to express the ratio between two values on a logarithmic scale. For the case of ultrasound it is the relative amplitude between echoes that is used to describe it. The ratio between the intensity of an ultrasound pulse propagating through tissue at two different depths can be express as in equation (17): [1]

$$\frac{I_2}{I_1}(dB) = 10\log\left(\frac{I_2}{I_1}\right)(dB) \tag{17}$$

It can be shown that the intensity ratio is proportional to the square of the pressure ratio

$$\frac{I_2}{I_1} = \frac{p_2^2}{p_1^2} = \left[\frac{p_2}{p_1}\right]^2$$

And this modifies equation (1) to:

$$\frac{I_2}{I_1}(dB) = 10\log\left[\frac{p_2}{p_1}\right]^2(dB) =$$

$$\frac{I_2}{I_1}(dB) = 20\log\left[\frac{p_2}{p_1}\right](dB) \tag{18}$$

Equation (17) is used for comparison of power or intensity levels while equation (18) is used for comparison of two amplitudes (pressure, voltage). One of the advantages of the dB scale is that since it is a logarithmic scale, ratios can simply be added together. A fractional decrease of 0.8, as the example in the text above suggests, would correspond to an approximate decrease of 1dB (0.969 dB) per cm. After 1 cm the pulse would have been attenuated by 1dB and after 2cm it would have been attenuated 2dB and so on for each centimeter travelled. [1]

As stated before a linear dependence between attenuation and frequency is assumed i.e. if the frequency is doubled the attenuation is increased by a factor of 2. In the next section this assumption together with equation (18) will be used to form a phenomenological model that can be used to estimate the attenuation of tissue mimicking materials.

2.1.3.1 Phenomenological model and experimental set-up for estimating attenuation

To estimate the attenuation in tissue mimicking materials a phenomenological model of the attenuation is constructed. In this model the amplitude (in the model and experimental set-up the voltage amplitude is assumed to be proportional to the pressure) is used and the amplitude decrease is modeled by a simple decay equation: [17]

$$\mathrm{A}(x) = A_0 e^{-\mu_a x} \tag{19}$$

The distance travelled, x, have the unit cm and the factor μ_a has the unit cm^{-1} and is called the amplitude attenuation factor. From equation (18) the amplitude decrease in decibels is obtained:

$$20 \log\left(\frac{A(x)}{A_0}\right) dB \tag{20}$$

The attenuation coefficient, α, can be defined as:

$$\alpha = 20 \ \log(e) * \mu_a \cong 8.7 * \mu_a \tag{21}$$

Above a linear dependence between attenuation and frequency was assumed and this can be modelled as:

$$\alpha = af^b = [b \ \approx 1] = af \tag{22}$$

Combining equation (21) and (22) transforms equation (19) to:

$$A(x, f) = A_0 e^{-afx/8.7} \tag{23}$$

The factor *a* in equation (23) is unknown and have the unit [dB/cm*MHz]. The factor can be estimated with a simple experimental set-up (figure 4). Two transducers submerged in a water tank with one connected to an arbitrary waveform/function generator working as the transmitter and one connected to an oscilloscope working as the receiver. The transducers need to be aligned properly to avoid reflections in the tank walls and the distance between them need to be long enough so that signal will not bounce between the transducers. The transmitted signal needs to be a short pulse or burst to resemble the type of pulse sent in an diagonstic ultrasound system. In this set-up the frequency used is 2MHz and this is due to the transducers being desginded to work at 2MHz.

Inserting slices of tissue mimicking materials between the transducers will reduce the received signal and by varying the thickness of the slices the attenuation factor can be calculated. Only two slices with different thickness is needed and z in equation (23) will be the thickness of the slices. The interest does not lay with absolute values of the amplitude but with relative values or ratios and therefore z becomes the slice thickness.

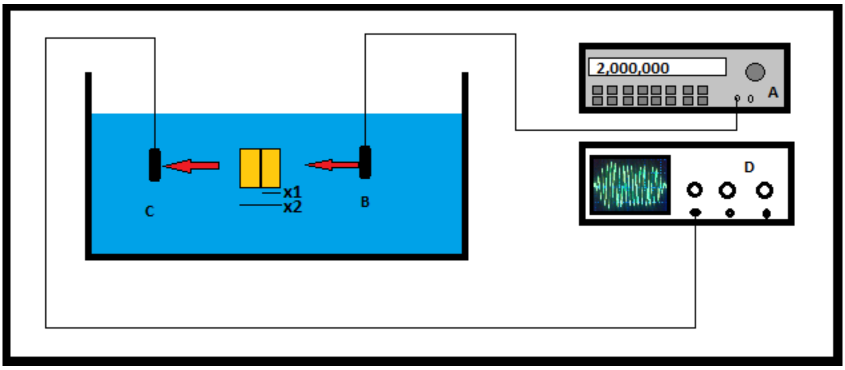

Figure 4 Experimental set-up for estimating the attenuation. A signal generetor (A) transmitts a pulse via transducer B. The signal is received by transducer C and is displayed on the oscilloscope (D)

With two slices, of thickness x_1 and x_2, equation (23) gives

$$\frac{A(x_2,f)}{A(x_1,f)} = \frac{A_0 e^{-\frac{afx_2}{8.7}}}{A_0 e^{-\frac{afx_1}{8.7}}} = e^{-\frac{af(x_2-x_1)}{8.7}} = e^{-\frac{af(\Delta x)}{8.7}} \qquad (24)$$

Since the ratio is wanted the two amplitudes are divided in equation (24) above, notice that $(x_2 - x_1)$ was replaced with Δx. The attenuation caused by the water is negligible compared to the attenuation from the samples and is ignored in this model. By taking the logarithm on both sides the factor a can be obtained:

$$\log\left(\frac{A(x_2,f)}{A(x_1,f)}\right) = \log\left(e^{-\frac{af(\Delta x)}{8.7}}\right) = -\frac{af(\Delta x)}{8.7}\log(e) \tag{25}$$

From equation (21) it is know that 20**log(e)≈8.7* which gives:

$$\log\left(\frac{A(x_2,f)}{A(x_1,f)}\right) = -\frac{af(\Delta x)}{8.7}\frac{8.7}{20} = -\frac{af(\Delta x)}{20} \tag{26}$$

By moving the factor 20 over the left side notice how this side resembles equation (20) (the amplitude decrease in dB):

$$20\log\left(\frac{A(x_2,f)}{A(x_1,f)}\right) = -\,af(\Delta x) \tag{27}$$

By moving *f* and Δ*x* over to the other side the attenuation of the tissue mimicking material in dB/[cm*MHz] can be obtained (if the frequency and difference in slice thickness is known):

$$a\left[\frac{dB}{cm*MHz}\right] = -\frac{20\log\left(\frac{A(x_2,f)}{A(x_1,f)}\right)}{f(\Delta x)} \tag{28}$$

Table 3 lists values of attenuation for some tissue types.

Table 3 Attenuation values for human tissues. Values from Hoskins et al **[1]**, Jensen **[16]** and Culjat et al **[7]**.

Tissue	Attenuation [dB/(cm*MHz)]
Liver	0.4-1.0
Kidney	0.8-1.0
Brain	0.44-0.6
Blood	0.2
Bone	6.9-20
Fat	0.5-1.0
Soft Tissue (Average)	0.54

The values in table 3 vary from source to source, the composition of tissue is very complex and measuring methods and models for estimating attenuation may vary too and therefor the values for attenuation may vary from source to source. [1] [7] [16]

2.1.4 The ultrasound pulse and beam

In the next chapter the properties of B-mode imaging will be explained in more detail, but in short a B-mode image is formed from the echoes produced by reflection at interfaces and scattering from small targets (see above). The process requires that the ultrasound is transmitted in the form of a pulse to produce a distinct echo that corresponds to a particular interface or object. The pulse also has to be short to allow closely spaced interfaces or objects to be resolved individually i.e. the axial extent of the pulse decides the axial resolution. [1]

The process not only requires that the ultrasound wave is sent in the form of a pulse it also requires the pulse to be limited in its extent in the transverse direction. In order to create the image the pulse must travel along a small path or beam. [1]

When several waves or pulses are propagating through the same tissue simultaneously, they will interfere with each other and the pressure at each point in the tissue will be the sum of the pressure each wave/pulse contributes. The interference between two waves or pulses can be either constructive, resulting amplitude at a given point is larger than the amplitude of the individual waves, or destructive, resulting amplitude at a given point is less than that of each individual wave. Consider two waves with the same amplitude and frequency propagating in the same direction. Consider two opposite cases; in the first case the two waves are in phase with each other (figure 5A) and in the second case they are fully out of phase with each other (figure 5B). The results for the two different cases are displayed in figure 5. In the first case constructive interference occurs and the resulting wave has twice the amplitude of the individual waves. In the second case destructive interference occurs and the two waves cancel each other out and the result is that there is no effect on the particles of the medium. [1]

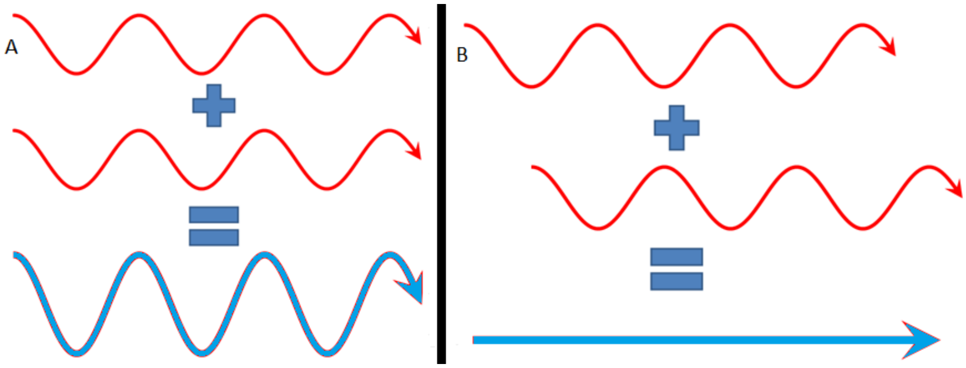

Figure 5 A) Constructive interference; Resulting wave has twice the amplitude of the individual waves. B) Destructive interference; Resulting wave is no wave at all **[22]**

How a wave spreads out as it travels away from its source is strongly dependent of the relationship between the wavelength of the wave and the width of the source. The waves created from a source much larger than the wavelength are relatively flat or plane and lay parallel to the source surface. These types of waves travel in directions perpendicular to the surface and experience very little sideways spread. Waves created from a source much smaller than the wavelength will diverge as they travel away from the source, an effect known as diffraction. A row of small sources (each much smaller than the wavelength) on a large surface can be linked to gain a large plane wave through interference of the waves. Each of the sources on the line creates a curved wave and trough constructive and destructive interference between different parts of the waves a larger plane wave is created. This principal is used when forming ultrasound beams in array transducers, see section 2.2. [1]

For image forming it would be ideal to have a transducer able to produce an ultrasound beam that is very narrow throughout the whole length of the beam. A wide transducer will give a narrow beam but will be too big and a narrow transducer will produce a beam that diverges too rapidly. With the frequencies available for diagnostic ultrasound it becomes a compromise between beam width and transducer size when designing the transducer. [1]

One way to improve the beam width is by focusing the beam. Focusing can be done in many different ways. One way is to use acoustic lenses to re-direct the sound towards a focus. Another way is by modifying the source in such a way that it produces waves that get narrower and narrower the closer the focus they get.

The frequency content of pulsed wave compared to a continuous wave is very different. A continuous wave source is able to produce a wave where the pressure varies as a pure sine wave and therefor this wave only contains one distinct frequency. The pulsed wave is typically constructed from a few oscillations from a range of frequencies around the nominal frequency of the wave. The different frequency components will interfere with each other and so the pulse formed. [1]

The time and distance resolution from a short pulse is very precise and the echoes contain information at a wider range of frequencies. The information in echoes from a longer pulse is concentrated at the nominal frequency and gives a very strong signal at this frequency but the distance resolution is significantly decreased with a longer pulse. Figure 6, shows the typical pressure waveform of a typical ultrasound pulse.

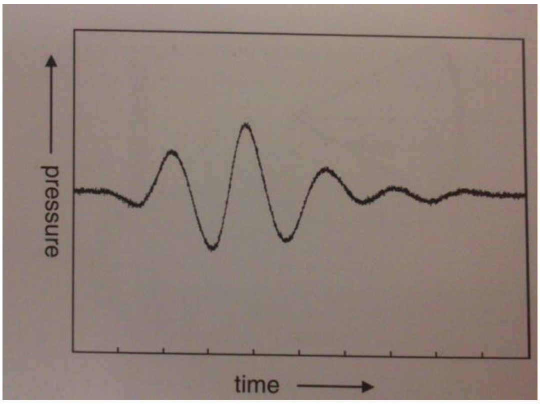

Figure 6 Pressure waveform of a typical ultrasound pulse **[1]**

2.2 Ultrasound Equipment

In this section the basics of a general ultrasound system will be explained. The modern systems available today are more complex than the system that will be explained here but in general it is still the same basic principles that apply to these systems.

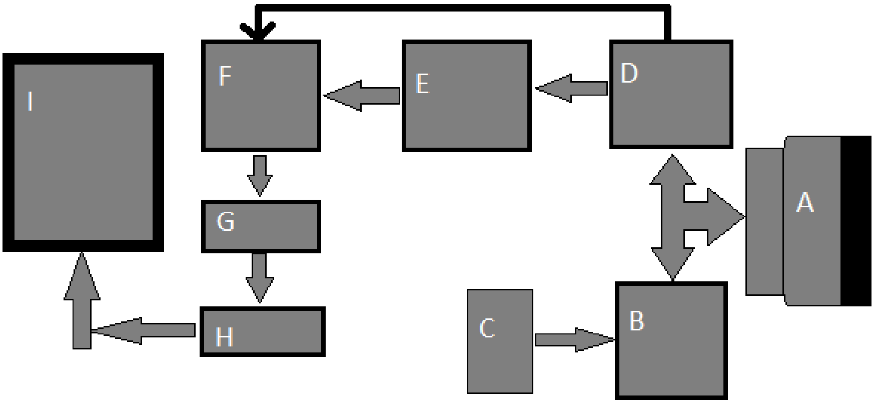

Figure 7 A basic ultrasound system **[1]** A) Transducer, B) Transmit beam former, C) Transmit Power Control, D) Receive/Digitize, Receive beam former, E) Amplitude processing (pre-processing), F) Image formation, G) Cine memory, H) Post-processing, I) Image Display

As seen in figure 7, the basic system has several different parts that are all needed to create an image. The system has three major parts; first the transducer and the beam formers (figure 7 A-D), both transmit and receive, that together both sends and receives the signals. Second part is the signal processing part (figure 7 D-F) that creates the image. The third and last part is the image display part (figure 7 G-I) that displays the image that the second part creates.

2.2.1 Basics of image formation

When creating the image the ultrasound system makes a few assumptions regarding the properties of human tissue and regarding the way the sound will travel. Some of the most important assumptions are listed below:

1. The speed of sound in tissue is constant at 1540 m/s
2. Attenuation in tissue is constant and uniform at ~0.5 dB/cm/MHz
3. The sound travels in a straight line along a straight beam axis
4. Each interface/object only produces one echo signal.
5. Echoes are only formed from objects inside the beam, the pulse travels from the transducer to an object and back to the transducer in a straight line.

The idea with B-mode imaging is to create a gray-scale image. The brightness of echoes will be displayed in relation to other echoes i.e. on a relative scale. Two identical or similar structures at different depths should in the image be displayed with the same amplitude or brightness.

The assumption of a constant propagation speed is needed when calculating the depth at which an echo is created. The ultrasound system uses the pulse-echo principle when calculating the depth of echoes. As previously explained the ultrasound is sent very short pulses and after sending a pulse the transducer becomes the receiver and listens for echoes. When an echo is registered the time, *t*, between the pulse being sent and the echo being registered is measured, the ‘go and return’-time. The distance, *d*, between the transducer and the echo-creating object/interface is then calculated using equation 29.

$$d = \frac{ct}{2} \tag{29}$$

Since the sound travels the distance between the transducer and the object twice, the time is divided by two and then multiplied with the speed to get the distance. The speed, *c*, used in diagnostic ultrasound is usually, as stated above, the average speed in human soft tissue of 1540 m/s. To create a full 2D B-mode image the pulse-echo sequence has to be repeated several times. Each time a small line of the image is created and the amount of lines the image is built up by depends on the transducer, more about transducers in section 2.2.2. Each of these scan lines creates one pulse-echo sequence that are put together to create the image. Modern transducers typically create the B-mode image from over 100 separate B-mode lines. To scan all lines to create one full B-mode image can be as fast as 1/30 of a second or even faster. This means that in one second thirty or more complete images are created displaying the B-mode image in real-time as the delay between obtaining an image and it being displayed is negligible.

Figure 8 User interface of a typical ultrasound machine, circled in red is the TGC interface

As explained in section 2.1.3 human tissue attenuates sound which means that the registered amplitude of echoes from deeper laying objects or structures is lower than the amplitude of echoes from objects close to the transducer. The amplitude of returning echoes is usually very low and need to be amplified before they can be processed further (figure 7E). The next step in the signal processing is to amplify echoes to compensate for the attenuation. This is done by assuming a constant and uniform value of the attenuation at 0.5dB/cm/MHz, as stated above. Most ultrasound systems have a built-in system called *Time-gain compensation* (TGC) that amplifies echoes increasingly as the ‘go and return’-time increases. With this system, identical or similar objects, structures or interfaces located at different depths should appear equally bright in the B-mode image. The base value is set to compensate for the average attenuation caused by the tissue and is applied to all the echoes that are received. As seen in table 3 the actual values for different tissue varies and most ultrasound systems allow the operator to manually adjust the TGC from the set base value to compensate for known tissue variations. As seen in figure 8 above, the most common interface for manual TGC adjustment is a set of slide controls. The base value is applied when the slides are centered and each slide increases or decreases the gain for echoes originating from a certain depth.

When all scan lines have been scanned and echoes have been properly converted from an analogue signal to a digital signal and amplified and compensated for the attenuation the amplitude signals are combined with the information from the beam former to write the B-mode image onto the memory. The beam former holds the information about the scan line i.e. where the echoes were created and where to place them in the image. On the display each pixel is given a value (from high to low i.e. from bright to dark) according to the echo information stored on the memory. Before the image is displayed there are different stages of signal processing done to the information to give each pixel a correct value compared to surrounding pixels and compared to pixels in other areas of the image. [1]

2.2.2 Transducers and Beam forming

The designs of ultrasound transducers are many and varies depending on the intended application, in this section the descriptions will be limited to common features of all transducers and of linear-array transducers.

2.2.2.1 Common features

The part of the transducer that creates and detects the sound waves is a piezoelectric plate. Piezoelectric materials are materials that generate voltage when an external mechanical force is applied to them and conversely undergoes expansion or compression when voltage is applied across them. [2] By applying an oscillating voltage at the desired frequency the piezoelectric plate can be made to oscillate at the desired frequency and as a result an ultrasound wave at the desired frequency is transmitted. The ultrasound pulse, as stated before, contains a wide range of frequencies centered on a nominal frequency and often the thickness of the piezoelectric plate is chosen to match half a wavelength at this frequency. This thickness is chosen due to the resonance phenomenon that occurs because of it. Parts of the wave will be reflected at the front and back ends of the piezoelectric plate as it propagates across the plate and the reflected parts continue to reverberate back and forth within the plate. Due to the choice of thickness the reflected parts will return in phase with the original wave after each round giving rise to resonance. The output at the center frequency will be large due to resonance and choice of plate thickness. [1]

Most piezoelectric materials used in ultrasound transducers have characteristic acoustic impedance in the range of 20-times that of human soft tissue. The reflected fraction in the case of direct contact with tissue can be estimated using equation (14) and for the 20:1 ratio this is approximately 80%. With the chosen plate thickness the result would be very strong internal reverberations, continuing long after the driving voltage have been applied. [1]

These two problems, the unwanted ringing and the low transmission ratio, are usually addressed by adding one layer at the back and one at the front end of the piezoelectric plate. The layer at the back end works as a dampener that absorbs the ultrasound energy that is transferred to it. The acoustic impedance of the backing layers is often chosen to be slightly lower than that of the piezoelectric plate, if the acoustic impedance was chosen to be equal to that of the piezoelectric plate the transducer would lose some sensitivity. Identical acoustic impedance would mean that no ultrasound would be reflected at the interface between the backing layer and the piezoelectric plate and all ultrasound energy transferred to the backing layer would be converted into heat. It would also mean that parts of the driving pulse and returning echoes would be absorbed in the backing layer and thus the reduction in sensitivity. The front layer or matching layer takes care of the rest of the unwanted ringing. [1]

As the name implies the matching layer is used to match the acoustic impedance of the piezoelectric plate to that of the tissue. The matching layer can consist of a single layer or of a series of layers where the matching is done progressively. For a single frequency a single matching layer can achieve 100% transmission by constructing it after two conditions. The first is that the acoustic impedance of the matching layer is chosen according to equation 30.

$$Z_{Match} = \sqrt{Z_{Piezo} * Z_{Tissue}} \tag{30}$$

Secondly the thickness of the matching layer has to be a quarter of a wavelength. The reason this construction works is the reverberations that occur within the matching layer. The chosen thickness of the matching layer creates reverberation waves that are in phase at the tissue interface but that are out of phase with the original wave reflected at the matching layer-piezo plate interface. The result is that the reflected wave is canceled out by the reverberation waves sent back into the piezoelectric plate and the waves transmitted into the tissue interfere constructively to create a larger and more powerful wave. [1]

The last common feature that most transducers have incorporated one way or another is a lens. The lens is used for focusing and the shape, size and function of it may vary between different transducer types. [1]

2.2.2.2 Linear array transducers

The linear array transducer is one of the most common types of transducers. The most common material used for the piezoelectric plate in these transducers is lead zirconate titanate (PZT). The PZT plate is divided into elements separated by some inert material like a polymer that creates very narrow barriers (kerfs) between the elements. The number of elements varies between different manufacturers but the usual number of elements is either 128 or 256. [1] With the technical evolution it is possible to construct transducers with as many as 512 transducer elements [23]. For signal processing reasons, computers use binary numbers (base of 2) so these number of elements are chosen to be ‘round’ in binary terms ($128 = 2^7$). it is more convenient to have these numbers rather than even numbers like 100 or 200. The size of the elements varies depending on the number of elements and the size of the face of the transducer, in common for all of them are that the beam a single element forms will diverge very quickly. [1] [24]

To get the ultrasound to propagate as deep as desired each scan line is formed using a set of elements, how many elements that are included in a group varies. The active group of elements is centered on the desired scan line as the ultrasound pulse is formed and sent. [1] [23] The transmit beam former (figure 8B) controls which elements that are used in forming the scan lines. In receiving mode the receive beam former (figure 8D) controls which elements that are used for detecting echo signals. As stated before each scan line is interrogated individually and for each line there is an active group of elements. When one line has been scanned the next group is activated and the next line is interrogated. This process is repeated until all scan lines have been scanned. [1]

The lens on a linear array transducer is usually a cylindrical lens that only limits the extent of the beam and focuses it in the elevation plane. The focus in the scan plane is achieved using an electronic focusing method. Focusing in this plane is needed to obtain good lateral resolution. To achieve focus at a desired depth the pulse signal from each element in the active group must arrive at the desired focus point simultaneously. The width of each element may be small but the difference in path length between the center element of the group and the edge elements is significant. This path length difference can be eliminated by transmitting the pulse from the centered elements slightly later than the pulses from the outer elements. The focus depth in transmission mode can be manually set by the operator. [1]

Focusing is also done in reception but here the focus point is controlled by the machine. The focus point is shifted automatically to have the highest sensitivity at the depth where echoes should be returning from. The same path length difference that is present in transmission is present when receiving echoes and in the same way the pulses from the centered elements are delayed in transmission, the echoes received at the centered elements are delayed to let the received signals at the other elements catch up before being added together for further processing. [1]

The main beam (the one described above) is unfortunately not the only beam that is formed with transducers such as the linear array transducer. Side lobes are weak off-axis beams that are created due to divergence and interference at the edge of the main beam when the main beam is formed. The side lobes occur due to how the piezoelectric elements expand in all directions when voltage is applied [1]. Grating lobes are weak replicas of the main beam that occur due to the size and spacing of the transducer elements. If the path difference between the pulses in a particular direction of propagation from two adjacent transducer elements is equal to or greater than one cycle (i.e. one wavelength) the two pulses will interfere constructively to create a grating lobe. At greater angles secondary and in some cases third-order grating lobes can be formed. [1] [25] The distance between two elements (center-to-center) is therefor often designed to be half a wavelength, or close to it. This means that the first grating lobe will be at a large angle. [1]

2.3 Artefacts

An image artefact is defined as *something observed that is not naturally present but occurs as a result of the preparative or investigative procedure* [26]. In diagnostic ultrasound that means misrepresentation of tissue structures and incorrect placement of anatomical structures that distorts the image. In this section the most common artefacts in B-mode imaging will be described and what causes them. Furthermore the artefacts in the goal picture will be categorized.

As stated in section 2.2.1 when the B-mode image is formed the ultrasound system makes a number of assumptions concerning ultrasound propagation and interaction with tissue. These assumptions may be the cause of some artefacts occurring. Most notably is the propagation speed in tissue and the attenuation assumptions.

In reality the attenuation and speed of sound varies with tissue types (see tables 2 and 3) and this is the reason for the occurrence of some artefacts. Some artefacts occur due to the transducer and how it forms the beam and others occur due to how the transducer is operated. [1] [4] [6]

2.3.1 Speed-of-sound artefacts

These are artefacts that occur due to the wrong assumption that the speed of sound is constant and the same in all types of tissue and that the sound travel in straight lines. As seen in table 2 the speed of sound in soft tissue varies from ~1430 m/s (fat) to ~1580 m/s (liver). Range and size errors, boundary displacement, refraction and edge shadowing are all artefacts that occur due the speed assumption. [1]

Range error means that an object is placed closer or further from the transducer in the image than it actually is. The distance in the image is calculated using the time that elapses between the pulse being transmitted and the registration of an echo (see section 2.2). The system assumes the average speed of 1540 m/s and if the actual average speed is higher an object will appear closer and if lower it appears further away in the image than it actually is.

In figure 9, [1], the displacement of an object is shown. Due to the lower average speed of sound the object will appear further from the transducer in the image than it actually is. The situation in the figure assumes a thick, uniform layer of fat and in this case all objects beyond the fat would be displaced equally and therefore the artefact will not be noticed. This situation may occur in patients with high amount of subcutaneous fat. [1]

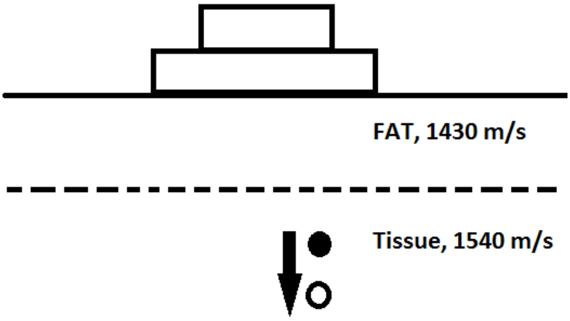

Figure 9 Range error due to difference in propagation speed between the two tissue types. The object is displayed deeper in the image than it is located **[1]**

Boundary distortion arises when there are smaller areas where the speed of sounds is higher or lower than the surrounding area. Figure 10 show how this would look schematically. The two areas of fat have lower speed than the surrounding tissue and as a result the deeper laying interface is distorted at the points where the sound has travelled through the fat area. This artefact can arise when scanning a liver containing much fat and usually it is the position of the diaphragm that is distorted. [1]

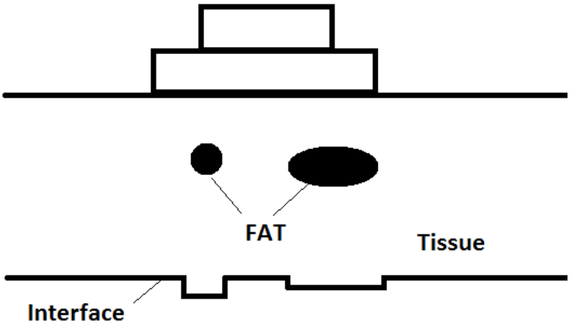

Figure 10 Boundary distortion due to the presence of areas of fat with a lower propagation speed than the surrounding area **[1]**

The phenomenon of *refraction* was explained in section 2.1.1. When the ultrasound beam has a non-perpendicular angle incidence against a large interface, where the two tissues have different speed of sound, it will change direction. The assumption that the sound travels in a straight line to and from reflecting objects is broken due to the change of propagation speed at the interface. This may cause objects that are not in the assumed path of the beam to be displayed wrongly, see figure 11. Due to refraction the blue object will be displayed as being in the assumed path of the ultrasound beam. This artefact is most commonly seen at the interface between adipose tissue (fat) adjacent to the liver or spleen and at the interface between the abdominal wall adipose tissue and the rectus abdominis muscle. In most cases changing the orientation of the transducer can eliminate these artefacts. [1] [4] [6]

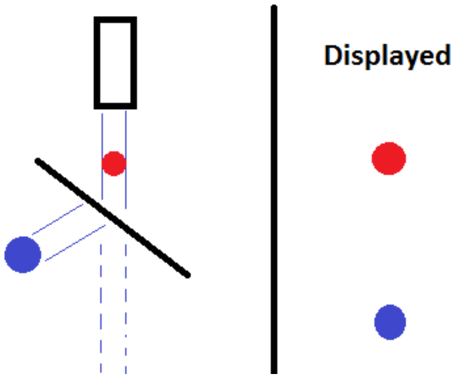

Figure 11 Refraction of the ultrasound beam cause objects that are not in the assumed path of the beam to display as if they are **[6]**

Refraction is also one of the causes of the artefact known as *edge shadowing*. This artefact occurs distal to the lateral edges of cysts and other smooth, rounded and fluid filled cavities, such as the bladder, blood vessels and aneurysms. When the beam encounters these structures the sound waves will be refracted and scattered at the interface and this leads to a loss of energy and echoes from distal areas, figure 12 describes the refraction schematically and figure 13 describes another possible cause of the artefact. This second cause is deflection at the tangential angle, which leads to an area where no echoes are generated. [3] [6] [27]

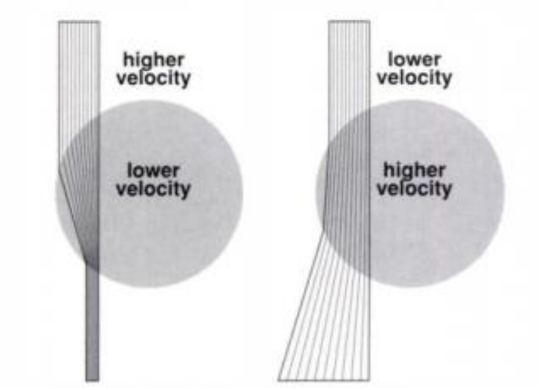

Figure 12 Left: Sound goes from media with higher speed into area with lower speed and out again. The difference in propagation speed causes the sound to refract and create an area where no echoes can return from. Right: Sound goes from lower to higher speed and out to lower speed again. This causes the the sound to be refracted and echoes distal to the edge will appear weaker **[3]**

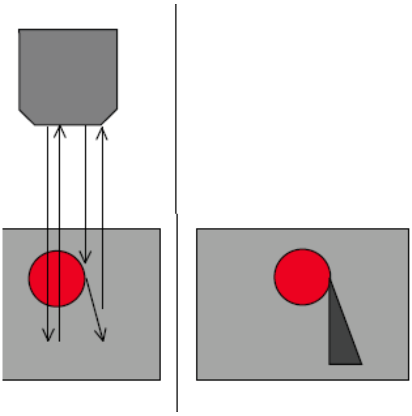

Figure 13 Deflection at the tangential angle creating an area from which no echoes are created **[6]**

Figure 14 shows an ultrasound image of the edge shadowing artefact (red arrows). The object in the image is made out of a tissue mimicking material (agar, see section 2.4 and 2.6.1) with a water filled cavity. By changing the orientation of the transducer (and by so the angle of the beam) the edge shadowing artefact may be eliminated.

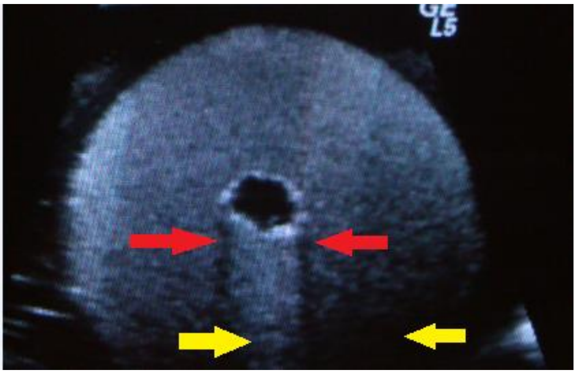

Figure 14 Ultrasound image showing the artifacts know as *Edge shadowing* and *Increased through-transmission* or *enhancement*. Image made during material testing, see chapter 3

2.3.2 Attenuation artefacts

This group of artefacts arises due to the assumption that sound is attenuated at a constant rate as it travels through tissue. Attenuation is the loss of energy and amplitude as the sound travels through a medium (see chapter 2.1.3) and different types of tissue cause more or less loss depending on tissue composition. In the image formation process all received echoes are amplified and how much an echo is amplified depends on the depth it originates from. Echoes from deeper structures are amplified more than echoes from shallow structures and two echoes from the same depth are amplified equally, see chapter 2.2.

Shadowing artefacts occur when the ultrasound beam encounters areas of tissue or objects that attenuate sound at a higher rate than assumed. Due to the higher attenuation the amplitude of the beam will be lower in the distal area of these structures compared to surrounding areas. Echoes returning from the distal area of these structures will have lower amplitude than echoes from the adjacent areas. Thus the distal area of highly attenuating structures will appear darker than surrounding areas in the ultrasound image. The shadowing artefacts can be divided into three categories depending on the appearance of the shadow. [1] [3] [4]

Partial shadowing have the hypoechoic appearance described above. It usually occurs beyond structures containing fat that is surrounded by other soft tissues. It can also occur distal to calcifications and gall/kidney stones if the diameter of these structures is small (approximately <0.5 mm). [3]

Clean shadowing occurs distal to structures that attenuate the sound at such a high rate that very little or no energy is left to create echoes in the distal area, any echoes created are attenuated before they reach the transducer. It is most commonly seen distal to bone, gall/kidney stones and calcifications. This artefact can also occur distal to highly reflecting structures, usually structures containing air. The appearance is clean anechoic signal beyond to the attenuating structure. [3] [4]

The third type of shadowing artefact is *dirty shadowing*. This can occur when the ultrasound beam encounters an interface between tissue and gas. In most cases this type interface will create a clean shadow. If the reflected signal is reflected back at the gas-tissue interface by interfaces that lay between the transducer and the gas and then reflected by the gas interface back to the transducer, see figure 15, weak echoes may appear in the shadow beyond the gas interface. [3]

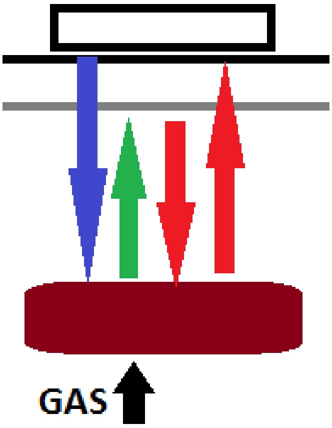

Figure 15 Dirty shadowing may arise when the ultrasound is reflected betwe en gas and a reflective interface before the echoes reach the transducer

When the ultrasound beam encounters structures or objects that attenuate the sound at a lower rate than assumed the *enhancement or increase through-transmission* artefact may occur. This is the reverse to partial shadowing. The enhancement appears as a hyperechoic area behind fluid-containing structures. Echoes returning from interfaces beyond these structures will appear brighter than echoes from the same depth in adjacent areas. Figure 14, in the previous section, show how the sound that travels through the water filled cavity is attenuated less than the sound that only travels though the tissue mimicking material (yellow arrows). In figure 16 a schematic image of clean (total) shadowing, partial shadowing and enhancement is displayed. [1] [3]

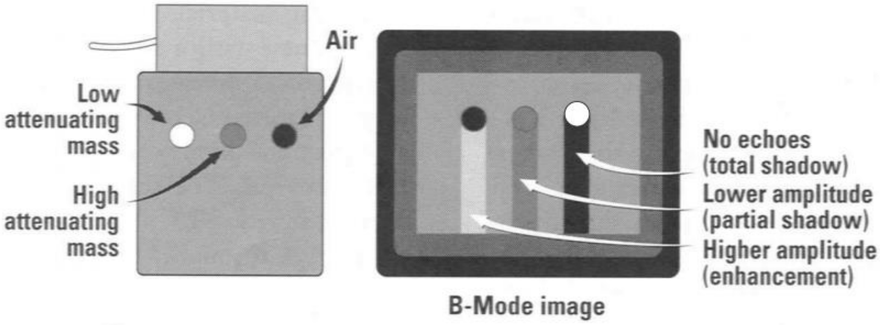

Figure 16 Schematic image of how total shadow, partial shadow and enhancement arise and appears in the B-mode image **[3]**

2.3.3 Reflection artefacts

This group of artefacts arises due to the assumption that each interface only will produce one echo signal and that the ultrasound beam travels along a straight beam axis. At an interface the difference is acoustic impedance between the two materials will determine how much of the sound that is transmitted and how that will be reflected. A large difference in acoustic impedance means that a majority of the sound will be reflected (see chapter 2.1.1). The angle of incidence against the interface and the distance to the transducer are important for the occurrence of the artefacts.

The reverberation artefact occurs when the ultrasound beam encounters a highly reflective, smooth interface close to the transducer or two closely spaced, highly reflective surfaces/reflectors (see figure 17). A highly reflective surface or interface close to the transducer will cause most of the sound to be reflected back at the transducer, due to the high amplitude of the echo a part of the sound will be reflected at the surface of the transducer and back at the interface (figure 17B). At the interface the sound will be reflected back at the transducer again and at the transducer some of the sound will be detected and some will be reflected again. This back and forth reflection i.e. reverberation will continue until the energy of the sound have been fully attenuated. The same may occur when the beam encounters two closely spaced reflectors (figure 17A). [1] [3] [4]

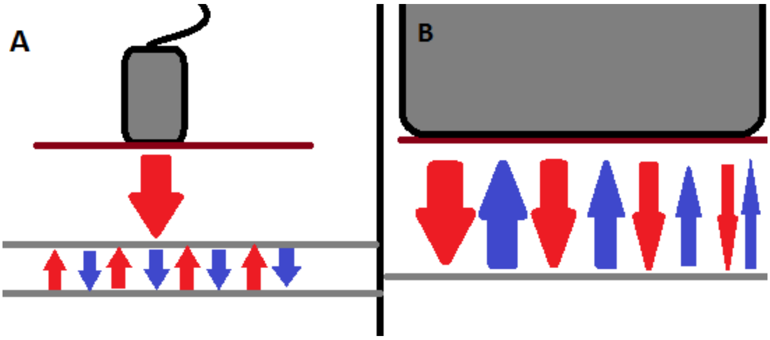

Figure 17 A) Reverberation between two closely spaced reflective surfaces, **B)** Reverberation between the transducer and a highly reflective surface placed close to the transducer

The part of the sound that is transmitted through the first interface will reverberate between the two reflectors and create a detectable echo each time it is reflected at the first interface. Each echo will be displayed equidistant to each other. If the depth of the surface is 1 cm the first reflection echo will be displayed at 2 cm (the original echo will be displayed at 1 cm). The second reflection echo will be displayed at 3cm and so on (see figure 18). For each reflection the signal or beam will become less and less focused and the echoes will be more diffuse as seen for the later echoes in figure 18. [1] [3] [4]

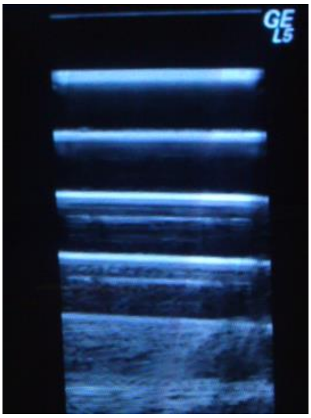

Figure 18 Ultrasound image of reverberation between the transducer and a metallic plate placed close to the transducer. For each reflection the echo gets less and less focused. . Image made during material testing, see chapter 3

The comet tail artefact is an artefact that is caused due reverberation between two highly reflective, closely spaced surfaces placed deeper in the target body or due to reverberation within small metallic objects or calcified structures placed deeper in the target body. The reverberations caused by these structures creates lines that are so closely spaced and blurry that individual lines are hard to distinguish and with the width of each line shrinking the appearance of these lines will resemble a comet tail (see figure 19). This shrinking of the width is due to energy loss at the edge. At the center the angle is more likely to be perpendicular after many reverberations and therefor the loss of energy is less there. [4] [6] [28]

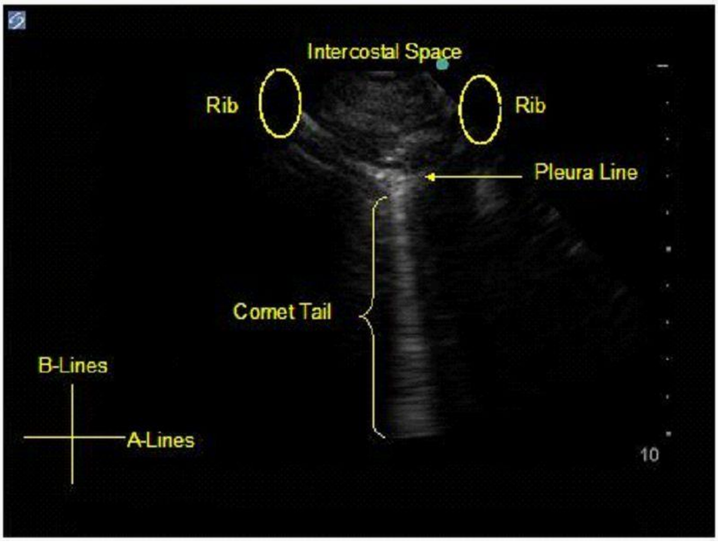

Figure 19 B-mode image displaying a possible comet tail artefact (the green arrow) **[29]**

The ring-down artefact resembles the comet tail artefact in appearance but it is not caused by the same type of phenomenon. This artefact is caused by resonant vibrations usually within small air bubbles or a small amount of fluid suspended in a tetrahedron of air bubbles that creates a continuous sound wave. This wave is transmitted back to the transducer and is displayed in the image as series of parallel bands or a line much like the comet tail artefact, see figure 20. [4] [6] [28]

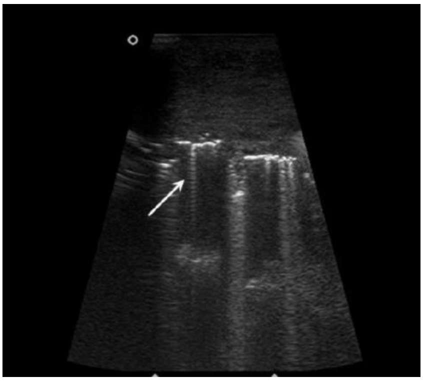

Figure 20 Ring-down artefact (white arrow) caused by Fournier gangrene **[28]**

The two artefacts may have similar appearance in the B-mode image but the causes behind them are different phenomenons. [28]

The last artefact among the reflection artefacts is the *Mirror image* artefact. This artefact arise due to the assumption that an echo created by the ultrasound pulse returns to the transducer without any other interactions. At highly reflective interfaces, such as the diaphragm, it is possible that a part of the echo generated at the interface is reflected at the back side (from the view of the transducer) of objects near the interface and back at the interface to create a secondary echo. In the B-mode image the secondary echo will be displayed as an identical image (a mirror image) on the other side of the interface, see figure 21, due to how the B-mode image is created (see chapter 2.2). To place the echo in the image the system only uses the time elapsed between the pulse being sent and the echo being registered and for the secondary echoes this time will of course be longer due to the increased path length and therefor they will be displayed deeper in the image. [1] [3] [4] [5] [6]

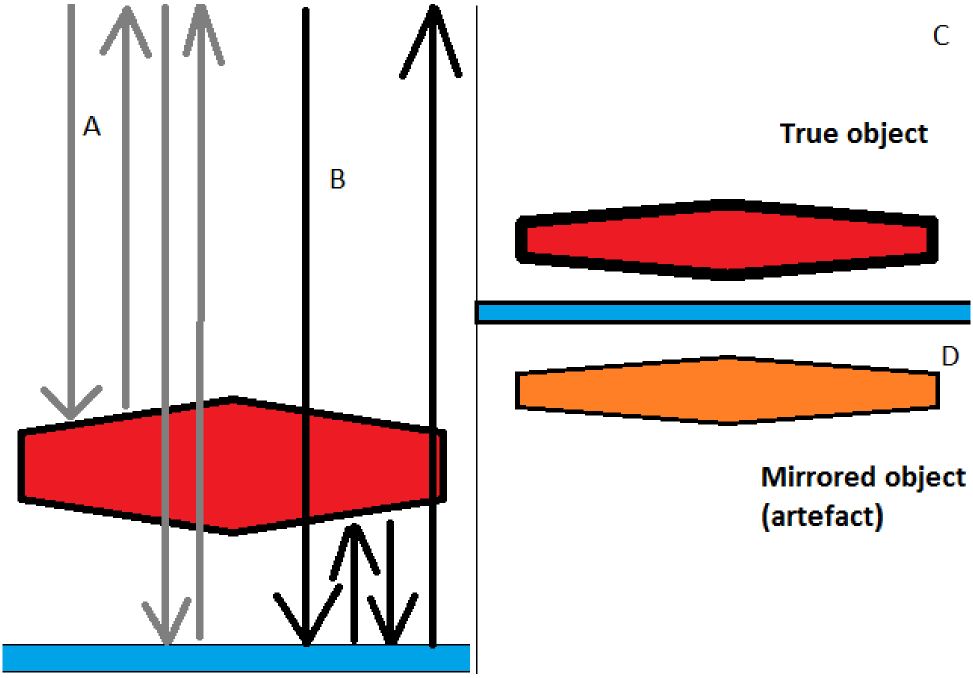

Figure 21 A) Grey arrows representing primary echoes generating object C in the B-mode image, B) Black arrows representing secondary echoes generating object D in the B-mode image

The artefact can be easily identified by moving the direction of transducer. The mirror image will change with the movement of the transducer and if placed in the right direction the artefact may disappear.

2.3.4 Other artefacts

The spatial resolution of the B-mode image can be divided into axial and lateral resolution. The axial resolution is determined by the length of the ultrasound pulse and the lateral resolution by the width of a single scan line and more exactly the width of the beam at the focus point. In both cases the resolution is defined as the minimum distance, in respective directions, between two identical objects for which the two objects can be resolved as individual objects in the B-mode image. If the system is unable to resolve closely spaced objects or interfaces, these will be displayed as one object or interface in the B-mode image. The B-mode image will be an incorrect representation of reality and can lead to misinterpretations of the real anatomic structure. [1]

Speckle is the granular fluctuations in the brightness of the B-mode image, see figure 19 and 20 for example. These fluctuations appear due to the type of scattering explained in section 2.1.2 and figure 2 B. The echoes from many small scatterers, too closely spaced for any to be resolved individually, in a small sample volume have a random amplitude and relative phase. When added together some of these low level echoes interfere constructively and some destructively with each other and other echoes to create the brightness fluctuations in the resulting B-mode image. The speckle may distort the image in such a way that different structures and/or interfaces are no longer visible. [30] [31]

The grating lobe and side lobes that may be formed when the main ultrasound beam is formed have the possibility to form image artefacts. One of the assumptions is that only objects within the main beam create echoes or that all echoes are created from objects within the main beam. Both side lobes and grating lobes have amplitudes much lower than the main beam but if strong reflectors are present in the path of these lobes strong echoes may be formed that can be detected by the transducer. The image system will assume these echoes are generated inside the main beam and will place them accordingly in the B-mode image. Like refraction and mirror image artefacts, these echoes produce an image that is a wrong representation of the true anatomy. [1] [4]

2.3.5 Categorization of the goal picture

The goal picture is, as mentioned in the introduction, a fake image of a phantom and a fake B-mode of the phantom, see figure 22. The fake phantom (figure 22, left) contains a number of objects that creates the artefacts in the fake B-mode image (figure 22, right). The B-mode image of the fake phantom may not be a correct representation of how a real B-mode image of a real phantom with the same objects would look like. In table 4 the artefacts in figure 22 are listed.

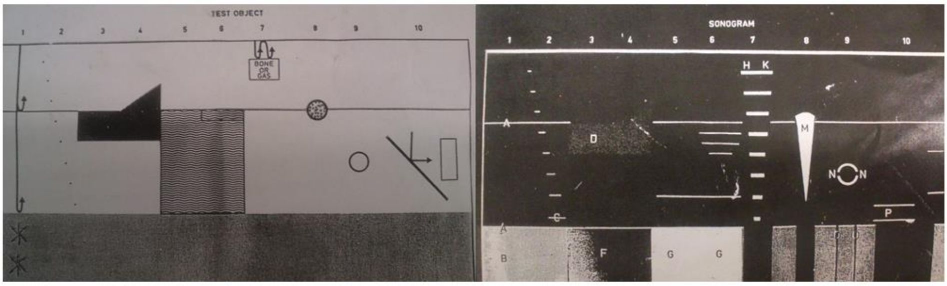

Figure 22 The goal picture containing 10 artefacts. Left: An image of a fake phantom containing objects creating the artefacts. Right: Fake ultrasound image of the fake phantom

The phantom has 3 layers of background material. The bottom layer is filled with some kind of scatterer and the top two layers separated by a thin layer or molded in a way that an interface is present and give a clear signal. The first artefact is not really an artefact as it is specular reflection at the interfaces between the three layers. Number two is a resolution artefact that is created by threads of some material suspended close in the lateral direction. The beam width decides the minimum width the ultrasound system can resolve. The third and fourth artefact is shadowing, as the object extends in the axial direction more of the original pulse is attenuated and from left to right it goes from partial shadowing to total shadowing.

Table 4 Categorization of the artefacts in figure 22

Number	Artefact
1	Specular reflection
2	Resolution artefact
3-4	Attenuation/Shadowing
5-6	Enhancement + Multiple Reflections
7	Reverberation
8	Comet-tail or Ring-down
9	Edge shadowing
10	Reflection artefact/Mirror Image

Artefacts five and six are enhancement or increased through-transmission and multiple reflections/reverberations. The first full line is the reflection at the interface and the deeper laying full line is a secondary echo of the same interface. At number six there is a little box that creates multiple reflections that are displayed as equidistant lines. Number seven is a typical example of reverberation. The ultrasound pulse encounters bone or gas and as a result the signal bounces back and forth between the transducers and the object to create equidistant lines and no signal reaches the area beyond the object. The eighth artefact is either a comet-tail or a ring-down artefact by looking at the appearance of the ultrasound image. If the object is a metallic object it is a comet-tail and if it is fluid trapped in gas it is a ring-down artefact. The ninth artefact is the edge shadowing artefact that can be easily identified by the two lines in the third background layer that gives no echoes. The tenth and last artefact is similar to the mirror image artefact, the ultrasound beam changes direction at a highly reflective surface and encounters an object that creates an echo. In this version of the artefact one scan line encounters the reflective surface and creates an image of the interfaces of the object from one direction while another scan line encounters the object directly and creates an image of the interfaces of the object from the correct direction.

2.4 Agar: Origin and properties

The substance agar is a gelatinous substance that has several different areas of use. The two most common areas are microbiology, as growth medium, and in culinary area, as an ingredient in primarily desserts. The substance is obtained from a group of red-purple algae and is as a phycocolloid or hydrocolloid substance. The first discovery of agar dates back to the middle of the 17th century in Japan and is credited to Minoya Tarozaemon.

All colloids have a few common traits; they are all substances in which insoluble particles are suspended throughout another substance. The particles are microscopically dispersed in the other substance. The dispersed substance alone is sometimes called the colloid. Phycocolloids are colloids extracted from seaweed or algae and hydrocolloids are colloids where the dispersed particles are hydrophilic polymers that disperse in water. Agar is a phycocolloid but can also be defined as a hydrocolloid.

Agar is, as mentioned above, extracted from certain algae. The components that make up agar are a mixture of the polysaccharide agarose and a mixture of smaller molecules called agaropectin. In the algae's that can be used to extract agar, the agarose forms a supporting structure in the cell walls of the algae. Chemically speaking, agar is a polymer constructed from subunits of the sugar galactose.

One of the most important properties of agar, which makes it suitable for ultrasound phantoms, is that it exhibits hysteresis. An agar solution (agar and water) of 1.5% that is heated to boiling and then cooled solidifies at a temperature of 32-40 degrees Celsius. This creates a firm gel that stays solid even in room temperature and that will not melt before it is heated up to a temperature of 85degrees Celsius. One of agars other important properties is the reversibility of the gel i.e. the gel can be melted and solidified repeatedly without it losing any of the original properties. A third property that makes agar suitable for phantoms is the fact that a simple water solution can utilize the great gelling power of agar without having to add other reagents and no special environment is needed. [32] [33] [34] [35]

2.5 Candle Gel

A common candle gel usually consists of a mixture of liquid and solid hydrocarbons and a polymer to control the texture of the gel [36]. Figure 23 shows a container of standard hobby candle gel from Panduro Hobby.

Figure 23 Standard hobby Candle Gel from Panduro Hobby **[37]**

In room temperature this gel is in a solid state, to turn it into a liquid moldable state it needs to be heated to at least 85 degrees Celsius, at this temperature the gel is still very viscous and starts to solidify instantly after being removed from the heating source. It is recommended to heat the gel indirectly in a metal bowl placed in water, letting the water heat up the bowl to melt the gel. When the gel has been melted it can be poured into a mold or container to solidify. Tests, see chapter 3 and 4, have shown that this material can be melted from its solid form to its liquid form repeatedly without any significant change in its properties i.e. the material is reversible. [38]

2.6 Ultrasound phantoms

Ultrasound phantoms are test objects constructed of tissue mimicking materials. Tissue mimicking materials are materials that can simulate physical and acoustic properties of tissue. The properties that are most common to simulate are speed of sound, attenuation coefficient, backscatter coefficient, thermal and mechanical properties and elasticity. [39] [40] Commercial ultrasound phantoms are mostly constructed to be used for quality assessment of diagnostic ultrasound systems. For this purpose most phantoms have different types of objects embedded in them or regions where the acoustic properties differ from the rest of the phantom. The tissue mimicking materials are different types of gel, plastic or rubber based materials among these are agar, urethane and different thermoplastic elastomers (TPE). [7]

A typical quality assessment (multi-purpose multi-tissue) phantom may have a schematic look as in figure 24. This particular phantom is produced by the company CIRS and is constructed from their own patented material Zerdine, a solid elastic water based polymer, and the wire targets (the small white dots) are made out of nylon wire. [41]

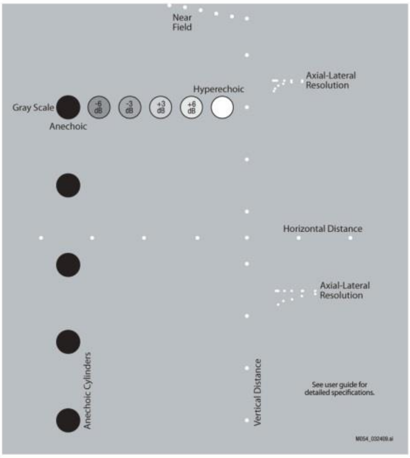

Figure 24 Schematic image of a typical quality assessment phantom **[42]**

Not all phantoms are designed for quality assessment as some are designed for the purpose of training. Experience and practice are two keys to recognizing and eliminating image artefacts. Training phantoms are designed to visualize true anatomical structures and internal organs of the human body. The idea behind training phantoms is to practice examinations on the phantom instead of a real patient in a stress-free environment. The variety of phantoms and what they visualize is huge on the market. Today there is everything from phantoms that visualize a single organ to phantoms that visualize a fetus, see figure 25 , and much more.

Figure 25 Training phantom of a fetus **[43]**

2.6.1 Agar Phantoms

The previous mentioned properties, reversibility, hysteresis and gelling power, of agar makes it suitable as a base for ultrasound phantoms (see section 2.4). The acoustic properties of an agar gel can be modified by adding granulated graphite, which increases scattering and absorption. [44] With the right ratio of agar, water and graphite the acoustics properties close to human soft tissue can be obtained. To produce a simple agar phantom the needed ingredients are agar in granulated form, graphite in granulated form and water, preferably distillated water or similarly processed water. Furthermore, some type of container is needed to hold and mold the phantom in and some echo-creating objects. Without any objects molded into the phantom the B-mode image of the phantom would only show a speckle pattern created by the small agar and graphite particles. Graphite will not only serve to increase the attenuation but it will also make the phantom dark, instead of the clear yellow color agar has, and will hide all or any objects molded into the phantom.

The manufacturing process can be divided into a few steps and as a whole the process is quite simple. First step is to measure and weigh agar and water to obtain the wanted ratio between the two ingredients. Next graphite is weighed and added to the agar/water mixture. To get a uniformly mixed solution the next step is centrifuging the mixture. After the mixing in the centrifuge the next step is heating the mixture to the boiling point in a microwave. The hot mixture is then to be centrifuged again to remove all or any air bubbles in it before cooling and solidifying. After the second round in the centrifuge the solution can be poured into the container or mold to cool down and solidify. Before or during the cooling process the objects chosen to be molded in to the phantom can be added and placed inside the container. To speed up the cooling/solidifying process the phantom can be placed in a refrigerator. Figure 26 shows the equipment used for making an agar phantom.

Figure 26 Scales, centrifuge and microwave oven used in the process of making an agar phantom

2.6.2 Pros and cons of using agar

The process of making a phantom using agar is quite simple as described in the previous section. The material is easy to manipulate and shape during the solidifying process and the acoustic properties can, as explained previously, be adjusted to resemble soft tissue. The melting temperature of the gel and the solidifying temperatures differ due to hysteresis and once solid the phantom will be solid at room temperature. Agar is colorless and has no smell. When making an agar phantom no special environment is needed and when the phantom is not needed anymore it can be easily disposed of, if there is no hazardous material molded into the phantom it can go right into normal waste.

Agar is a biological material and will deteriorate with time. A phantom made of agar will not be usable for more than a few weeks after construction. By adding some type of preservative the life-span of the phantom can be increased but no long-lasting effect. The process of making the phantom is easy but it is difficult to make large batches of agar gel at once. For precision, the right concentration and uniformly distributed/dispersed particles, it is better to make smaller batches of gel, which makes it cumbersome to make larger phantoms. The size of the equipment, in this case mainly the size of the centrifuge, is also a limitation to how large one batch can be. There is also a risk that the agar gel will form unwanted layers in the phantom when produced in small batches due to the previous batch solidifying too much before the next batch is added.

2.6.3 Candle Gel Phantoms

This type of gel is, as the name implies, mainly used for making candles and not ultrasound phantoms but the texture and reversibility of the material makes it an interesting candidate to test as background material for ultrasound phantoms. Because the gel is primarily not used for the purpose of making ultrasound phantoms the acoustic properties of it must be tested, measured and estimated. These tests and the results of them will be described and presented in chapters 3 and 4. The properties that need to be investigated are the speed of sound, the rate of attenuation, the density and the acoustic impedance of the gel.

When the gel is melted and molded as described in section 2.5 the risk of air bubbles appearing and settling in the solidifying gel is high. Bubbles in a phantom will, due to the large difference in acoustic impedance, distort the B-mode image. For this reason a series of bubble-reduction tests must be performed to find an optimal process for making phantoms with candle gel, see chapter 3.

3. Methods and Material testing

The purpose of this chapter is to present all tests that were made in order to create the final phantoms. A large number of tests were performed to find objects that in a B-mode image would resemble the artefacts seen in the goal picture, see figure 22 and table 4. Tests were made on the two possible background materials, agar and candle gel, to be able to compare the two materials and choose the most optimal material for the phantoms. More tests were made on the candle gel to estimate its acoustic properties and to reduce the creation of bubbles in the gel during the solidifying process.

3.1 Material and object testing for artefacts

The purpose of the materiel testing is to find materials and/or objects that in a real B-mode image resemble the artefacts seen in the fake sonogram in figure 22. The setup to test these materials and objects consists of a small water tank filled with water, an ultrasound machine, GE Logiq 5, with a 10 MHz linear array transducer, sound dampening pads and a block made out of agar, see figure 27.

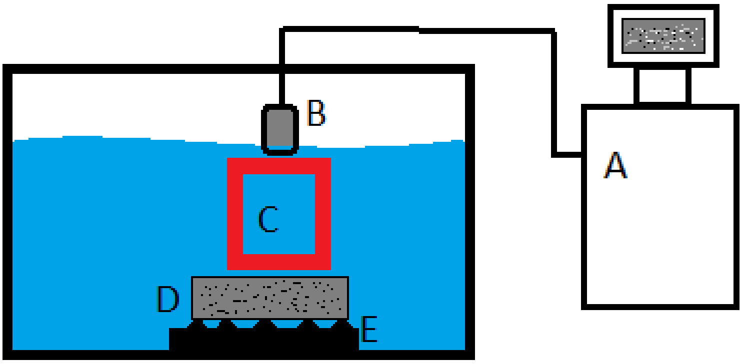

Figure 27 The schematic setup for materiel testing. A) Ultrasound system, GE Logiq 5. B) 10 MHz Linear array transducer. C) Testing area. D) Block of agar for scattering. E) Sound dampening pad

The damping pads are placed on the bottom of the water tank and along the sides of the test zone, figure 27C, and on the far sides of the water tank. This is to avoid reflections in the water tank walls being created and registered as echoes. The block of agar, with graphite imbedded, is placed at the bottom to create the scattering pattern seen in the bottom of figure 22. Figure 28 shows the setup with water tank, transducer and damping pads.

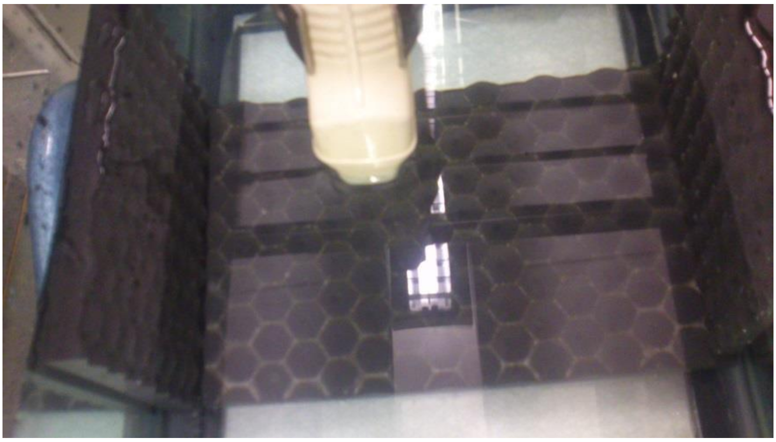

Figure 28 Transducer and dampening pads in the water tank

3.1.1 Artefact #1: Specular reflection

Artefact #1 is not really an artefact since it is regular specular reflection at an interface between two similar materials. This reflection should be present along the whole length of the phantom. In table 5 the different materials tested for artefact #1 are listed.

Table 5 Materials tested for artefact #1

Materials
Agar in layers
Candle gel in layers
Stretched plastic glove
Plastic foil

The agar and candle gel samples were molded into separate containers. The plastic glove was stretched across the opening of a container. The plastic foil was molded into candle gel for testing.

3.1.2 Artefact #2: Resolution artefact

This resolution artefact has one property that need to be tested. Different thickness of strings needs to be tested to see if this property in any way affects the occurrence of the artefact. The lateral resolution is decided by the beam width and by the focus.

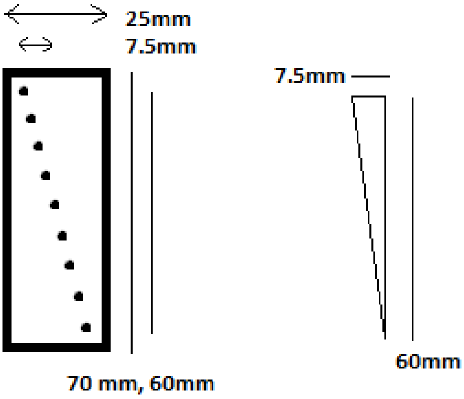

Figure 29 Schematics for the frame used to test the different strings

For the purpose of testing the strings a metallic frame has been fabricated. This frame has a lateral distance of 7.5 mm between the top and bottom holes and an axial distance of 60mm, the schematic can be seen above in figure 29. In figure 30 the real frame is shown.

The two different types of string that is going to be tested is a common black sewing cotton (approximately 0.1mm thickness) and a nylon wire (0.5 mm thickness).

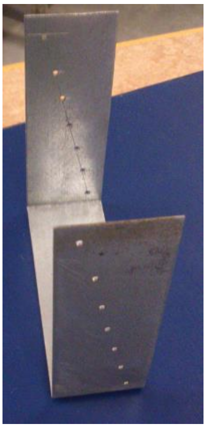

Figure 30 The testing frame with the larger lateral distance between the top and bottom hole

3.1.3 Artefact #3 and #4: Attenuation (Shadowing) artefact

This artefact is created by an object that attenuates sound at a higher rate than the surrounding material thus creating a shadowing effect. At the same time the acoustic impedance of this object and the surrounding material is equal since there is no reflection along the edges of the object and there is very little scattering from inside the object. For this object a mold that can be used several times needs to be made. Then different materials, with similar acoustic impedance as the two background materials, needs to be used in the mold to create test objects that can be molded into test phantoms. The object mold will be done in a latex material and the materials that will be tested are agar and candle gel with different concentrations of graphite embedded.

3.1.4 Artefact #5 and #6: Enhancement and multiple reflections

This artefact is a combination of two artefacts. First is the multiple reflections that occur at the top edge of the object and inside the small object at #6. Secondly is the enhancement or increased through transmission. Multiple reflections of the strength seen in figure 22 usually means the reflection is very strong, which would mean that less transmission. This means that the material inside the object attenuates sound at such a low rate that it overcompensates for the loss in amplitude from the reflection. For this artefact several tests will be made, the tests are listed in table 6.

Table 6 Tests made for the enhancement artefact

Test	Object/Method
1	Water cavity in agar
2	Water cavity in candle gel
3	Block of agar in candle gel

3.1.5 Artefact #7: Reverberation

To create this artefact different highly reflecting materials and objects with a flat surface interface will be tested. The materials that are going to be tested are listed in table 7.

Table 7 Objects to be tested for the reverberation artefact

Test	Object
1	Metal plates of different thickness
2	Hard plastic of different thickness (from the 3D printer)
3	Wood
4	Miscellaneous materials

Apart from finding a material or object that gives a good reverberation effect some kind of solution for fixating the object at an appropriate height must be constructed. As seen in figure 22 the object causing the reverberation is place very close to surface of the phantom and the transducer and for the best result the object needs parallel to the surface. The two solutions that will be tested for the suspension is one based on suspended strings and one based on a 3D-printed rack.

3.1.6 Artefact #8: Comet-tail or Ring-down artefact

As explained earlier in chapter 2, these two artefacts are very similar in appearance. The object creating the artefact decides what it should be called. In this case it is easier to use metallic objects to try to create this artefact, compared to trying to trap gas in fluid. When metallic objects create this artefact it is referred to as the comet tail artefact. In table 8 the different objects that are going to be tested for the comet tail artefact are listed.

Table 8 Test objects for the comet tail artefact

Test	Object
1	Metallic ball ~5mm diameter
2	Metallic ball ~10mm diameter
3	Metallic ball ~15mm diameter
4	Metallic ball ~20mm diameter
5	Metallic wires 0.2-1mm diameter

Like needed for the reverberation artefact there is a need of a solution to hold the object at a specific height in the phantom.

3.1.7 Artefact #9: Edge shadowing artefact

For this artefact some type of cylindrical or circular object is needed, as seen in figures 12, 13 and 14. Listed in table 9 are the different objects tested for the edge shadowing artefact.

Table 9 Objects to be tested for the edge shadowing artefact

Test	Object
1	Tubes with varying inner and outer diameter
2	Nerf dart (see figure 31)
3	Dish rag (see figure 31)
4	Plastic glove

In figure 31 test object 2 and 3 are shown. The nerf dart is a type of foam dart for a toy gun.

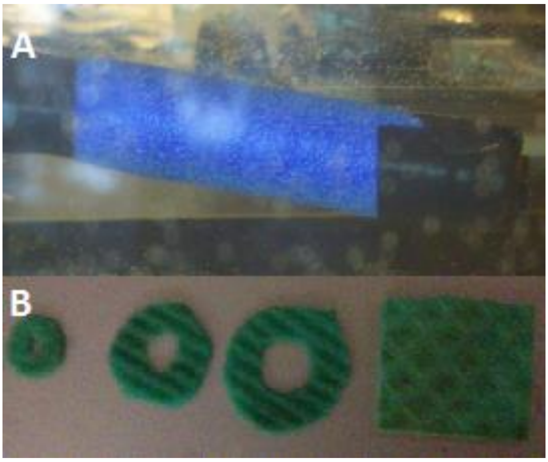

Figure 31 A) Nerf dart. B) Pieces of a dish rag

3.1.8 Artefact #10: Reflection/Mirror image artefact

This is a two-part artefact, first part is a reflector and the second part is an echo giving object. The results from the test for the reverberation artefact will also be used when choosing the material for the reflector. The idea of the reflector is to reflect the part of the ultrasound beam that encounters it towards the object, see figure 22. The tests for this artefact will be focused on the object and in table 10 potential objects are listed.

Table 10 Potential objects for the mirror image artefact

Test	**Object**
1	Plexiglas piece
2	Plastic piece from 3D-printer
3	Piece of candle gel wrapped in plastic foil

The biggest issue with this artefact is figuring out the solution for holding the reflector steady at a given angle. The two different suspension solutions that will be tested for this purpose are the same as for the reverberation artefact, one based on suspended strings and one on a 3D-printed rack/holder.

3.1.9 Post-aquarium tests

After objects and materials have been tested in the aquarium setup, see figure 28, and results of these tests analyzed. After the background materials have been tested and one background material has been chosen further tests will be made. The primary test is to mold test objects into test-phantoms and test these phantoms in the ultrasound machine. This step is needed to secure that the objects gives the same type of B-mode image in the background material as they did in water.

3.2 Background material testing

Previously, in chapter 2, two different materials were describe, both possible candidates to be used as background material for the final phantoms. These two materials were agar and candle gel. How to make a phantom using each of these materials were also described in chapter 2 and some of the pros and cons of using each material was presented. In short the procedure for each material can be summarized as follows.

Agar phantom:

1. Weigh agar, water and possibly graphite
2. Mix agar, water and possibly graphite
3. Mix the solution in a centrifuge
4. Heat the solution to the point of boiling
5. Mix a second time in the centrifuge
6. Pour into mold and let it solidify

The ratios between agar and water and between agar/water solution and graphite are listed in table 11.

Table 11 Concentration ratios used for making agar phantoms

Material	**Grams**
Agar	3g
Water	97g
Graphite	3g (per 100g agar/water solution

Candle gel phantom:

1. Measure and put candle gel into a metallic bowl
2. Place the bowl in a pot filled with water
3. Heat the pot on the stove and let the gel melt in the bowl
4. When the gel has melted, pour it into a mold and let it solidify

As mentioned in section 2.6.3 when melting and molding the candle gel in the way described above the chance or risk of air bubbles appearing is high, see figure 32. Due to the bubbles a series of tests on improving the melting and molding process is to be done.

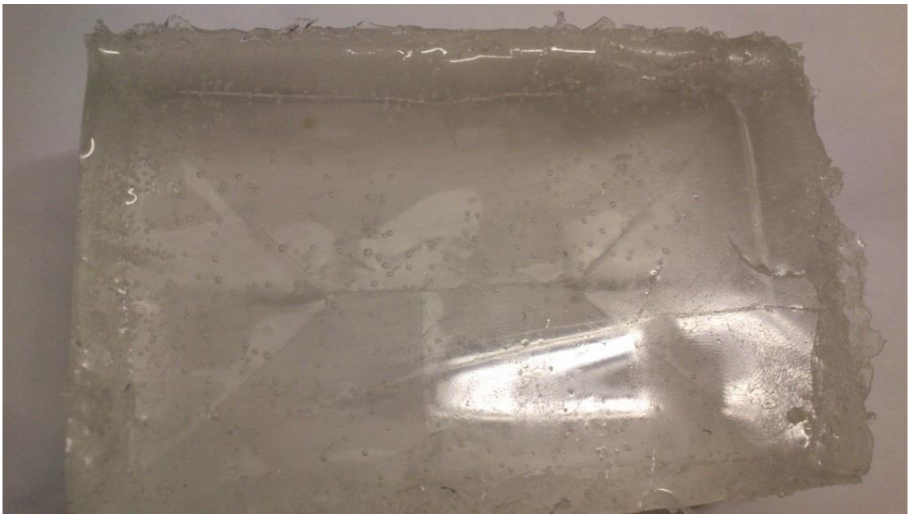

Figure 32 Example of candle gel with bubbles

3.2.1 Candle gel melting and molding tests

If the candle gel is to be used as background material for the final phantoms the amount of bubbles in the solidified gel must be reduced as much as possible. As mentioned above the suggested method, supposed to be used for making candles, means too many bubbles are created and this method needs to be improved. The following nine methods are going to be tested:

1. Melt the gel in the suggested way and pour it into a container and vacuum pump until it has solidified.
2. Melt the gel in the suggested way, vacuum pump the gel in the bowl ~15 minutes, melt the gel again and last pour it into a container and vacuum pump until it has solidified.
3. Melt in the bowl and leave to solidify and cool down in the pot.
4. Replace bowl with glass beaker, melt in water bath, vacuum pump for ~15minutes, melt again, then pour into another beaker and vacuum pump for ~15 minutes and solidify and cool down in room temperature.
5. Melt in beaker in oven at 120 degrees, vacuum pump for ~15 minutes, melt in oven again, vacuum pump for ~15 minutes again and solidify and cool down in room temperature.
6. Same procedure as in #4 but without pouring into a second beaker.
7. Same procedure as in #5 with the addition of pouring between the second melting and second vacuum pumping.
8. Melt in oven, vacuum pump for ~15 minutes, melt in oven again, pour into second beaker and solidify and cool down in room temperature.
9. Melt in oven, pour into second beaker and solidify and cool down in room temperature.

The vacuum pump system that is going to be used is a water-driven system, see figure 33.

Figure 33 The water driven vacuum pump system

3.2.2 Estimation of attenuation, speed of sound, acoustic impedance and density

For agar or agarose based phantoms all these properties are listed in the article by Culjat et al. [7]. The values vary depending on concentration ratio between agar and water, but it is clear that an agar phantom can be made to have specific values. For candle gel none of these properties are known and all need to be tested. The attenuation in clear agar will also be tested.

The attenuation is to be tested using the setup described in section 2.1.3.1 and figure 4. The real setup can be seen in figure 34.

Figure 34 A) Aquarium with two 2 MHz transducers (circular), B) Function generator connected to the right transducer, C) Oscilloscope connected to the left transducer

The right transducer will send out a short pulse or burst at 2MHz. The burst will consist of approximately 15 wave cycles creating stable amplitude in the middle where values can be taken. Between the two transducers slabs of candle gel respectively agar will be placed and the decrease in amplitude will be measured on the oscilloscope. The thicknesses of the slabs that will be used are 1cm and 2cm. To calculate the rate of attenuation equation 28 will be used. With the chosen thicknesses and frequency equation 28 will be reduced to:

$$a \left[\frac{dB}{cm*MHz}\right] = \frac{20\log\left(\frac{A(2,2)}{A(1,2)}\right)}{2*(1)} = 10\log\left(\frac{A(2,2)}{A(1,2)}\right) \qquad (31)$$

To estimate the attenuation in the unit of dB/cm/MHz the only values needed are the amplitudes after passing through 1cm and 2cm slabs of each material.

To estimate the density [kg/m^3] of the candle gel the 2cm slab will be measured in all three dimensions and weighed. The speed of sound in the candle gel will be estimated from an ultrasound image of a test phantom. Measurements of the true physical dimensions of the phantom will be made and then the same dimensions will be measured using the ultrasound machine’s measurement tool. Using equation (3) the characteristic acoustic impedance for the candle gel can be estimated. This will be a very rough estimation of both the speed of sound and the acoustic impedance but will still give a good idea of the gels acoustic properties as a whole.

3.3 Container construction

The final phantoms need to be molded in some type of containers. From a teaching point-of-view it is desirable for these containers to be see-through from the sides. For this purpose the containers will be constructed out of Plexiglas and more precisely from 3mm PMMA. The glass can be cut with either a saw, classic glass cutter or in the mill. Each of these methods will be tested to find the best one. The idea is to make three containers with the dimensions listed in table 12.

Table 12 The dimensions for the containers

Dimension	Size(cm)
Length	15
Depth	8
Height	10

Each container will be constructed from five pieces, one bottom piece (15x8 cm), two long side pieces (15x10cm) and 2 short side pieces (10x8 cm). These five pieces will be glued together to form a container. Three different glues will be tested, two types of epoxy and one type of superglue. To ensure that there are no holes or leakage the inside edges of the containers will be sealed with a silicon-glue.

4. Results

In this chapter the results from the tests described and performed in chapter 3 will be presented. The results have been divided into 5 categories, background material results, phantom and artefact design, the final phantoms and ultrasound images of them and laboratory instructions for the phantoms.

4.1 Background materials

Two materials were tested as background material for the phantoms, agar and candle gel. The candle gel had issues with bubbles appearing with the suggested procedure and for this reason a series of tests were performed to try to improve the procedure, see section 3.2.1. In table 13 the results for each of the nine procedures that were tested are listed. Tests 1-3 gave the same kind of result that can be seen in figure 32.

Table 13 Results from the test for improving the candle gel melting and solidifying process

Procedure	Result (more/less/no bubbles, or no improvement)
1	More bubbles
2	More bubbles
3	No improvement
4	Less bubbles
5	Less bubbles
6	Less bubbles
7	No bubbles
8	No bubbles
9	Less bubbles

After these tests the best procedure or method for melting and molding candle gel can be summed as:

1. Measure and put the solid candle gel in a glass beaker
2. Place the beaker in an oven at 120 degrees Celsius and let the gel melt

3. Put the beaker with the melted gel in a vacuum pump system for approximately 15 minutes
4. Put the beaker back into the oven until it is melted again
5. Take the beaker out of the oven and pour the gel slowly and carefully into your container or mold and let it cool down and solidify in room temperature.

In figure 35 the results of the attenuation measurements are shown and in table 14 the values from the graphs are listed.

Figure 35 Attenuation measurements for Agar and candle gel

Table 14 Values from the graphs in figure 35. The amplitudes are the peak-to-peak voltage

Material	Amplitude (V) (peak to peak voltage)
Agar 1cm	2,92
Agar 2cm	2,82
Candle Gel 1cm	2,74
Candle Gel 2cm	2,40

In table 15 the attenuation rates calculated using equation 31 is listed. In table 15 the results from the estimations of the other properties for the candle gel are also listed.

Table 15 Estimation of acoustic properties of the candle gel and agar

Property	Value
Attenuation in Candle Gel (α)	~0.54 dB/(cm * MHz)
Attenuation in Agar (α)	~0.18 dB/(cm * MHz)
Speed of Sound in Candle Gel	~1320 m/s
Speed of Sound in Agar	~1500 m/s
Density of Candle gel (ρ)	828 kg/m^3
Acoustic Impedance of Candle Gel	1.09*10^6 kg/m^{2}s

4.2 Artefact materials and objects

In sections 3.1.1-3.1.8 different objects and materials were tested for the different artefacts seen in figure 22. All the objects were tested in the aquarium setup, see figures 27 and 28, and in addition some of them were molded into miniature phantoms and tested again. In table 16 the chosen solution for each artefact is listed.

Table 16 Materials and objects chosen for the artefacts

Artefact	Chosen solution/design
#1: Specular reflection	Plastic foil

#2: Resolution artefact	3D-printed frame and 0.5mm nylon thread
#3-4: Attenuation artefact	Candle gel embedded with graphite
#5-6: Enhancement artefact	Block of Agar
#7: Reverberation artefact	Metallic plate on 3D-printed table
#8: Comet tail artefact	1mm metallic wire
#9: Edge shadowing	Plastic glove
#10: Mirror Image artefact	Metallic plate on 3D-printed rack + Plexiglas piece

4.3 Containers and Artefact placement

Due to the number of artefacts and the purpose of the phantoms themselves it was decided that the artefacts were to be divided among three phantoms and hence three containers were built to hold the objects. In figure 36 an empty container is shown.

Figure 36 Empty phantom container made from 3mm PMMA

Since some of the artefacts belong to the same main group of artefacts (reflection artefacts etc.) it was decided to place artefacts belonging to the same main group in different phantoms. In table 17 the placement of the artefacts in the phantoms are listed.

Table 17 Placement of the different artefacts in the three phantoms

Phantom	Artefact #1	Artefact #2	Artefact #3
1	#1: Specular reflection	#3-4: Shadowing artefact	#7: Reverberation
2	#5-6: Enhancement artefact	#8: Comet-tail artefact	#9: Edge shadowing artefact
3	#2: Resolution artefact	#10: Mirror image artefact	

4.4 The final phantoms

In figures 37-39 schematic images of the three phantoms are shown. For the background material candle gel was chosen. The bottom layer is candle gel embedded with graphite (black layer) and the top layer is candle gel embedded with blue candle color (blue layer). The middle layer is clear candle gel.

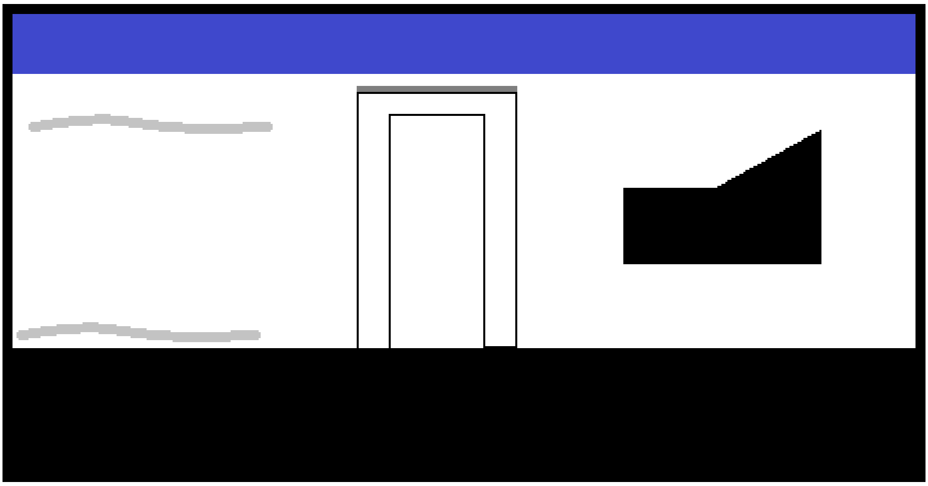

Figure 37 Phantom #1, containing artefacts #1, #7 and #3-4

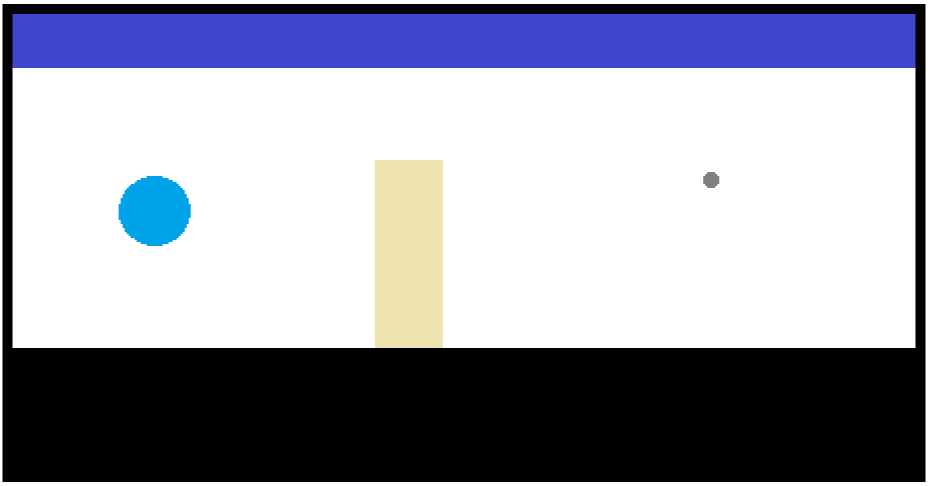

Figure 38 Phantom #2 containing artefacts #5-6, #8 and #9.

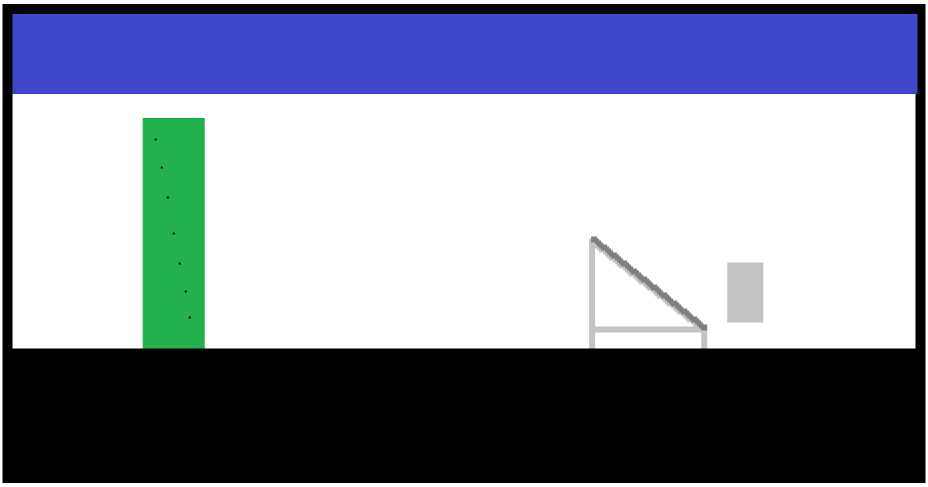

Figure 39 Phantom #3 containing artefact #2 and #10

The first step in creating the phantoms is melting gel and mixing it graphite, this is done after the first time in the oven and before vacuum pumping. When the gel has been vacuum pumped and melted again, it is poured into the container and objects that need to rest on the bottom of the container are put into place. Before the next layer of gel can be added the graphite layer needs to completely solidify. When the graphite layer has solidified more, uncolored, gel can be added. The uncolored gel is also added in layers so that objects that need to be placed at a certain height can be placed. When all objects have been placed and covered in sufficient amount of uncolored gel, the gel has to solidify before the blue layer can be added. The blue gel is mixed in the same way as the graphite gel. After the gel has been melted the coloring is added, the gel is then vacuum pumped and melted again and lastly carefully poured on top of the uncolored gel.

In figures 40-42 steps in creating the three different phantoms are shown. In figure 40 the first phantom in shown, the top left picture show the phantom from the side. At this point a layer of plastic foil is to be added on the left side of the table, top right picture, and the right side of the table is the object made of gel embedded with graphite. After the plastic foil has been added more gel is poured into the container and after clear gel has solidified the blue layer is added, see figure 43.

Figure 40 Part of the creation process for phantom #1

In figure 41 the second phantom is shown, the top left picture show the graphite layer and the first layer of clear gel. The block of agar is standing on the graphite layer and metallic string is pushed into the first clear gel layer.

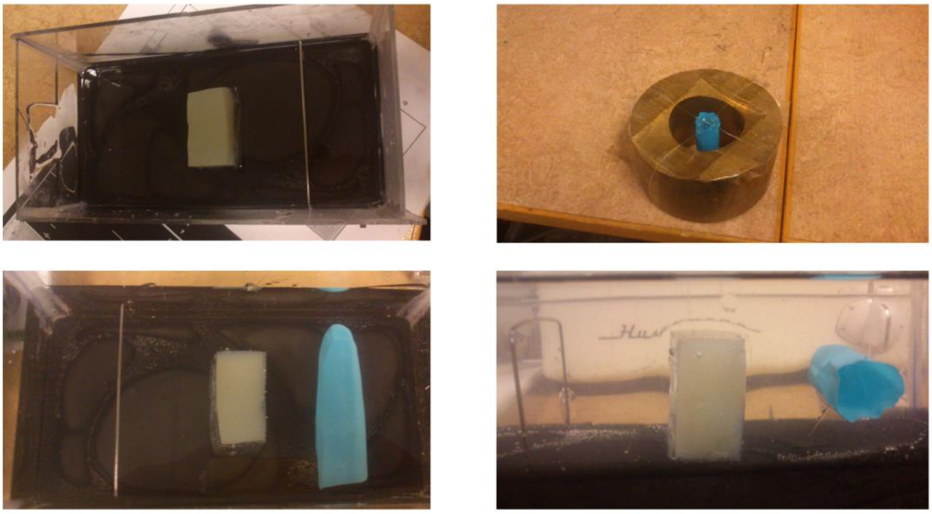

Figure 41 Steps in the creation of phantom #2

The top right picture show how a finger from a plastic glove is suspended to be able to fill it with clear gel. The bottom pictures show how the gel-filled finger has been placed in the phantom and how the phantom looks from the side after all three objects have been sufficiently covered with clear gel. When the clear gel has solidified a layer of blue gel is added, see figure 44.

In figure 42 the third and final phantom is shown. In the top left picture the graphite layer and one layer of clear gel has been added. The Plexiglas block is resting on the clear gel layer. For each picture more and more clear gel has been added. In the bottom right picture all objects are sufficiently covered in clear gel and once it is solid a layer of blue gel is added, see figure 45.

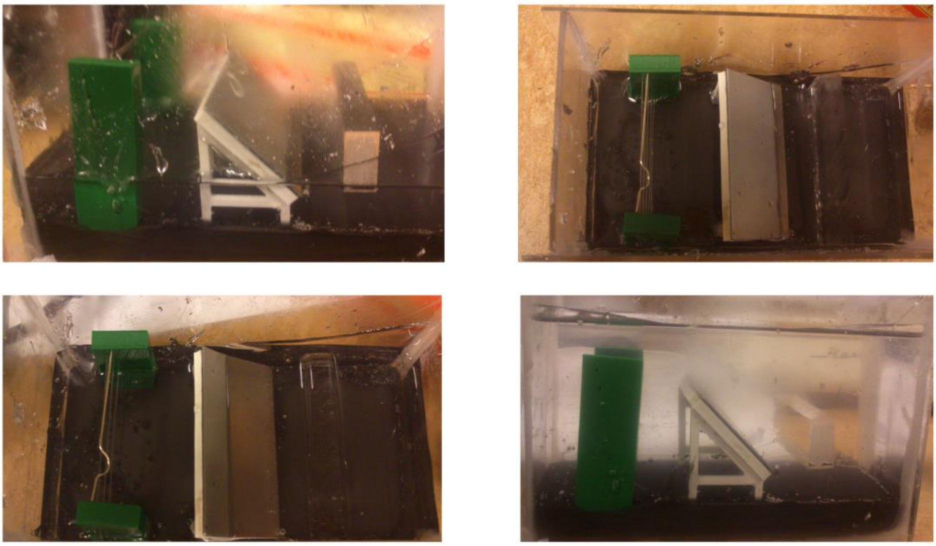

Figure 42 Steps in creating the third and final phantom

In figures 43-45 the final phantoms with a layer of blue gel on the top are shown. The first phantom, seen in figure 43, contains three artefacts as described above. The first object is a bit hard to see but can be seen clearer in the ultrasound image in figure 46.

Figure 43 Phantom #1 from different angles. Top image from the front. Middle image from the front and to the side. Bottom image is from above

In figure 44 the second phantom is shown. This phantom also contains three objects creating three different artefacts.

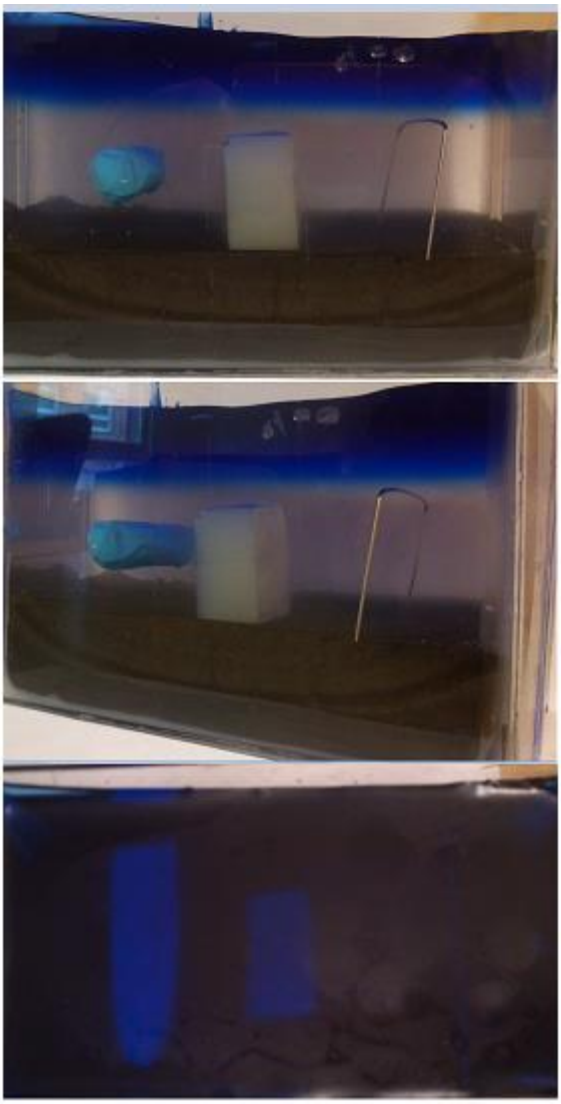

Figure 44 Phantom #2 from different angles. Top image from the front. Middle image from the front and to the side. Bottom image is from above

The third phantom only contains two artefacts and can be seen in figure 45.

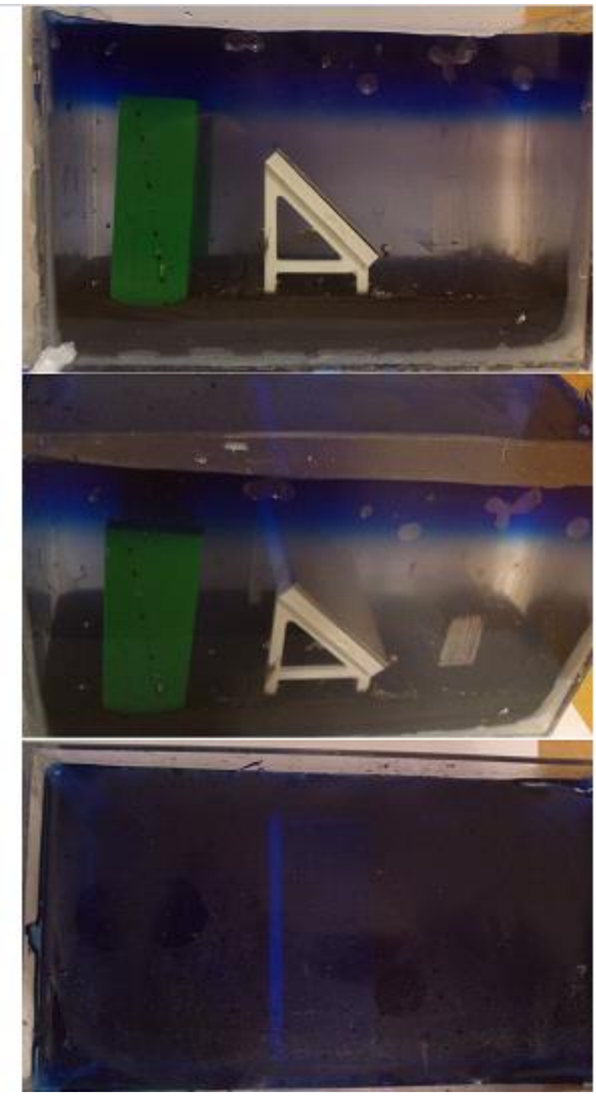

Figure 45 Phantom #3 from different angles. Top image from the front. Middle image from the front and to the side. Bottom image is from above

In the following figures the B-mode images of each artefact in the three phantoms are shown. Due to image-transfer problems these images were made with another machine than the one that was used for the tests.

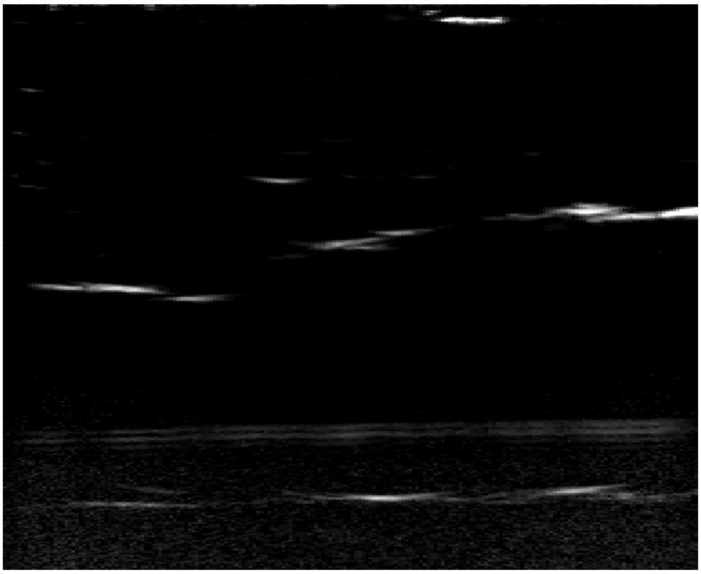

Figure 46 Artefact #1 seen in a B-mode image

In figure 46 a B-mode image of artefact #1 is seen. The short lines in the middle of the image are one layer of plastic foil that has moved up a bit at some places. Near the bottom the same type of line can be seen, that is also created from plastic foil. The two gray lines just above are reflections from the edge of the phantom container. Figure 47 shows the reverberation artefact. For each reflection the echo signal gets weaker and less focused. In figure 48 an attempt to show shadowing is seen. In figure 49 an attempt to show edge shadowing is seen. The edges of the object do disappear but it is hard to see if the shadowing continues down. In figure 50 the enhancement artefact can be seen. This object and B-mode image is interesting because the object itself is scattering but is enhancing the signal. A second effect is also seen here and that is speed displacement. The speed of sound in the object is a bit higher than in the surrounding material and therefor the bottom of the object, the second sharp line, is higher placed than the corresponding edge. In figure 51 the comet-tail artefact can be seen. In figure 52 the resolution artefact can be seen. Lastly in figure 53 the mirror-image artefact can be seen.

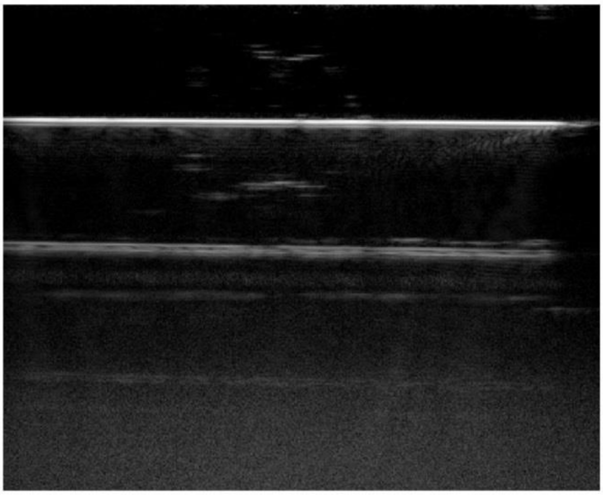

Figure 47 Artefact #7 seen in a B-mode image

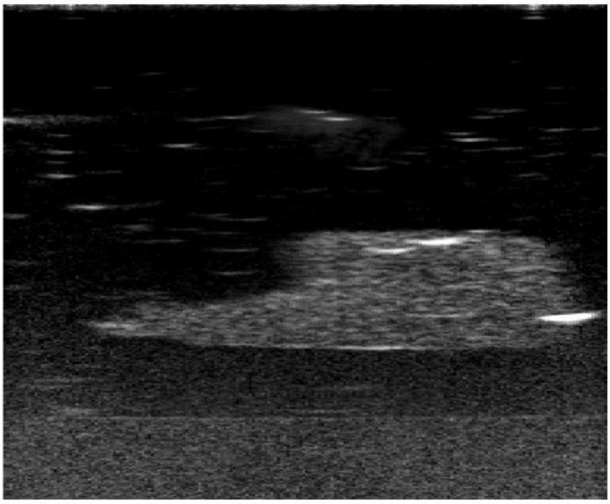

Figure 48 Artefact #3-4 seen in a B-mode image

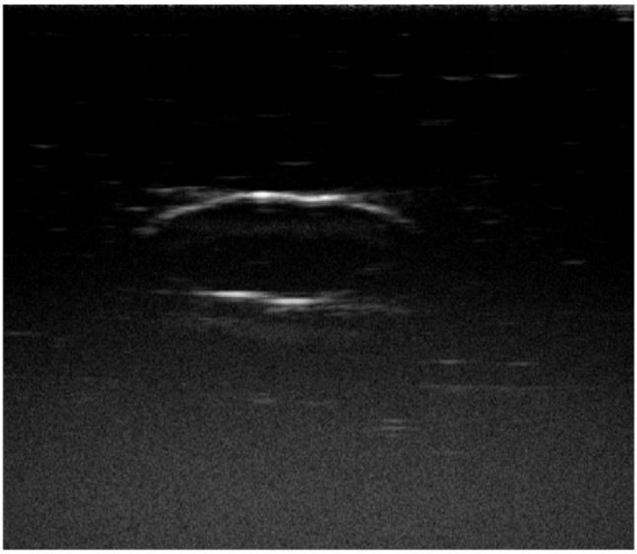

Figure 49 Artefact #9 seen in a B-mode image

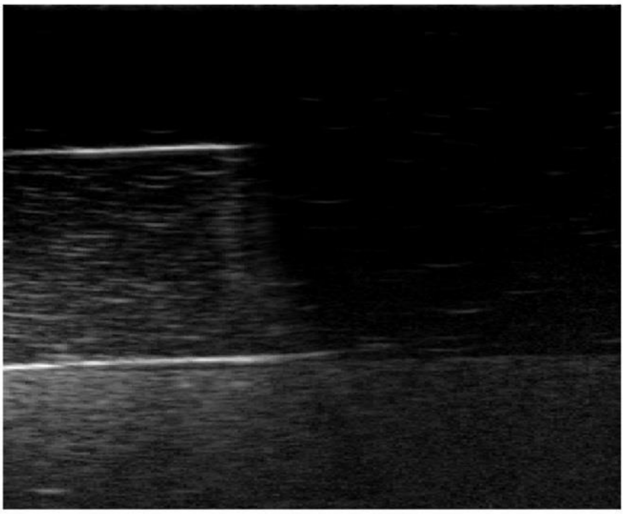

Figure 50 Artefact #5-6 seen in a B-mode image

Figure 51 Artefact #8 seen in a B-mode image

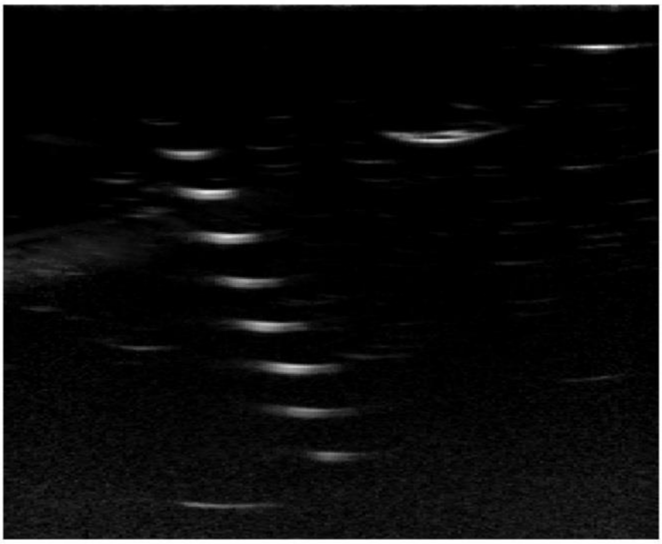

Figure 52 Artefact #2 seen in a B-mode image

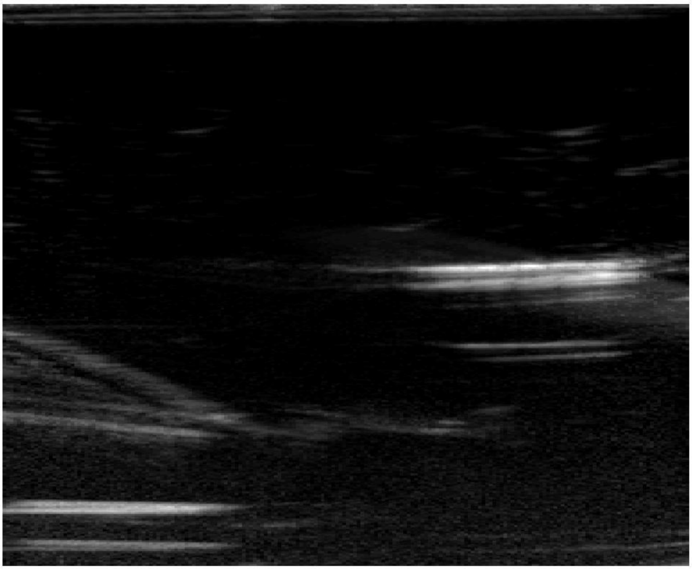

Figure 53 Artefact #10 seen in a B-mode image

4.5 Suggestion for instructions for a laboratory exercise using the artefact phantoms

The goal with the phantoms is to use them in a laboratory exercise and for that reason a suggestion for instructions to the laboratory exercise is to be presented, for Swedish version and answers to the questions see appendix A and B.

Ultrasound systems: Artefacts

Equipment: Ultrasound machine and artefact phantoms (3 phantoms)

Preparation: Artefacts in diagnostic ultrasound and B-mode imaging are not hidden treasures in the image but irregularities that distort the image and to give a false representation of the anatomy of the body. Most artefacts arise due to one of a number of false assumptions. Which are 4

most important assumptions?
Are there any other factors that may cause artefacts to arise?

NOTE! The phantoms are fragile and should be handled with care. Make sure that there is sufficient amount of water or ultrasound gel between the transducer and phantom surface. Avoid dragging the transducer across the surface; lift the transducer every time you want to change the position. Insufficient contact and dragging the transducer can cause the surface to crack and break. In some of the phantoms there are bubbles that are not actual parts of the artefacts, they are a bi-product of the production process.

<u>Investigate the phantoms:</u> The three phantoms contain an unknown number of objects. Each object creates a common B-mode artefact and it is your task to figure out which object/artefact is placed where and how many there are; in other words a small treasure hunt to find the hidden artefacts. Again be careful with the phantoms and lift the transducer when moving it around, **do not** drag it across the surface.

Carefully scan each of the three phantoms and answer the following and fill out the table:

1. How many artefacts can be seen in each phantom?
2. What can cause each of these artefacts, both in the phantoms (sketch the objects, no peeking) and in a human?
3. Name each of the artefacts you see in the phantoms.
4. Compare your sketches to the phantoms.
5. Compare the phantoms and their ultrasound image to the fake image that the phantoms are based on. (Ask the instructor to give the fake image to you).

Phantom	# of artefacts:	Names of the artefacts:	Caused by:
1			
2			
3			

5. Discussion and Conclusions

The subject of image artefacts in diagnostic ultrasound and in B-mode imaging especially is a well-documented subject in both articles and literature; see Feldman et al. [4], Hindi et al. [6] , Scanlan [5] and Hoskins et al. [1]. Commercial phantoms are usually either quality assessment phantoms or training phantoms. The first kind is used to secure that the ultrasound system is up to standard and the second type is mainly used for simulating a certain type of examination. In research many phantoms are made ad hoc and thrown away after usage, these phantoms are usually made to investigate if certain effects can be seen or to see how certain things behave in an ultrasound image. Few or no phantoms are designed to give a certain image or resemble a certain effect. Creating phantoms that show a certain image or effect is a bit unconventional and demands a lot creativity and ingenuity.

5.1 Background material

The choice to use the candle gel as background material for the phantoms was made because of the properties the gel have that a material like agar does not have. The first property is the ability to last over time. Unlike agar the candle gel does not dry out to the same extent, so far there have not been any signs of the gel exhibiting the same kind of shrinking like agar. This is a major advantage; it means long-lasting phantoms can be made. One of the initial problems with the gel was the creation of bubbles in the gel. After a series of tests a process to reduce the bubble to almost zero was found. Evaluating and comparing the different methods used a number of conclusions can be made. The gel was, in the first tests, not heated to a high enough temperature to make the gel viscous enough for the created bubbles to be able to escape. Vacuum pumping the gel may have had the opposite affect than the wanted one i.e. vacuum pumping the gel may have created more bubbles than it removed. Heating the gel to a temperature well above one hundred degrees, without bringing it to a boil, is the main reason the bubbles disappeared. There were still bubbles created in the phantoms, most of these came from the objects molded into the gel.

One more important property of the gel is the transparency of the gel. When clean and clear agar has solidified it has a yellow color and is not transparent but the candle gel is. Since the phantoms are supposed to be used in a laboratory exercise it is nice to be able to see the objects creating the artefacts in the image. At the same time it is desirable not to see what is inside the phantoms until after the investigation has been made. This is the reason behind why a thin layer of dyed gel was added on the top of each the phantoms.

Comparing the acoustic properties of the gel listed in table 15 to the averages for human tissue listed in tables 1-3, it is clear that both the speed of sound and acoustic impedance of the gel is lower than the soft-tissue averages but that the attenuation is about the same. For agar the acoustic properties are the opposite, the speed of sound and acoustic impedance is about the same but the attenuation is much lower than the soft-tissue averages. The clearness of the gel combined with the attenuation rate in the gel means that there is no need to add something to the gel to increase the attenuation. The option available for this purpose would have been adding graphite, see Burlew et al. [44], and this would make the gel non-transparent.

In conclusion, the candle gel was chosen over agar as background material because the melting and molding process is less complicated and more gel can be melted and processed at once compared to agar. Secondly the gel is clear and the reversibility of the candle gel is better than the reversibility of agar. The candle gel is long-lasting and does not exhibit the same rate of dehydration and shrinking as agar does. Even though both the speed of sound and acoustic impedance of the candle gel is lower than the corresponding values for soft-tissue (average value), the fact that the attenuation is about the same was another reason to choose candle gel over agar.

5.2 Artefacts and phantoms: Design and results

As seen in sections 3.1.1-3.1.8 a number of different solutions for each of the artefacts were tested and in section 4.2, table 16, the chosen objects are listed. The B-mode images for each of the eight chosen objects are shown in figures 47-54. As mentioned above it is a unconventional to design and construct phantoms in the way that it has been done in this project and for some of the artefacts seen in figure 22 it have become apparent that reproducing the exact same image is more or less impossible. Comparing the B-mode images of the phantoms to the fake sonogram in figure 22 it is apparent that some artefacts have been reproduced better than others.

Artefacts #2, 7, 8 and 10 (figures 53, 48, 52 and 54) are the ones that have been reproduced with the best result. For artefact #2 both images display the same kind of smearing of the echoes from the deeper laying threads. The image of the phantom very much resembles the image in figure 22. The issue with this detail happened during the production process. The 3D-plastic starts going soft and bend already around seventy or eighty degrees and the candle gel were heated up over one hundred degrees. With the tension from the suspended strings the frame started to bend and a supporting rod had to be inserted to prevent the bending, see figure 43.

The real image of artefact #7 displays multiple lines but since the plate itself if place further from the phantom surface and that it is wider than the object in figure 22, it means that the reverberation echoes are further apart in the phantom and does not get narrower in the same way. If the plate was placed closer to the surface more reflection echoes would be seen.

The appearance of the comet-tail artefact in the phantom, figure 52, and in figure 22 is not completely the same. In figure 22 the artefact has a very sharp conical shape and the image of the phantom is wider and not as sharp. This is a difficult artefact to reproduce and the real appearance (when appearing in a human) of this artefact may vary (see figure 19) and the sharp shape seen in figure 22 may not be possible to recreate.

The image of artefact #10, the mirror-image artefact, may be one of the best results among all the artefacts. First off the reflector only gives a very weak echo just as the reflector in figure 22. Secondly, both the real echoes from the object from above and the reflection echoes from the side can be seen in the same image and these echoes are very clear. Each sequence of echoes from the Plexiglas piece are two clean lines, one for the first interface and one for the second interface just like the image in figure 22.

The results for artefacts #1, 5-6 (figures 47 and 51) are moderately good. For artefact #1 the plastic foil was chosen. During the placement of the foil air pockets were created underneath the foil. When the gel was poured onto the foil the air trapped under the foil tried to escape, which lead to the lifting of the foil and hence the wavy appearance in the B-mode image. The echoes from the interfaces created by the foil are clear and can be easily identified.

For artefact #5-6 it was not possible to recreate the multiple reflection part of the image in figure 22. The enhancement part of the artefact was easily created by using a block of agar. In figure 51 it is clear that the area distal to agar block is lighter than the adjacent area where the ultrasound only has travelled through the candle gel. Even if parts of the ultrasound is scattered inside the agar block the attenuation in the block is only about 40% of that in the surrounding gel. The object in the phantom and the B-mode image may not look exactly like the corresponding images in Figure 22 but the main effect, the enhancement “shadow”, is seen. The object in figure 22 is most likely a liquid-filled glass container made from very thin glass. The reflection at the first interface is probably very high but this is compensated by having a liquid that does not attenuate at a very high rate inside the container. This construction is something that might be worth trying if the phantoms are ever re-made.

The results for artefacts #3-4 and 9 (figures 49 and 50) are the least good results. Artefact #3-4 was supposed to show the shadowing effect as it is seen in figure 22. The shape of the object has been reproduced but little or no shadowing is seen in figure 49. One reason may be that the amount of graphite added to the gel that the object is made of is too low, a higher concentration of graphite is needed in the gel that is used to mold the object. There is one part of the result for this artefact that is positive and that is that there are no strong reflections along the edges of the object, except for what looks like a few air bubbles.

The B-mode image of artefact #9 is the image that resembles its counterpart in figure 22 the least. In figure 50 the top and bottom edges of the plastic glove-finger is seen and it does look like the side-edges are missing. The regions with no echoes, distal to these edges are not seen in the image. This might be due to the settings of the ultrasound machine or it might be due to the design of the object. If the plastic is not fully stretched to form a circle the regions without echoes might not appear.

In conclusion, four of the eight objects in the phantoms created B-images that resembled the corresponding images in figure 22 very well and beyond expectations in some cases. Two of the eight objects gave an image that was okay but not more and could use some more thought if the phantoms are re-molded in the future. The last two objects did not give the expected and wanted image beyond the objects themselves. The images of the objects were close to the images in figure 22 but the areas distal to the objects did not look as excepted. These two objects would need more testing if the phantoms are re-molded in the future.

5.3 Final conclusions

As stated in the introduction one of the goals with this project, the main goal, was to design and build one or a few phantoms that could be used in a laboratory exercise in the course '*Ultrasound physics and Technology'* to make learning about artefacts more interactive. The result became the three phantoms presented above. These three phantoms have already been used in the laboratory exercise this semester (spring of 2015). The idea to add the layer of colored gel came from the students that had the first laboratory session with the phantoms. In section 4.5 a suggestion for laboratory instructions is presented, this is a rough idea of how the phantoms can be integrated into the laboratory exercise.

The other two questions that was the base for this thesis were:

1. What is an ultrasound artefact and what are the physical properties that cause them?
2. How can the artefacts be visualized in phantoms?

These questions have been more or less answered in chapter 2.3 and forward. After reading literature and articles about the artefacts it became clear that it is the assumptions made about the acoustic properties of human soft-tissue and not properties themselves that are the reason behind the occurrence of many of the artefacts. These assumptions are listed in section 2.2.1, page 22, and when one or several of these assumptions are false the risk of certain artefacts appearing is large. How the artefacts in figure 22 have been visualized in phantoms have been presented in chapters 3 and 4 and have been discussed above.

5.4 Outlook and Future work

As discussed above some of the artefacts were not perfectly reproduced. Future work could include improving these particular artefacts and it could also include designing new phantoms containing artefacts mentioned in section 2.3 that were not present in figure 22. The artefacts mentioned in section 2.3 are artefacts that mainly arise in standard B-mode imaging but there are many other applications that have application-specific artefacts that also could be investigated and phantoms containing these artefacts could be designed. For example there are some artefacts that arise in Doppler-applications that can not arise in B-mode imaging. Further work could include designing Doppler-artefact phantoms.

As mentioned in the previous section the current phantoms were used in a laboratory exercise already in February 2015 and the hope is that the phantoms, in their current form or in an improved form, will be continued to be used in this exercise. In addition to learning about artefacts and phantoms in a more interactive way the hope is for the students get a feeling for how the ultrasound image of an object may differ from the actual physical form of the object.

Improvements could be done with the phantom containers to ensure that the students cannot see the inside of the phantoms until after they have investigated them. A small improvement was done between the first and second groups of students that had the pleasure of being the first to use the phantoms during the laboratory exercise and as mentioned above this improvement was the addition of a top layer of blue-colored gel.

6. References

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Appendix A: Laboratory instructions

English Version

Ultrasound systems: Artefacts

Equipment: Ultrasound machine and artefact phantoms (3 phantoms)

Preparation: Artefacts in diagnostic ultrasound and B-mode imaging are not hidden treasures in the image but irregularities that distort the image and to give a false representation of the anatomy of the body. Most artefacts arise due to one of a number of false assumptions. Which are 4 most important assumptions?

1. ………………………
2. ………………………
3. ………………………
4. ………………………

Are there any other factors that may cause artefacts to arise?

NOTE! The phantoms are fragile and should be handled with care. Make sure that there is sufficient amount of water or ultrasound gel between the transducer and phantom surface. Avoid dragging the transducer across the surface; lift the transducer every time you want to change the position. Insufficient contact and dragging the transducer can cause the surface to crack and break. In some of the phantoms there are bubbles that are not actual parts of the artefacts; they are a bi-product of the production process.

Investigate the phantoms: The three phantoms each contain an unknown number of objects. Each object creates a common B-mode artefact and it is your task to figure out which object/artefact is placed where and how many there are; in other words a small treasure hunt to find the hidden artefacts. Again be careful with the phantoms and lift the transducer when moving it around, **do not** drag it across the surface.

Carefully scan each of the three phantoms and answer the following and fill out the table:

1. How many artefacts can be seen in each phantom?
2. Name the artefacts you see in each phantom.
3. What can cause each of these artefacts, both in the phantoms (sketch the objects, no peeking) and in a human?
4. Compare your sketches to the phantoms.
5. Compare the phantoms and their ultrasound image to the fake image that the phantoms are based on. (Ask the instructor to give the fake image to you).

Phantom	# of objects /artefacts:	Name of the artefacts:	Created by:
1			
2			
3			

Discuss your findings with the instructor.

Swedish version/Svensk version

Ultraljudssystem: Artefakter

Utrustning: Ultraljudsmaskin och artefaktsfantom (3 fantomer)

Inledning: Artefakter i diagnostiskt ultraljud är inte gömda skatter i B-mode bilden utan är störningar av olika slag som förvränger bilden och gör att ultraljudsbilden blir en felaktig återgivning av den sanna anatomin. De flesta artefakter uppstår på grund av ett antal felaktiga antaganden. Vilka är de fyra (4) viktigaste antagandena?

1. ……………..
2. ……………..
3. ……………..
4. ……………..

Vilka andra faktorer kan också bidra till att artefakter uppstår?

OBS! Fantomen är ömtåliga och skall behandlas varsamt. Se till att kontakten mellan givaren och ytan är bra och mängden vatten eller ultraljudsgel är tillräcklig. Undvik att dra givaren över ytan, när du skall flytta givaren från en position till en annan lyft givaren från ytan. Om givaren dras över ytan är risken stor att ytan förstörs och går sönder. Detta påverkar också bilden. I några av fantomen finns det bubblor som inte är en del av artefakterna. Dessa är en biprodukt av tillverkningsprocessen.

Undersök fantomen: De tre fantomerna innehåller var för sig ett okänt antal objekt som var för sig skapar en allmänt känd artefakt. Uppgiften är att hitta var dessa objekt är och vilken artefakt de skapar; med andra ord en liten skattjakt. Än en gång så är det viktigt att vara försiktig och lyfta givaren när man byter position och att **inte** dra givaren över ytan.

Undersök varje fantom och svara på följande och fyll i tabellen:

1. Hur många artefakter ser ni varje fantom?
2. Vad kan orsaka denna artefakt, både i fantomen och i en människa? (Skissa objekten och smygtitta inte)

3. Namnge artefakterna ni ser.
4. Jämför era skisser mot fantomen.
5. Jämför fantomen med den bild som fantomen är baserade på.

Fantom	Antal objekt /artefakter:	Artefakternas namn:	Skapas av:
1			
2			
3			

Diskutera vad ni har hittat med laborationshandledaren.

Answers: English Version

The four assumptions we are looking for are:

1. Speed of sound
2. Attenuation,
3. Beam propagation
4. Echo-origin (one object/interface = one echo and echoes from the last pulse only)

Other possible causes are:

1. Side and grating lobes. These may create echoes from objects outside the main beam. If these echoes are strong enough to get detected they will be displayed as coming from objects inside the main beam.
2. Different resolution artefacts. Two or more objects that are too closely spaced to be resolved individually. Depends on the pulse length (axial direction) and beam width (of one scan line in the lateral direction)

The table:

1. Phantom 1: 3 artefacts. Name: Specular reflection, Reverberation and Shadowing. Caused by: Plastic foil, Metallic plate and Gel detail.
2. Phantom 2: 3 artefacts. Name: Edge shadowing, Enhancement and Comet-tail. Caused by: Plastic glove, block of agar and metallic string
3. Phantom 3: 2 artefacts. Name: Resolution artefact and Mirror Image. Caused by: Suspended strings, Reflector and Plexiglas piece.

In the human body:

1. Specular reflection occurs at most tissue-to-tissue interfaces.
2. Reverberation occurs with bones or big collections of gas.
3. Shadowing occurs in calcifications and gallstones or similar high attenuation structures.

4. Edge shadowing can appear around blood vessels or around cysts.
5. Enhancement is the opposite of shadowing, usually behind fluid-filled cavities.
6. Comet-tail is cause by metallic objects. If the cause is from internal structures it is called ring-down.
7. Two or more objects that are too closely spaced to be resolved individually. Depends on the pulse length (axial direction) and beam width (of one scan line in the lateral direction)
8. Close to high reflecting surfaces like the diaphragm.

Answers: Swedish version/Svensk version

De fyra antagandena vi söker är antaganden om:

1. Ljudhastigheten
2. Dämpningen i vävnaden
3. Hur ljudet propagerar genom vävnaden. Vi antar att det är rakt ner och lika rakt tillbaka.
4. Ekots ursprung. Varje objekt/yta på vägen ger endast ett eko, alla eko kommer från objekt innanför huvud-ultraljudsstrålen och alla eko är ett resultat av den senast utsända pulsen.

Andra saker som kan orsaka artefakter:

1. Sido- och gitterlober. Kan ge ekon från objekt utan för huvudstrålen som sedan visas som att objekten ligger i huvudstrålen.
2. Upplösningsartefakter. Om två objekt ligger för nära varandra finns det en risk att de ej kommer att visas som enskilda objekt. I den axiala riktningen är det pulslängden som bestämmer och i den laterala riktningen är det bredden på ultraljudsstrålen.

Tabellen:

1. Fantom 1: 3 artefakter, Namn: Vanlig reflektion, Reverberation och Skuggning. Skapas av: Plastfolie, Metallplatta och Gel-detalj.
2. Fantom 2: 3 artefakter, Namn: Kantskuggning, Förstärkning och Kometsvans. Skapad av: Plasthandskefinger, Agarblock och Ståltråd.

3. Fantom 3: 2 artefakter. Namn: Upplösningsartefakt och Spegelbildsartefakt. Skapad av: Uppspända trådar, Reflektor och plexiglas stav.

I kroppen

1. Uppstår vid mer eller mindre varje vävnad-till-vävnads övergång.
2. Reverberation kan uppstå vid ben eller stora samlingar av gas.
3. Förkalkningar kan orsaka skuggning, gallsten också. Eller andra likande strukturer som dämpar mycket.
4. Kantskuggningen kan uppstå runt runda blodkärl eller runt vätskefyllda cystor.
5. Förstärkning är motsatsen till skuggning. Uppstår oftast bortom vätskefyllda områden.
6. Kometsvansen orsakas av metallobjekt. Om det är naturligt förekommande strukturer som orsakar artefakten kallas den för ”ring-down”.
7. Om två objekt ligger för nära varandra finns det en risk att de ej kommer att visas som enskilda objekt
8. Spegelbildsartefakter kan uppstå nära kraftigt reflekterande ytor så som diafragman.

Appendix B: Extensive protocol for Candle gel phantoms

In chapters 2.5, 2.6.3, 3.2, 3.2.1 and 4.1 the initial process, the tests to improve the process and the final improved process for using candle gel to make ultrasound phantoms are presented. The idea of this appendix is to give a more detailed description of how to use the candle gel to make ultrasound phantoms.

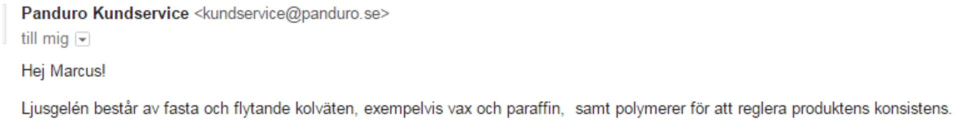
The gel is reversible and can be molded and re-molded many times over, an exact number of times has not been tried. From the solid state the gel needs to be heated to a minimum of 85 degrees Celsius. After the tests it was determined that heating the gel was best done in an oven and to get rid of all and any bubbles the required temperature was well above 100 degrees. In this case the oven was set to 120 degrees and this worked well. The gel was placed in glass beakers with a tip to pour from (see figure 35, page 62) to melt in. The pouring has to be done very carefully to avoid bubbles. The following list is an extended version of the list seen in chapter 4.1, pages 61-62, and the discussion in chapter 5.1.

1. Set the oven to 120 degrees Celsius and let it heat up.
2. Measure and put the solid candle gel in a glass beaker, when the phantoms were made 3 250ml beakers were used.
3. Place the beakers in the oven and let the gel melt. By heating the gel well above 100 degrees it will become very viscous and any bubble created or present will be able to escape.
4. Make sure to use gloves that protect against heat when handling the heated beakers in the following steps.
5. If this is the first or last layer being prepared this is the time to add either the graphite or the gel coloring to the melted gel. Since adding either of these requires stirring doing it before vacuum pumping is ideal.
6. Put the beaker with the melted gel in a vacuum pump system for approximately 15 minutes. This is step is made to ensure that no bubble are left in the gel, especially if graphite or coloring was added to the gel.

7. Put the beaker back into the oven until it is melted again. During the previous step the gel will solidify slightly and therefor need to be heated and melted again.
8. Take the beaker out of the oven and pour the gel slowly and carefully into your container or mold and let it cool down and solidify in room temperature.
9. After adding the first layer with graphite it is important to let this layer solidify completely before adding the next layer. When adding the last layer with coloring it is important that all previous layers have solidified completely. This to prevent too much of the mixing of the graphite/colored gel and the clear gel.
10. Depending on where an object needs to be placed different layers need to solidify so that objects can be placed. Some objects can be placed before adding the first layer and some need to have a layer to rest on unless some kind of suspension mechanism has been designed.

Appendix C

Correspondence with Panduro Hobby’s customer service.



Panduro Kundservice <kundservice@panduro.se>
till mig

Hej Marcus!

Ljusgelén består av fasta och flytande kolväten, exempelvis vax och paraffin, samt polymerer för att reglera produktens konsistens.

Popular scientific summary

Ultrasound artefacts – Hidden treasures or fool’s gold?

Ultrasound is an important medical imaging technique and recognizing errors or artefacts in the images is important. Some artefacts may be a sign of illness while others are not. Finding an ultrasound artefact that is a sign of illness and being able to use it to make a correct diagnosis is like finding a hidden treasure. The opposite can be said when finding an artefact that is not, then it is like finding fool’s gold. Knowing the difference and what to look for is therefore the key and practicing on doing ultrasound examinations is crucial. Using ultrasound phantoms is one of the best ways to practice. An ultrasound phantom is an object filled with a material made to mimic tissue and the acoustic properties of tissue. In a phantom a vast number of objects can be placed to create a certain ultrasound image.

Three phantoms containing different items that create eight different common ultrasound artefacts have been designed. The reason behind designing these phantoms was to make the teaching and learning about ultrasound artefacts in the course ‘*Ultrasound physics and Technology’* more interactive than before (this is a course given at the Department of Biomedical Engineering). It was decided that the best way was to make phantoms that could be used by students in a laboratory exercise. The idea is for students to both learn about some of the most common ultrasound artefacts and how the ultrasound image of an object in many ways can be different from the true physical appearance of that object.

A vast number of materials and items were tested in order to find the perfect item for each of the artefacts. This was one of the biggest issues in the project, finding the right materials, since the items needed to have a very specific look in the ultrasound image. The tests to find the best items and materials were done in an experimental setup using water as the background material (instead of a tissue mimicking material). Water is a great medium to do tests like this in because sound loses very little energy when traveling in water. The next step in the testing was to test how the best items and materials looked when molded into the background material. After these tests the items and materials that looked best compared to a reference image were chosen to be molded into the final phantoms. Two background materials, agar and candle gel, were available and after many different tests, including tests of some of the acoustic properties of the two materials, it was decided that the best background material was the candle gel. With the background material and items decided the final design could be made.

The main goal was to design and build phantoms that could be used by students in a laboratory exercise and the phantoms were used by students for the first time in February 2015. The ultrasound images of the three phantoms were overall very good compared to the reference image that was used as inspiration and the eight different artefacts could be seen. Some improvements could be done with these phantoms. The work also opens up the possibility to design more phantoms showing off other artefacts.