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MATERIAL DEVELOPMENT FOR ULTRASOUND QUALITY ASSURANCE

Master of Science Thesis

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ABSTRACT

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Ultrasound transducers are usually the weakest point in an ultrasonic device. Malfunction in the transducer can cause distortion in an ultrasound image. Ultrasonic devices should therefore be checked in a regular basis to prevent the usage of broken devices although there are no necessary standards for ultrasound quality assurance. Progress is slow because ultrasound is considered as a safe imaging method, which doesn’t need such accurate supervision. Studies have shown that there are several ultrasonic devices in use, which have some kind of malfunction. With the quality assurance phantom, the operation ability of ultrasonic devices and especially the functionality of the transducer can be improved via testing transducers regularly. Phantoms in clinical use are usually meant to mimic the human body or properties of tissues. Phantoms are used in studies, tests and trainings where in vivo models are inappropriate.

The main objective of this thesis is to study the materials, which are used in ultrasound phantoms, and to study the functionality of materials for the application. The most common materials used in phantom materials are gelatin and agar. These materials are of animal origin and they are exposed to bacterial growth easily, which shortens their lifetime. Other materials are polymer based like polyurethane, polyvinyl alcohol and polyacrylamide. All materials mentioned are water-based, which cause hydration. Materials usually retain their acoustical properties only a few months, some couple of years. There are commercially available ultrasound phantoms but they are expensive. Therefore new materials, which would be more stable and cheaper of a price, were studied for ultrasound quality assurance.

Study of more stable materials was started with silicones, which do not show property changes during a long period of time. However, the acoustical properties of silicones are not suitable for ultrasound phantom application. Next step was to study the acoustical properties of experimental material. The properties turned out suitable for the ultrasound phantom application. Study of this material was carried out and different concentrations of experimental material were tested. The experimental material still needs further studies to be able to be used as the ultrasound phantom.

TIIVISTELMÄ

TAMPEREEN TEKNILLINEN YLIOPISTO
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Ultraäänianturi on ultraäänilaitteen heikoin osa, jonka toimintahäiriö voi aiheuttaa vääristymiä ultraäänikuvaan. Ultraäänilaitteet tulisi tarkastaa säännöllisesti, jotta toimintahäiriöt voidaan estää. Ultraäänilaitteille ei kuitenkaan ole olemassa määrättyjä standardeja laadunvalvontaan. Standardien laadinta on hidasta, koska ultraääntä pidetään turvallisena kuvantamismenetelmänä, joka ei vaadi tarkkaa valvontaa. Tutkimukset ovat kuitenkin osoittaneet, että useita rikkinäisiä ultraäänianturеita on käytössä. Laadunvalvontafantomin avulla ultraäänilaitteen toimintakykyä voidaan parantaa testaamalla anturit säännöllisesti. Kliinisessä käytössä olevat fantomit jäljittelevät ihmiskehoa tai kudosten ominaisuuksia. Fantomeita käytetään tutkimuksissa, testeissä sekä opetus- ja harjoittelutilanteissa, joissa elävän mallin käyttäminen on sopimatonta.

Tämän tutkimuksen päätarkoitus on selvittää käytössä olevien fantomi materiaalien ominaisuuksia ja soveltuvuutta fantomi käyttöön. Yleisimpiä fantomi materiaaleja ovat agar ja gelatiini, jotka ovat eläinperäisiä materiaaleja. Nämä materiaalit altistuvat herkästi bakteereille, jolloin niiden käyttöikä heikkenee. Muut fantomi materiaalit ovat polymeeri-pohjaisia kuten polyuretaani, polyvinyyli alkoholi ja polyakrylamidi. Kaikki edellä mainitut materiaalit ovat vesi-pohjaisia, joka aiheuttaa niiden altistumisen kuivumiselle. Materiaalit säilyttävät akustiset ominaisuutensa vain muutamia kuukausia, osa joitakin vuosia. Kaupallisesti on saatavilla laadunvalvontafantomeja, jotka ovat hyvin kalliita ja siksi uusia materiaaleja, joiden tulisi olla kestävämpiä ja halvempia, on tutkittu tässä työssä.

Tutkimus aloitettiin silikoneista, koska niiden ominaisuudet eivät muutu pitkänkään ajan kuluessa. Silikoni-materiaalien akustiset ominaisuudet osoittautuivat huonoiksi ultraääni fantomille. Seuraava askel oli tutkia erään kokeellisen materiaalin akustisia ominaisuuksia. Ominaisuudet osoittautuvat hyviksi käyttökohteen kannalta ja materiaalin eri konsentraatioiden akustiset ominaisuudet tutkittiin. Tulokset ovat lupaavia, mutta materiaali tarvitsee vielä lisää tutkimista, jotta sitä voidaan käyttää ultraäänifantomissa.

PREFACE

This work was done for the department of Electronics and Communication Engineering in the Tampere University of Technology as a Master of Science Thesis work.

I would like to thank professor Jyrki Vuorinen and professor Hannu Eskola for supervising my thesis and commenting and answering the questions during the past few months. Thanks to the employee of the department of Material Science who has given me help with the laboratory work and ideas of executing the testes.

Finally, I want to thank my boyfriend who has encouraged me to keep going with the thesis and to see the things in right light.

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Tanja Parviainen

CONTENTS

TERMS AND DEFINITIONS

A	Area
α	Attenuation coefficient
AAPM	American Association of Physicist in Medicine
ABS	Acrylonitrile butadiene styrene
ACR	American College of Radiation
AIUM	American Institute of Ultrasound in Medicine
A-mode	Ultrasound monitoring type, which shows the reflections in time axis
B-mode	Ultrasound monitoring type, which shows the ultrasound signal as a function of depth
BSA	Bovine serum albumin
c	Sound velocity in medium
CIRS	Computerized Imaging Reference System
CT	Computed tomography
Doppler	Ultrasound method to visualize and measure the flow
E	Energy / Young’s modulus
f	Frequency
FirstCall	Test method for ultrasound transducer
I	Sound intensity
I_0	Intensity of reference sound
λ	Wavelength
IEP	Isoelectric point
M-mode	Ultrasound monitoring type, which shows the place of the interfaces in real time
MRI	Magnetic resonance imaging
NaCl	Sodium chloride
PAA	Polyacrylamide
PMMA	Polymethyl methacrylate
PP	Polypropylene
PU	Polyurethane
PVA	Polyvinyl alcohol
PVA-C	Polyvinyl alcohol cryogel
PVC	Polyvinyl chloride
PVCP	Polyvinyl chloride-plastisol
PZT	Zirconate titanate
ρ	Density of medium
TPE	Thermoplastic elastomer
V	Volume
w	Energy density
X-ray	X-radiation

Z	Acoustical impedance of medium
Δt	Time

1 INTRODUCTION

Ultrasound is one of the most used imaging methods in clinical practice. Ultrasound is found to be a safe and effective method of studying human soft tissues. Even tough the ultrasound is widely used; it does not have proper standards for the quality assurance of devices even if other imaging methods require the regular quality assurance. The most fragile part of an ultrasonic device is a transducer. The transducer should be tested regularly and an effective method for testing them is an ultrasound quality phantom.

Phantoms are used to mimic human body in different areas in clinical practice. Ultrasound phantoms are usually made of material solutions that mimic the acoustic properties of human soft tissue. Phantoms can be made of any material and the most common ones are gelatin and agar. Nowadays polyvinyl alcohol cryogel (PVA-C) is popularly used material. These materials are used phantoms that are made in laboratories for the researchers' own use but commercially available ultrasound phantoms are in markets.

The aim of this work is to study the most used ultrasound phantom materials and their functionality in ultrasound phantom application. The biggest disadvantage of the used materials is their exposure on bacterial growth and dehydration, which cause chances in acoustical properties. Commercially available phantom materials have similar problems in dehydration. Other disadvantage is their price. Commercially available ultrasound quality phantoms are expensive and they are usable only a couple of years.

Other aim of this thesis is to study possible materials for ultrasound phantom application. Measuring the sound velocity and attenuation coefficient was used to test sample materials. One rather good material was found and therefore very many materials were not tested. The acoustical properties of the experimental material proved to be promising for the ultrasound phantom. With further studies and development of the experimental material, the new phantom prototype could be build to meet the needs of ultrasound quality assurance.

2 PRINCIPLES OF ULTRASOUND IMAGING

Ultrasound is a mechanical wave motion, which transports energy [1]. In clinical ultrasound, the ultrasound wave is developed by piezoelectric crystal, which vibrates mechanically on its natural frequency. Ultrasound frequency is over 20 kHz. [2; 3] Human can not hear the ultrasound because of the high frequency of it [4]. In clinical use, the ultrasound is used in frequency range from 1 to 30 MHz and there are different applications, which ultrasound is used for. In diagnostic, the ultrasound is used to image different soft tissue objects. Other applications are warming the tissue as a physical treatment or therapy and destructing the tissue for example crushing the kidney stones. [2-5] Reflection and refraction of the ultrasound wave in medium and the propagation velocity of the ultrasound in different tissues have the major impact on the formation of the ultrasound image. Ultrasound needs medium to proceed; therefore it does not proceed in the vacuum. [6; 7]

Ultrasound is the most widely used imaging system in clinical practice. Ultrasound can be found almost in every hospital and clinic. Its popularity is explained by its ease of use, safety and relatively low cost. [8; 9]

2.1 Properties of ultrasound in medium

The ultrasound is a mechanical vibration of medium, which is wave motion. A progressive pressure wave is formed in medium when atoms vibrate transmitting the energy forward. Ultrasound can progress in medium either longitudinal or transverse wave motion. In soft tissue, the wave motion is longitudinal and its frequency (f) is composed by the amount of waves during one second. The frequency uses the unit hertz (Hz). In clinical ultrasound, the frequency is usually megahertz (MHz). [6; 10]

Sound velocity

Sound velocity in this work refers to the propagation velocity of the ultrasound wave in the medium. Sound velocity (c) is dependent on density (ρ) and Young’s modulus (E) of medium. Velocity in solid medium can be calculated with equation (1):

$$c = \frac{E}{\rho} \tag{1}$$

[4]. Sound velocity can be calculated also with wave equation (2):

$$c = \lambda f \,, \tag{2}$$

where λ is wavelength and f is the frequency of sound [10; 11]. In solids and liquids the sound velocity is higher than in gases. This results from the vibration of the molecules that transports the wave forward; in solids the molecules are the closest and in gases they are furthest. [4; 12] The temperature has an impact on the sound velocity. In the air the sound velocity at 0 °C is 331 m/s and in 20 °C it is 343 m/s [12]. Typical sound velocity value, which is used as an average in literature and clinical ultrasound imaging, for soft tissue, is 1540 m/s. [9; 10] Soft tissue includes the tissues such as muscles, tendons, ligaments, fascia's, fat, fibrous tissues, synovial membranes, nerves and blood vessels [13].

Sound wave transports energy. The sound energy density (w) is determined by the ratio of energy (E) and volume (V) in equation (3):

$$w = \frac{E}{V} \,. \tag{3}$$

The volume (V) can be determined in equation (4):

$$V = Ac\Delta t \,, \tag{4}$$

where A is the area vertically direction of propagation of the wave, c is sound velocity and Δt is time. Energy (E), which is transported through area A in time Δt, can be calculated by joining the equation (3) and (4) for equation (5).

$$E = wAc\Delta t \,. \tag{5}$$

Sound intensity (I) is defined as a transferred energy per unit of area in equation (6):

$$I = \frac{E}{A\Delta t} = wc \,. \tag{6}$$

Sound intensity is acoustic power per unit of area. [4]

Acoustic impedance

Acoustic impedance models the resistance of the medium and it is characteristic of each material. Acoustic impedance (Z) is the ratio of the pressure to particle velocity in medium. Acoustic impedance can be calculated the revenue of sound velocity (c) and density (ρ) of medium as in equation (7):

$$Z = \rho c \tag{7}$$

The unit of acoustic impedance is kg/(m^2s). The acoustic impedance of air is 410 kg/(m^2/s). [4; 10; 14] When the ultrasound wave confronts the interface, part of it is reflected. When the acoustic impedance of two mediums is the same, the ultrasound wave doesn't reflect from the interface. The reflection occurs if the acoustic impedance of these two mediums differs from each other's. The acoustic impedance of the air and human skin differs. This is a reason a water-based gel between the transducer and skin is needed in ultrasound research. The gel acts as an impedance adapter. [4]

Attenuation coefficient

When the wave is traveling in medium, it encounters losses. That means the wave attenuates because of reflection, transmission, refraction and mode conversion. [11; 15] Addition to the losses of ultrasound in medium the transducer creates many plane waves that are sprayed in different directions. This phenomenon is called diffraction. When the ultrasound wave is scattered from an object similar effect occurs. [15]

When waves propagate in medium, they lose energy. Lost energy transfers to the surrounding tissues as a heat energy. Energy transfer and reflection cause the attenuation of the ultrasound wave. Attenuation in different materials can be compared with the attenuation coefficient. The attenuation coefficient (α) can be calculated from equation (8):

$$\alpha = \frac{10}{xf}\log\left(\frac{I}{I_0}\right), \tag{8}$$

where x is the thickness of the medium, f is the frequency of the ultrasound transducer, I is the intensity of medium and I_0 is the intensity of the reference sound. The unit of attenuation coefficient is usually dB/cm if the frequency where the attenuation is measured is known. The unit dB/cmMHz is used if the frequency is not known or is not informed. [4; 6; 15] In soft tissue, the average attenuation coefficient that is used is between 0.5 and 0.7 dB/cmMHz [2].

Acoustic properties of tissues

The acoustic properties of different tissues vary. In Table 1 is shown sound velocity (c), attenuation coefficient (α), acoustic impedance (Z) and density (ρ) of different tissues. Soft tissues have very similar acoustic properties because they all have high water content. In most soft tissues, the water content is about 60 %. [15]

Table 1. *Sound velocity (c), attenuation coefficient (α), acoustic impedance (Z) and density (ρ) of different human tissues, air and water.*

Tissue	c (m/s)	α (dB/cmMHz)	Z ($g/cm^2/s$)	ρ (kg/m^3)	Ref.
Blood	1560	0.18	1.65	1058	[16]
Bone, cortical	3476	6.90	7.38	1975	[13]
Bone, trabecular	1886	9.94	1.45	1055	[13]
Dentin	3800	80.0	8.00	2900	[13]
Tooth enamel	5700	120.0	16.5	2100	[13]
Brain	1562	0.58	1.62	1035	[17]
Breast	1510	0.75	1.54	1020	[17]
Cardiac	1576	0.52	1.67	1060	[13]
Connective tissue	1613	1.57	1.81	1120	[13]
Fat	1450	0.50	1.34	924	[16]
Kidney	1560	10.00	1.64	1050	[17]
Liver	1578	0.45	1.66	1050	[17]
Muscle	1547	1.09	1.62	1050	[13]
Skin	1540	9.20	1.71	1110	[16]
Spleen	1553	0.40	1.65	1054	[17]
Tendon	1670	4.70	1.84	1100	[13]
Air	334	12.00	0.0004	1.20	[4; 13]
Water	1500	0.0022	1.50	1000	[4; 13]

Different values of property can vary slightly between various references because the properties of living tissue are difficult to measure. In Table 1, the different tissues acoustical properties are collected from various references. Water has similar sound velocity and acoustic impedance than human soft tissues. The attenuation coefficient, however, is much lower than the value of soft tissues. Because of the low attenuation coefficient of water, it is not usually suitable for phantom material. Although water is much used in phantoms because it is cheap and easily available. Air in the other hand is much further away as for the acoustic properties of soft tissue.

Human soft tissue includes muscles, tendons, ligaments, fascia's, fat, fibrous tissues, synovial membranes, nerves and blood vessels [13]. In the middle of Table 1, the soft tissue tissues and their acoustical properties are listed. On top of Table 1 are other tissues like bone, dentin and blood. Their acoustical properties are very different from the values of soft tissues. For soft tissues like muscle, heart, liver, kidney and spleen the sound velocity is near each other's. In the attenuation coefficient, the variation is higher but the acoustic impedance and density are again near each other's.

2.2 Ultrasonic imaging

The ultrasonic device consists of display, transducers and a system control panel. These three components are the main external parts in the ultrasound imaging system. In Figure 1, these components are on the top of the device. Other parts that are shown in Figure 1 are transducer connector bays, peripheral devices, a power button, wheels, assembly and a foot pedal. Power button is shown in the figure because usually it is hard to find in the devices of different manufacturers. [18]

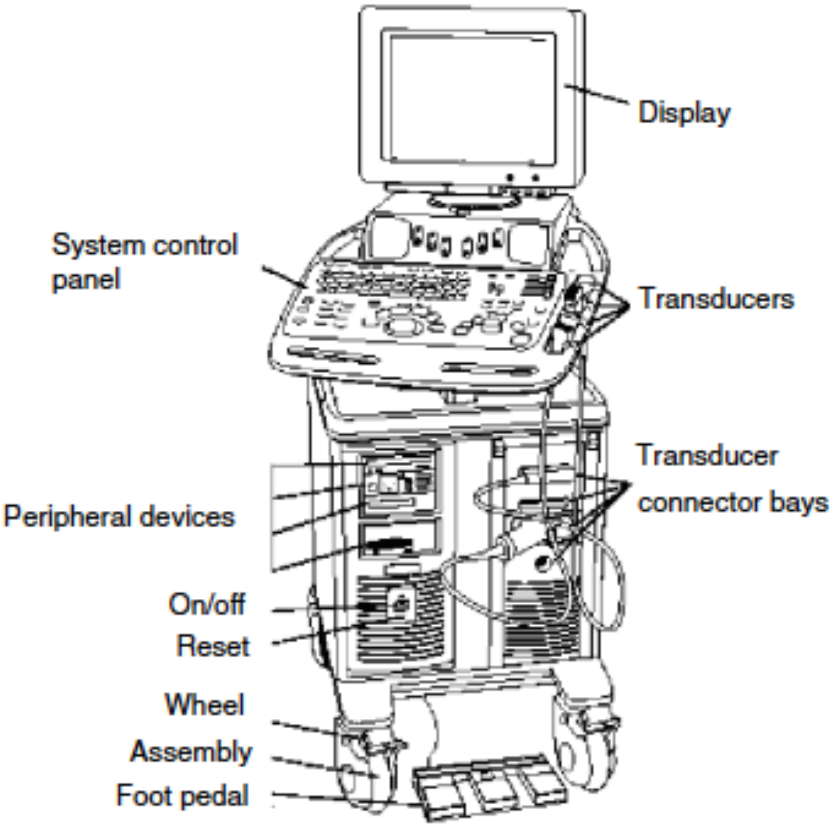


Figure 1. *Ultrasound imaging system (Philips Medical Systems). [18]*

In Figure 2 is a portable ultrasonic device. In the portable version of the ultrasonic device, there are display, a transducer and a control panel. Parts like wheels, food penal and assembly are not needed in the portable ultrasonic device.

Figure 2. *Portable ultrasonic device from Siemens. [19]*

A transducer is the most important element in the ultrasonic device. It is made from piezoelectric material and zirconate titanate (PZT) is the most common one. Because the ideal transducers should have the perfect match to human body tissue in acoustic impedance, it has high efficiency and high sensitivity as a transmitter and receiver but also a wide frequency response to pulse operation. [20] To be able to form a data and image from the ultrasound wave there must be a sender and receiver. In imaging application the transducer does both. The transducer emits a short burst of ultrasound direct to tissue. Parts of the ultrasound waves are reflected from an acoustical interface and they travel back to the transducer, which receives the signal. This way echoes are produced. The distance between the transducer and the interface can be calculated and form an image by timing the period elapsed between the emission of the pulse and the reception of the echo. This method is called pulse echo measurement. [2; 3] Usually, the returning echo signal is weak, so it must be strengthened. The deeper the echo returns the weaker the signal is. The echo signal must be filtered because of the noise and it must be scaled to fit the dynamics before monitoring. [3]

In Figure 3, the ultrasound transducer is presented. The transducer consists of a power cable, metal outer casting, backing block, electrodes, piezoelectric crystal, plastic “nose” and acoustic insulator. In medicine, the ultrasound transducer is build from several crystals, which works together. These several crystals form a beam that is a wide strip of several waves. The ultrasound beam scatters during proceeding. This causes bad quality to the image. The ultrasound beam can be focused on a wanted direction to allow the control of the ultrasound field electrically. [3]

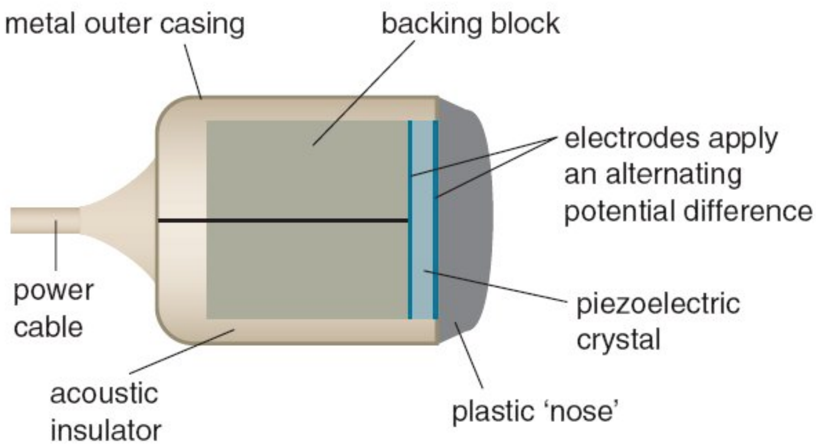
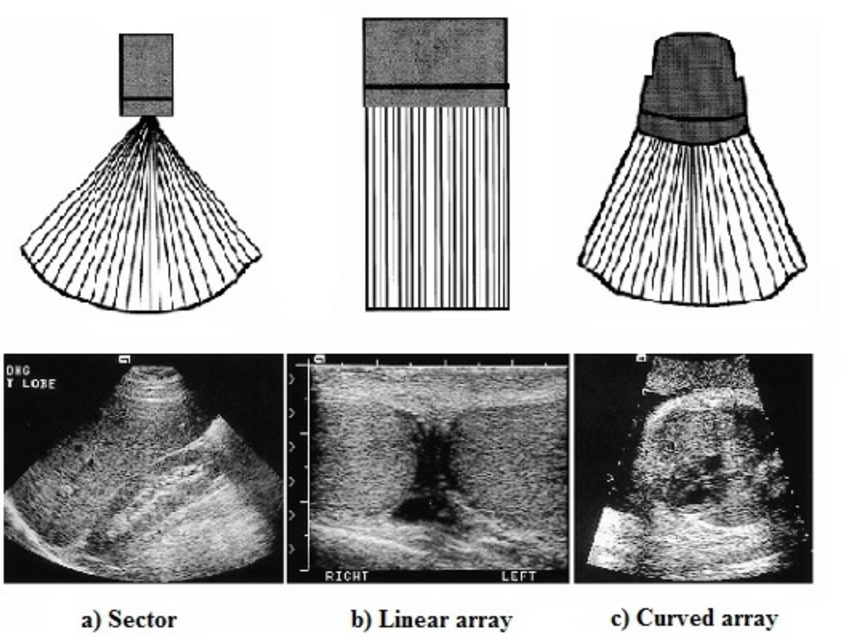


Figure 3. *Ultrasound transducer. [21]*

Three different transducer types are the most common ones in ultrasound imaging. These transducers are a sector, linear array and curved array transducers. These transducer types are shown in Figure 4. [22]



a) Sector **b) Linear array** **c) Curved array**

Figure 4. *Transducer types and the image they form. [22]*

In Figure 4 under the transducer type can bee seen the image that different transducers form. These different transducers can be used to image different kinds of objects. A sector transducer is ideal for image large organs between the ribs because it produces an image that are narrow in the near field but have a wide view in the far field. A rectangular image is produced with the linear array transducer. These transducers are used to detecting the anatomy in the near field like object that is just beneath the surface of the skin. With curved array transducers, the near field can be imaged while retaining a broad view in the far field. The face if the transducer is wide and gently curved. [9; 22]

2.3 Ultrasound monitoring methods

Different monitoring types are available for ultrasound. A-mode, B-mode, M-mode and Doppler are the common ones that are used. Other monitoring types are in use but they have more specific properties and they are not so common. A-mode monitoring is the simplest monitoring method. In the A-mode method, the data from the object is in one dimension. A-mode monitoring gives the best accuracy in distance between two objects and amplitudes of echoes. [3; 4; 6] In Figure 5, A-mode image is shown. The amplitude of echoes that are reflected from objects is represented in function of depth of the tissue or as a function of time of the echo. Different spikes in Figure 5 represent different objects. From the area of the spikes, the distance of the object can be calculated. A-mode imaging is nevertheless nowadays not in commonly used in the modern ultrasonic device [3].

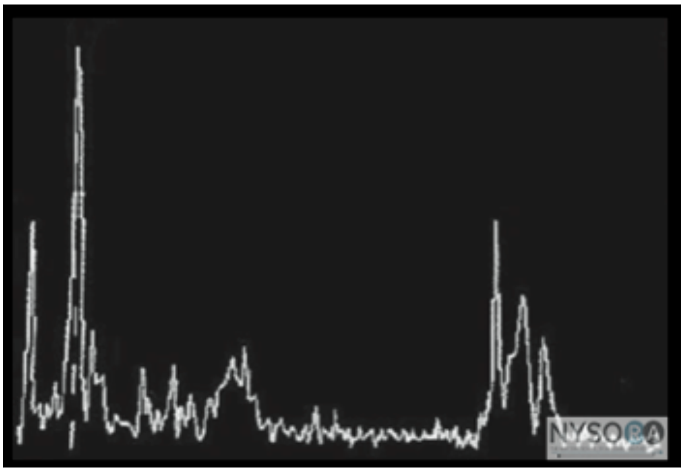


Figure 5. *A-mode ultrasound image. [23]*

B-mode imaging method gives an image that is brightness modulates. In B-mode monitoring the position of the echo is placed, where it is formed. Different amplitude echoes are represented in different shades of gray. In B-mode imaging linear, curved and sector transducers are used. The type of transducers affects the form of the image. B-mode imaging can be used to illustrate nearly all of the soft tissue structures. [3; 9; 24] Figure 6 shows the B-mode image of the fetus in the uterus. With B-mode imaging the image is like photo of the object.

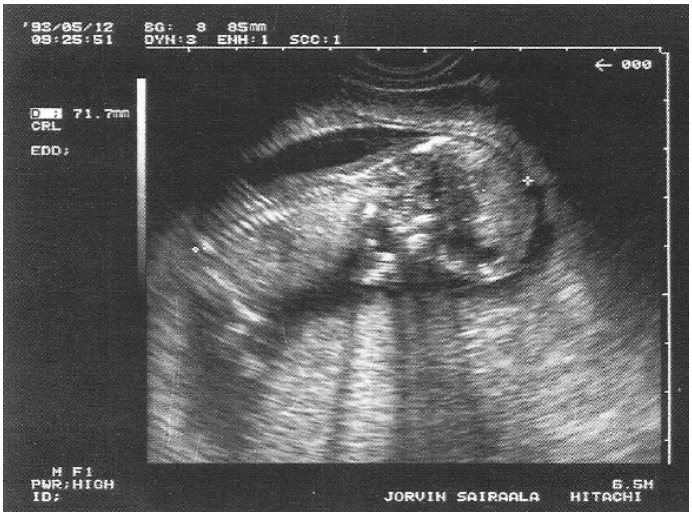


Figure 6. *B-mode ultrasound image. [7]*

M-mode imaging is brightness modulated. It shows the place of the acoustic interfaces in real-time and gray scaled. It introduces the movement of the interfaces. This is very useful in to image the heart. M-mode is used to image moving interfaces to obtain diagnostic information. [2; 3; 18] In Figure 7 is the M-mode image. In the right top corner of Figure 7 is the image of the object. In the foot of Figure 7 is wavelike graphic, which represents the movement of the tissue or structure. M-mode imaging is used in cardiac imaging.

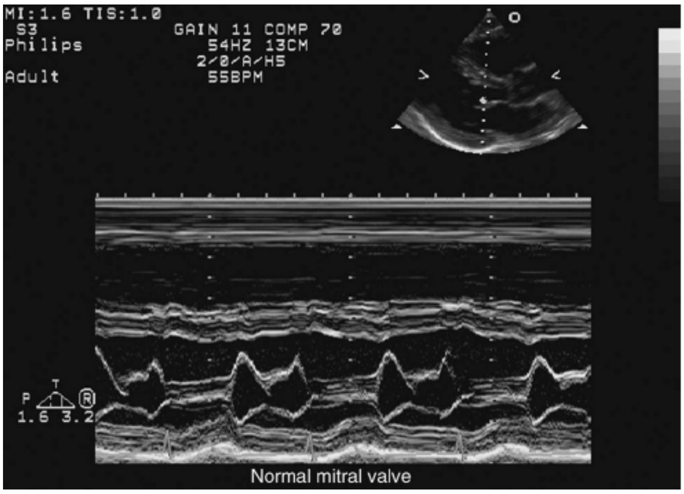


Figure 7. *M-mode ultrasound image. [18]*

The speed of fluids can be determined with Doppler measurements. Determining the velocity of the blood is based on the difference in frequency between transduced and received sound, which is affected by the velocity of blood cells. If the blood flow is laminar (steady), the certain profile of flow, the similar frequency chance is formed. The Doppler signal contains various frequencies when the flow turns turbulent. Doppler measurement is based on the use of either pulsed Doppler or continous Doppler machine. In the pulsed Doppler, the same transducer transmits and receives the signal. In continous Doppler there are separate transducers for transmitting the signal and receiving the signal. Doppler is used to image and measure the cardiological object as the heart and vessels. [3; 9] In Figure 8, the Doppler image is shown.

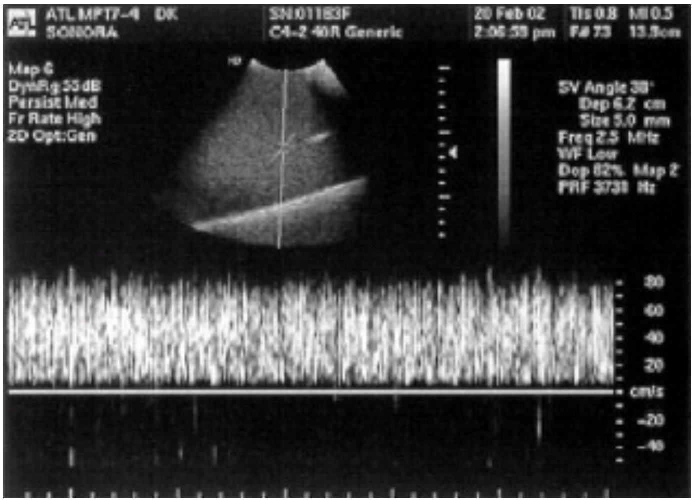


Figure 8. *Doppler ultrasound image. [25]*

In the middle top of Figure 8 is the B-mode image that is formed from the object. Velocity of the fluid can be calculated from the difference in the noise signal that the flowing fluid generates to the transceiver. This noise signal graph is represented below the B-mode image. The velocity of fluid is calculated from the graph by measuring the difference between the highest and lowest peak or by reading the middle value from the graph.

2.4 Quality assurance of ultrasound

There are no standard methods of assuring the quality of the medical ultrasonic device despite the attempt to do so during over the last 30 years by various international committees. Progress has been slow because of the development of the equipment feature, difference between opinions and lack of subjective assessment in case of image quality. [26] Other reasons for the lack of quality assurance in medical ultrasound imaging are the relatively low costs of devices, ultrasound includes no irradiation that is harmful and there are no agreements of the methods how the parameters should be measured. [27] Ultrasound quality control has been seen to be unnecessary because the equipment rarely break down, they are reliable and malfunction can be tested if there is a suspicion of an error [28].

The quality control of the ultrasonic devices is done to assure the acceptable capacity. Values can be compared with the limits the manufacturer gives, literature values and previous capacity of the device. Some standards have been made to cover the area of ultrasound quality control. American Association of Physicists in Medicine (AAPM), American Institute of Ultrasound in Medicine (AIUM) and The American College of Radiology (ACR) have made the earliest standards. [6]

According to the ACR standard, the regular control should be done annually. It includes the physical and mechanical inspections, image uniformity, artifact survey, geometric accuracy, contrast resolution, fidelity of ultrasound scanner electron image display and system sensitivity. The same tests should be done when a new ultrasonic device or a transducer is received to ward. [29]

In Austria, a similar guideline for the technical quality assurance of ultrasound devices has been written. It is a more specific guideline for the quality assurance. It includes four levels that can be done in different intervals. Level 1 is done monthly, level 2 is done annually, level 3 when the ultrasound device is received and level 4 can be done optionally or when requested. [30]

Despite all the standards and regulations the quality assurance of the ultrasonic device is not mandatory. The functionality of the ultrasound transducers was tested in the X-Ray unit of Helsinki University Hospital. Transducers were tested with a reference method (smoothness, aerial view and transducer measurement) and with a phantom. Overall 66 transducers were tested. With reference methods 13 (20 %) transducers were discovered defective and with phantom tests 23 (35 %) of transducers were defective. [10] Similar test were done using the different testing method. In this, study total of 151 transducers were tested. Methods were FirstCall, phantom and visual testing of transducers. 17 % of the transducers were defective. [27]

In tests, a quality assurance phantom was used. The imaging properties of the ultrasonic transducer can be tested with the phantom. The phantom is made of materials that mimic the properties of human tissue. [20] Materials used in phantoms have to have similar acoustic properties than the tissues in the human body. In literature and in clinical tests widely used values for the acoustic properties of soft tissue are; the sound velocity 1540 m/s and the attenuation coefficient between 0.5 and 0.7 dB/cm^{2}MHz. [31; 32] With the quality assurance phantom, the operation ability of the ultrasonic device and especially the functionality of the transducer can be improved via testing transducers regularly.

3 MATERIALS FOR ULTRASOUND TESTS

Phantoms in clinical use are usually meant to mimic human body. Phantoms are used to test different clinical devices, such as computed tomography (CT), X-ray, magnetic resonance imaging (MRI) or ultrasonic devices. A phantom can also be a model of some body part for training purposes. Lumbar Training Phantom (CIRS Model 034), in Figure 9, can be used training for example epidurals, injections, and discography and nerve or facet blocks.

Figure 9. *CIRS Model 034; Lumbar Training Phantom. [33]*

Phantoms are used in studies where in vivo models are inappropriate. These kinds of situations can occur when a model must stay still for a long period of time. Phantoms are used when the exact structure must be known. The phantom structure is made precisely and can be used as a truth in study. A structure of a phantom is usually simpler than an anatomical model. The problems can be simplified focusing on the structure of the phantom to a specific problem. The environment where the measurements are done can be standardized with phantoms. [13; 31]

3.1 Ultrasound phantoms

Ultrasound phantoms are used to detect the malfunction of ultrasound transducers. The imaging forming properties of transducers is tested with phantoms and these properties are display monitor fidelity, image uniformity, the depth of visualization, hardcopy fidelity (a number of gray levels), hardcopy fidelity (the density of four gray bars (the lowest, the highest and the two in between)), vertical distance accuracy, horizontal distance accuracy, axial resolution, lateral resolution and dead zone. [28]

The ideal phantom for ultrasound testing has the sound velocity of 1540 m/s and attenuation coefficient between 0.5 and 0.7 dB/cmMHz [28; 32]. These are the commonly used average values for the acoustical properties of soft tissue.

Generally, an ultrasound phantom can be any material because it does not need to be in touch with human body or skin. Although toxic materials can be difficult to use because of the safety procedures they must be handled. The simplest phantom material is water. It has been in use since the earliest days of ultrasound is developed. [13]

Many different materials have been studied to fit the acoustic properties of the human tissue. Gelatin is one of the first materials used as a phantom material to mimic the human soft tissue. After gelatin, materials like condensed milk and agar has been widely used and agar is the most described material in references. Polyacrylamide (PAA), polyurethane (PUR) and polyvinyl alcohol (PVA) are newer materials used in phantoms and their acoustical properties are close to required values for the ultrasound phantom. These and other materials, their acoustical properties and suitability as a phantom material are described detailed in this chapter. [13; 34]

All of the materials mentioned above have been blended with water. All of these materials have desired acoustic properties, but the problem is their stability. As water based materials, they are susceptible to dehydration and biological attacks. [34] Dehydration can cause chances to the acoustic properties of materials [28].

Commercially available phantoms manufacture four companies; ATS laboratories, Gammex, Kyoto Kagaku and CIRS, and one smaller company in Europe; Dansk Fantom Service. ATS Laboratories manufacture several multipurpose phantoms that can be used for ultrasound testing. Their phantoms use rubber-based material or hydrogel material that is water-based. Company offers customers a choice between these two materials. A rubber-based phantom doesn’t have the sound velocity of 1540 m/s; rather “targets are physically moved to compensate for the difference in the speed of sound”. The sound velocity of hydrogel-based material is 1540 m/s but its estimated life-time is 2-3 years compared with the life-time of rubber-based material (7-10 years or more). ATS Laboratories give rubber-based phantom warranty for a lifetime and hydrogel phantom for one year because of their different life-time expectations. [35] ATS Laboratories Basic QA Ultrasound phantom ATS 535-H model (Figure 10, A) cost approximately 1845 US dollars (about 1650 €) [36].

Gammex manufactures ultrasound phantoms for different purposes. They use MultiFrequency HE Gel^{TM}, which is condensed milk-based material, as a tissue mimicking material in their phantoms. In the tissue mimicking phantom guide from Gammez the phantom material is described in order to be “water-based gel with the appearance of human tissue”. They give the warranty of one year for their products. [37] Gammex 410 Multi-Purpose Accreditation Phantom model (Figure 10, B) costs between 2100 and 3020 US dollars (approximately 1880 to 2710 €) depending on the attenuation coefficient customer wants for the phantom [38].

Third ultrasound phantom manufacturer is Asian company Kyoto Kagaku. They have one model for the ultrasound quality assurance phantom, which is manufactured of urethane elastomer. [39] Kyoto Kagaku Multipurpose and QA phantom (Figure 10, C) cost 2000 US dollars (about 1790 €) [36].

CIRS have several ultrasound phantoms that can be used in the quality control of ultrasound. The most common one is their Multi-Purpose Multi-Tissue Ultrasound Phantom. CIRS gives the warranty of 48 moths (4 years) for the model 040 phantoms. CIRS phantoms are made of material called Zerdine®. CIRS also has phantoms made of proprietary urethane matrix. This phantom is also for the general-purpose ultrasound phantom. [33] CIRS Multi-Purpose Multi-Tissue Ultrasound Phantom CIRS 040GSE model (Figure 10, D) cost 3200 US dollars (about 2870 €) [36].

Figure 10. *Commercially available multipurpose ultrasound phantoms. Modified from [33; 35; 37; 39; 40]*

A smaller scale manufacturer can be found in Scandinavia in Denmark. The ultrasound phantoms of Dansk Fantom Service are handmade (Figure 10, E). Their phantoms are hydrogel-based and materials like Benzalkonium Chloride, Na-Benzoate and K-EDTA, Acnibio OCS and nitric acid or Crotan BA21 are used. Company gives instruction to maintain the phantoms by adding distilled or demineralized water if fluid has disappeared from the phantom. Hydrogels are sensitive to microbes and to prevent microbial growth or to destroy it 0.5 % solution of H_2O_2 in water can be used. [40]

Ultrasound quality assurance phantoms include different objects that can be viewed with ultrasound. Objects have exact places in order to test the proper functionality of the transducers. In Figure 11 is an example of CIRS Model 040 object map in the phantom. [33]

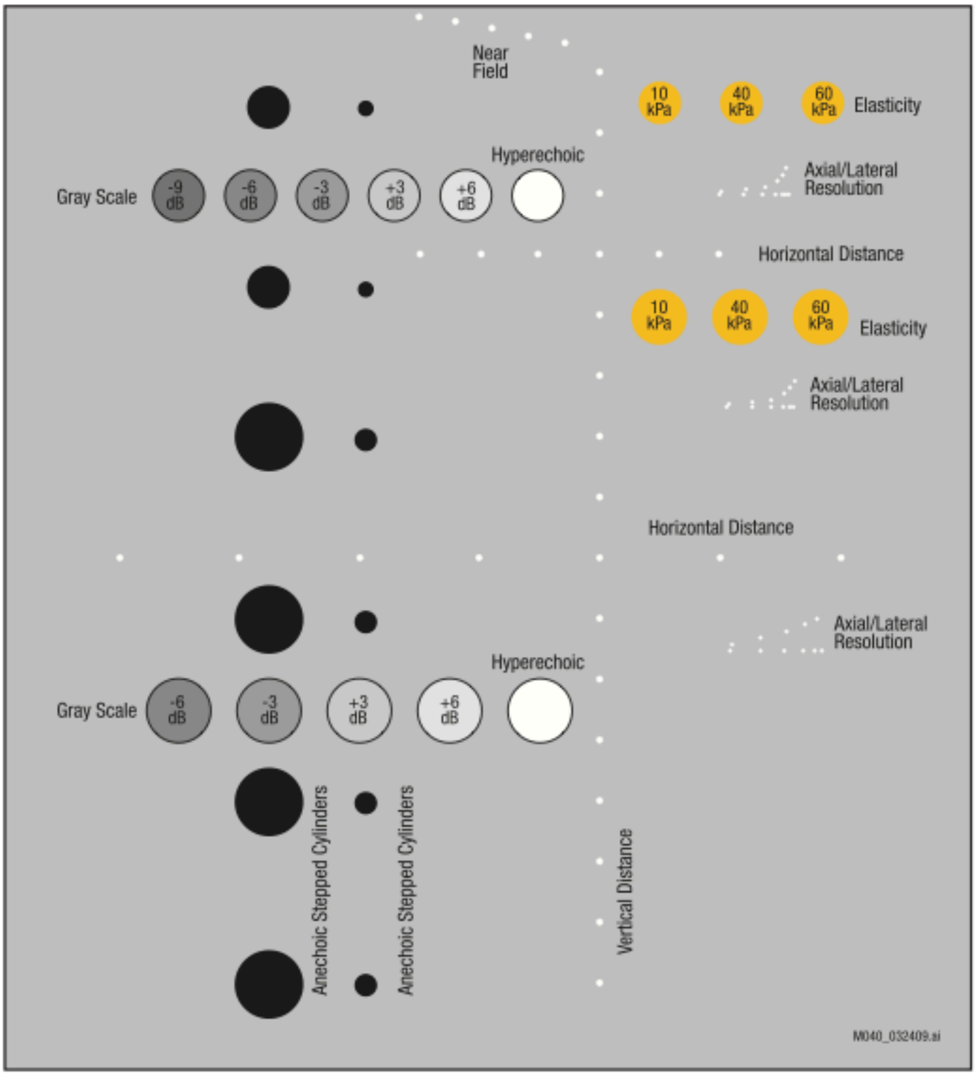


Figure 11. *CIRC Model 040 object map. [33]*

Uniformity of a picture the ultrasound transducer forms can be evaluated by taking a picture of a phantom and observing if all echoes from the same depth and magnitude have the same brightness. A dead zone is measured with near field group, which are the white dots on top of Figure 11. The dead zone is the distances from the front face of the transducer to the closest identifiably echo. The ultrasound system cannot send and receive data simultaneously, which causes the dead zone. White dots that are vertically are vertical distance groups. They are used to measure the depth of penetration, which is the greatest distance the transducer can detect. Horizontal distance groups consist of similar white dots as vertical distance groups but they are in horizontal line in two depth. Both horizontal and vertical distance groups are used to measure the accuracy of distances the transducer detects. Axial and lateral resolution groups are in Figure 11 in the right side white dot groups. Axial resolution determines how close two objects can be along the axis of the beam still be detected as two distinct objects. Lateral resolution is concerned with the resolution perpendicular to the beam axis; otherwise it is similar to axial resolution. Big vertical black dots are anechoic stepped cylinders. With these objects, the fill-in effect can be evaluated. The fill-in effect occurs when the ultrasonic device represents low contrast structures smaller than they actually are. Gray scale targets are the horizontal dots that change the color from gray to white from left to right. Gray scale targets are used to evaluate the dynamic range of an ultrasound imager. Yellow dots in Figure 11 are elasticity target groups. Elasticity targets are used for assessing the dynamic range of sonoelastography system, for optimizing the imaging settings and for checking their performance. [41] These are the most commonly tested properties of the ultrasound transducers. Other commercially available phantoms have similar objects that are used to evaluate the imaging properties. [35; 37; 39]

The acoustical properties of three of these commercially available phantoms have been studied; CIRS Model 040 (Zerdine®), ATS Laboratories (urethane rubber) and Gammex (condensed milk). Gammex has two phantom materials according to the wanted attenuation coefficient. The test results can be seen in Table 2. The measurements are done in room temperature, where the phantoms are normally used. In Table 2, the phantoms of CIRS and ATS Laboratories have two different attenuation coefficient values. This is due to the structure of the phantoms. The phantoms have two sides, which are separated and made of different materials to have the attenuation coefficient values of 0,5 and 0,7 dB/cmMHz.

Table 2. *Acoustical properties of commercially available phantoms; CIRS, ATS Laboratories and Gammex multipurpose ultrasound phantoms. [42]*

Material	c (m/s)	α (dB/cmMHz)
CIRS	1540	0.5 / 0.7
ATS Laboratories	1460	0.5 / 0.7
Gammex 0,5	1540	0.5
Gammex 0,7	1540	0.7

The temperature affects differently different materials. The study of the temperature effect on the sound velocity and attenuation coefficient for these three commercial phantoms has been made and the results are shown in Figures 12 and 13.

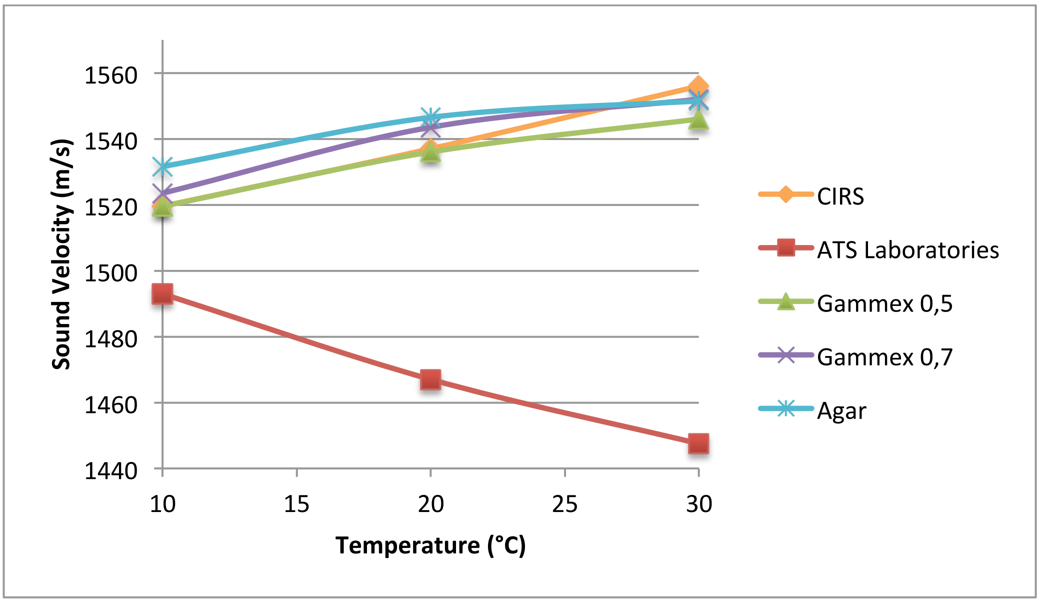


Figure 12. *The effect of the temperature on sound velocity. Modified from [42]*

The measurements for both the sound velocity and attenuation coefficient were made in three different temperatures; 10, 20 and 30 °C. The measurements were carried out with two different frequencies; 2.25 and 15 MHz. The results for these measurements are calculated as average values.

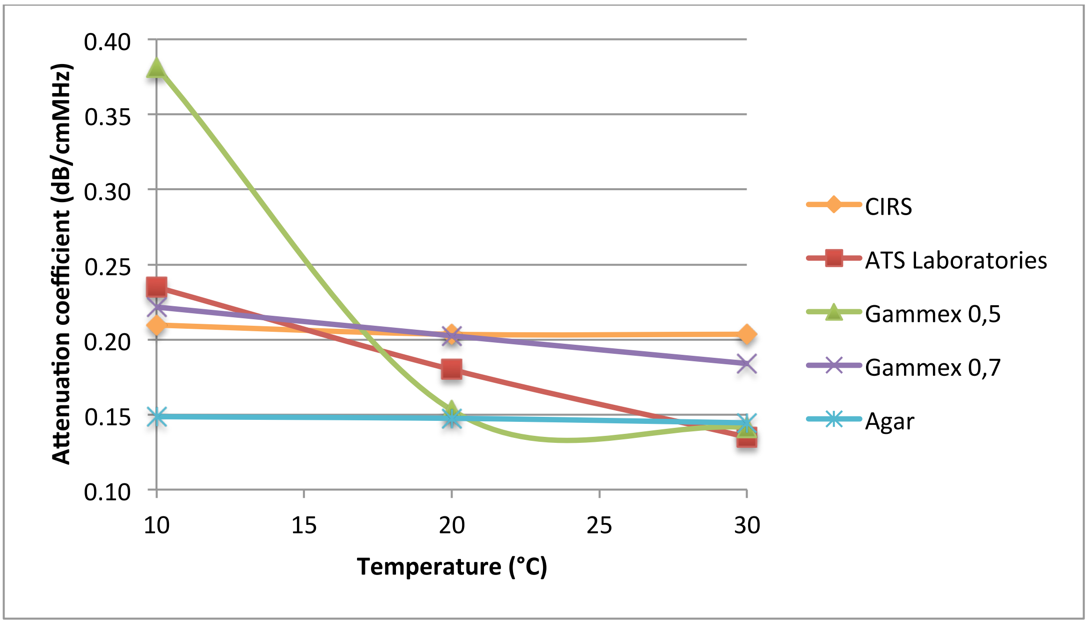


Figure 13. *The effect of the temperature on attenuation coefficient. Modified from [42]*

From Figures 12 and 13, can be seen that the affect of the temperature to the acoustic properties is dependent on the material. The ATS Laboratories phantom, which is manufactured from urethane rubber, has the largest affect on the temperature to the sound velocity. Gammex, which uses condensed milk based material in their ultrasound phantom, has the largest affect on the temperature when measuring the attenuation coefficient.

3.1.1 Gelatin

Gelatin is the earliest phantom material used in ultrasound phantoms, excluding the water. Gelatin is homogenous colloid gel from animal sources and usually it is produced from the skin or bone of an animal. Gelatin is derived from collagen that consists of three different chain types (α-chain, β-chain and γ-chain). [13; 43] Gelatin is biodegradable and biocompatible in physiological environments and this is the reason for the great favor in pharmaceutical and medical applications. [44; 45] Gelatin is widely used also in other applications like food and cosmetic industries and paperboard or paper products [43].

Gelatin can be modified during the fabrication process. It is possible to manufacture gelatin into negatively charged acidic gelatin or positively charged basic gelatin. A chemical structure of gelatin is showed in Figure 14. In Figure 14, the positive and negative charge is placed in the structure. The fabrication process of negatively and positively charged gelatin differs in the pretreatment of collagen. The manufacturing of the positively charged gelatin is carried out by pretreating the collagen with alkaline. In this process, the target is to hydrolyze the amide groups of asparagine and glutamine into carboxyl groups. The negatively charged gelatin is manufactured by pretreating the collagen with acidic, which affect a little to the amide groups. Difference between the two gelatin types is in their electrical nature. The negatively charged acidic gelatin has the higher isoelectric point (IEP) than positively charged gelatin has. Manufacturers of the gelatin offer gelatin with different values of IEP. [44]

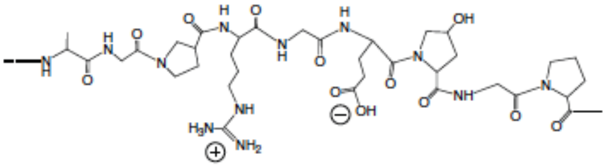


__Figure 14.__ The chemical structure of gelatin. [46]

Pure gelatin cannot be used as a phantom material. Gelatin powder is mixed with water and they form a solution that hardens during a few hours. Gelatin-based phantoms usually need different additive materials to prevent bacterial growth in the material and to improve the scattering and absorption of ultrasound waves. [47]

In the study of the acoustical properties of gelatin-based material, the gelatin was mixed with graphite powder. The graphite particles absorb and scatter incident ultrasound waves. N-propanol and formaldehyde were added to the solution because different concentration can regulate sound velocity. Sodium benzoate is used to destroy the bacteria from the solution. The sound velocity and attenuation coefficient of the test materials were measured after three years of storage. These results are presented in Figures 15 and 16. [47]

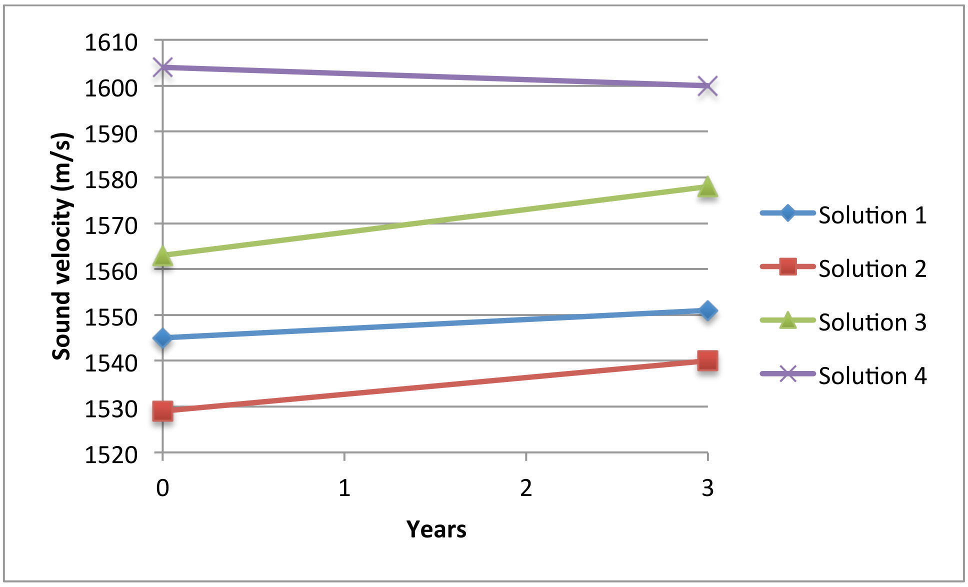


Figure 15. *The change of sound velocity in gelatin-based phantoms during three years. Modified from [47]*

In Figure 15, all solutions of water and gelatin include n-propanol, formaldehyde, benzoate, oil and kerosene. The amount of graphite powder differs in the solutions. In solution 1 (cyst phantom) there are no graphite particles at all. In solution 2 (breast phantom) has graphite particles 49 g/l and in solution 3 (cancer phantom) 94 g/l. In solution 4 (broadenoma phantom) has 70 % gelatin and water solution, which has 170 g/l graphite particles, and 30 % of fat particles.

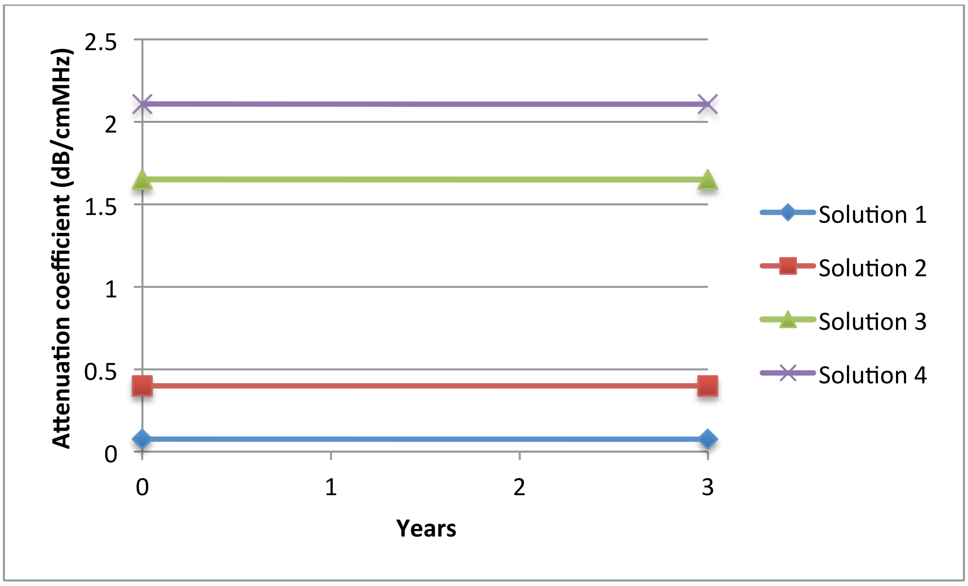


Figure 16. *The change of attenuation coefficient in gelatin-based phantoms during three years. Modified from [47]*

Figure 15 shows that the sound velocity changes between 5 to 15 m/s in three years. The change of the attenuation coefficient is not as big as the change of the sound velocity as seen in Figure 16. The changes are rather small but during several years they might be bigger. Depending on the solution composition the acoustic properties of gelatin-based phantom materials are close to human soft tissue.

Advantages of gelatin-based phantoms are the low price of gelatin, acoustic properties can be modified to mimic the properties of the human soft tissue. The stability of gelatin-based phantom materials depends on the storage conditions and additives used in the phantom. A problem in stability is the evaporation of the water or dehydration because the phantom is water based. Disadvantages of gelatin-based phantom materials are the stability in room temperature and the bacterial growth if the sterilization is not done properly. [13; 47]

3.1.2 Agar

Agar-based phantoms are widely used and described in references. Agar is strongly gelling hydrocolloid from marine algae. Agar consists of polysaccharides, which are extracted from red seaweed. Agar is a liner natural polymer. Chemically agar is a mixture of agarose and agaropectin. The mixture relation is dependent on original raw material and a manufacturing process. A chemical structure of agar is shown in Figure 17. Agar becomes gel when it is first solubilized around 90-100 °C and cooled afterwards. Industrial agar is nowadays produced from plant. Agar is used in similar applications than gelatin. The main industry is food industry and other big area is biotechnological industry like medicine. [43; 48; 49]

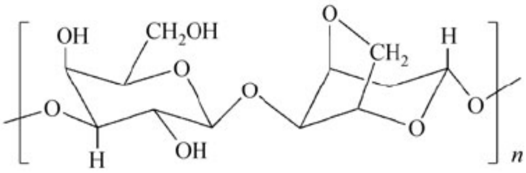


Figure 17. *The chemical structure of agar. [49]*

Agar is used often together with gelatin as a tissue mimicking material because agar ensures stiffness and cohesion. Gelatin in the mixture contributes to the elastic character of the resulting material. [50] There are many different recipes for agar-based phantoms [13]. Agar-based phantom solutions include many additives to prevent the bacterial growth and regulate the sound velocity in the material similar to gelatin. In Table 3 some agar-based phantom materials and their acoustical properties are listed.

Table 3. *Agar-based phantom materials and their acoustical properties. All the measurements are done at room temperature (22 °C). Modified from [16; 51; 52]*

Material	c (m/s)	α (dB/cmMHz)	ρ (kg/m^3)
1	1538	0.49	1030
2	1538	0.50	1030
3	1500	0.40	1040
4	1537	0.38	
5	1544	0.78	

Material 1 includes agar and water solution with additives and graphite powder. Material 2 is similar to material 1 with an addition of glass beads. Material 3 includes only 2 % of agar and rest is water and necessary additives. Materials 4 and 5 are similar and they include agar and water solution with additives and condensed milk. Material 5 includes glass beads but material 4 do not. [16; 51; 52]

Advantages in the use of agar-based phantoms are that they have well-characterized performance and they are easy to fabricate. The fabrication process provides flexibility compared with other materials in the phantom fabrication. Agar is mixed with water and propanol solution. Water in solution causes the dehydration over time. The stability of agar-based phantoms is therefore maximum two and a half years. Other disadvantages of the agar-based phantom are its need to be stored under optimal condition and receptivity for bacteria. Optimal storage conditions must maintain to obtain the stability of two and a half years. If the material is not stored properly, the stability can be only one to a few months. [13]

3.1.3 Polyrethane rubber (PUR)

Polyurethane rubber (PUR) is quite new material in phantom applications [32]. Polyurethane elastomers are copolymers. They have a hard segment that contains aromatic rings and a soft segment consist of polyether or polyester. In Figure 18, the chemical structure of polyurethane is shown. Polyurethanes are manufactured from aromatic diisocyanate, oligomeric diol and low molecular weight diol. Polyurethanes are expensive materials and they are used in high performance structural applications as well foams. Polyurethanes are produced by step growth polymerization where two reactive functional groups react with each other' by forming a polymer. Polyurethanes are classified to three groups; foams, coatings and thermoplastic elastomers (TPE). Polyurethanes can be synthesized in two different methods; solution or bulk synthetization. Solution polymerized polyurethanes has batter uniformity in hard and soft segment distributions than in bulk polymerized polyurethanes. Bulk polymerized polyurethanes nevertheless have higher molecular weight than solution polymerized polyurethanes. [53]

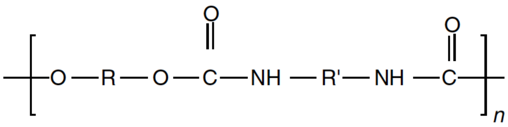


__Figure 18.__ The chemical structure of polyurethane. [54]

The results of the study of the acoustical properties of polyurethanes are shown in Table 4. The acoustical properties of the commercially available ultrasound phantom materials have been measured in this study. ATS Laboratories use polyurethane rubber-based material in their phantom.

Table 4. *Acoustical properties of polyurethane rubber-based phantom materials. Modified from [13; 42; 55]*

Material	c (m/s)	α (dB/cmMHz)	ρ (kg/m^3)
1	1468	0.13	1130
2	1460	0.5 - 0.7	900
3	1460	0.5 / 0.7	

In Table 4, material 1 is polyurethane gel, which is manufactured in a laboratory. Detailed information about the material is not available. Material 2 is a sample of polyurethane rubber-based phantom material from ATS Laboratories. Material 3 is manufacturers (ATS Laboratories) reported values for their urethane-rubber-based ultrasound multipurpose phantom material. Material 1 was measured at 26 °C temperature and materials 2 and 3 were measured at room temperature (about 22 °C). [13; 42; 55]

The acoustical properties of polyurethane-based phantom materials depend on the molecular structure and density of the material. Properties of polyurethane can be modified during the manufacturing process. The addition of additives into the material affect properties, also the selection of raw material (for example choose of aromatic isosyanates or polyols) has impact on properties. Surface modification is possible for polyurethanes, which means the modification of only a material surface not the whole material. Advantage of polyurethane as a phantom material is its stability. Urethane rubber does not dry like other materials and it has longer lifetime and therefore the acoustical properties stay stable over time. Polyurethane is also immune to bacterial invasion. [13; 32; 55; 56]

A drawback of polyurethane as a phantom material is the acoustical properties of the material. The sound velocity is lower than an ideal ultrasound phantom should have. The other drawback of this material is that the manufacturing is a complex process. The complexity of the manufacturing process is due to the synthetization of polyurethane in the manufacturing process and the modification of material during the manufacturing. [13; 32; 55]

3.1.4 Polyacrylamide (PAA)

Polyacrylamide (PAA) has become familiar as a phantom material in the 21st century. Polyacrylamide belongs to vinyl polymers class. Polyacrylamide is copolymerized from acrylamide and bis-acrylamide. Polymer chains are randomly cross-linked by bis and this results in polyacrylamide gel, which is porous. The porosity of gel depends on the condition of polymerization and monomer concentration. The chemical and photochemical polymerization of polyacrylamide is possible. A chemical structure of polyacrylamide is shown in Figure 19. PAA is amorphous and it has high affinity for water. Application for PAA is paper manufacturing, mining and oil recovery as absorbents and flocculants in water treatment. [57-59]

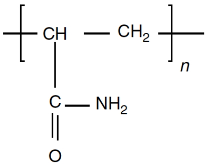


Figure 19. *The chemical structure of polyacrylamide. [54]*

The acoustical properties of polyacrylamide can be found in many references. PAA is normally mixed in water. The mixing ratio of PAA affects the acoustical properties. These effects can be seen in Table 5. The increase of PAA content in water solution increases the sound velocity and the same occurs with the attenuation coefficient. Change in PAA concentration doesn't have radical effect on the density of the material and it stays rather constant. The sound velocity of PAA solution is suitable for tissue mimicking material but the attenuation coefficient is overly low.

In Table 5 is showed the acoustical properties that are measured for PAA and water solution. Because the attenuation coefficient of PAA is not high enough for soft tissue mimicking material; different additives have been added into the PAA solution to improve the acoustical properties to match the human soft tissue. Bovine albumin serum (BSA) protein was added to PAA water solution. The solution includes 7 % of PAA in water and 3 to 9 % of BSA. [59] The result of BSA impact on acoustical properties is shown in Table 5. The sound velocity is ideal for tissue mimicking material and it stays constant during the change of BSA content. In the study, the attenuation coefficient was measured with different frequencies. Table 5 shows the average values of the attenuation coefficient. An increase in BSA content increases the attenuation coefficient but the values are not much higher than without different concentrations of PAA in water. Changes in BSA content don't have an effect on the density.

Table 5. *The effect of the amount of PAA and additives on acoustic properties. The measurements are done at 25 °C temperature. [59-61]*

Material	**c (m/s)**	**α (dB/cmMHz)**	**ρ (kg/cm^3)**
PAA 10%	1546	0.075	1024
PAA 12.5%	1558	0.096	1031
PAA 15%	1568	0.118	1038
PAA 17.5%	1582	0.132	1043
PAA 20%	1595	0.136	1052
PAA with 3% BSA	1544	0.08	1044
PAA with 5% BSA	1544	0.10	1044
PAA with 7% BSA	1544	0.14	1044
PAA with 9% BSA	1544	0.17	1044
PAA with 10% egg white	1539	0.14	990
PAA with 20% egg white	1541	0.18	1000
PAA with 30% egg white	1542	0.21	990
PAA with 40% egg white	1544	0.24	1000

Other study to improve the acoustical properties of PAA was made adding the egg white to PAA. The egg white was used to replace the BSA as a protein because the egg white is cheaper than BSA [61]. Results of the study are represented in Table 5. Adding the egg white increases the sound velocity but it doesn't stay constant as adding the BSA. Sound velocity is however close to the value of human soft tissue with 30 and 40 % of egg white. Attenuation coefficient increases during the addition of egg white but it is still low to mimic human soft tissue. Density of material varies between 990 and 1000 kg/m^3.

Effect of the temperature on the acoustical properties of PAA with BSA and egg white was studied. Usually, the ultrasound phantom is used in the room temperature like the usage of ultrasound transducers. In Figures 12 and 13 (in Chapter 3.1) the effect of temperature was presented for the commercially available ultrasound phantom materials. In Figure 20, the temperature affect on the sound velocity of PAA with 7 % of BSA and PAA with 10 % of egg white is presented. The results are collected from two references and therefore the measurement results are in slightly different temperature range. The sound velocity of both materials increases when the temperature increases. If the effect of the temperature was carried out to higher temperatures in PAA with egg white, it would perhaps act like the PAA with BSA and the sound velocity would have started to decrease after 65 °C.

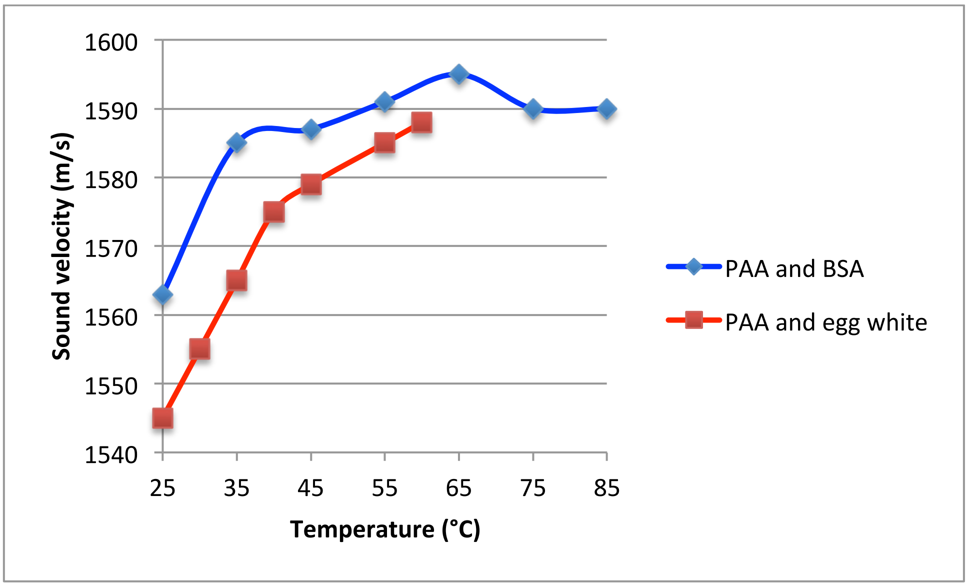


Figure 20. *The effect of the temperature on sound velocity. Modified from [59; 62]*

In Figure 21, the changes in the attenuation coefficient over the temperature are represented. The study has done for the same materials as in Figure 20. As the temperature increases, the attenuation coefficient decreases up to the temperature of 55 °C. Attenuation coefficient starts to increase while the temperature increases above 55 °C. PAA with BSA and egg white reacts similar to the temperature changes in both sound velocity and attenuation coefficient measurements. Figures 20 and 21 prove that the sound velocity and attenuation coefficient are strongly dependent on the temperature. If the materials are used in the temperatures besides room temperature, the changes in acoustical properties must be considered.

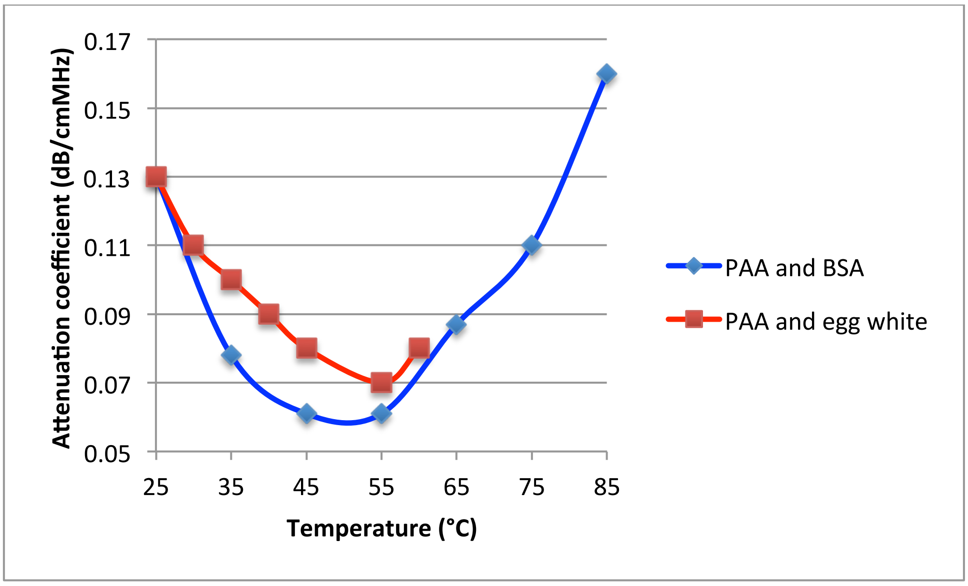
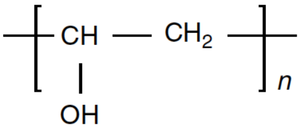


Figure 21. *The effect of the temperature on attenuation coefficient. Modified from [59; 62]*

Advantage of PAA as a phantom material is its stability in contrast to previously introduced material. The sound velocity of PAA is very suitable for ultrasound phantom application. Disadvantages are the low attenuation coefficient and toxicity of PAA. Because of the toxic material, the preparation of the PAA has to be carried out carefully. PAA is mixed with water like previously introduced material. It has the same dehydration problem with stability as other materials if not stored in appropriate conditions. Even if the material is stored properly the dehydration occurs over time. [13]

3.1.5 Polyvinyl alcohol (PVA)

Polyvinyl alcohol (PVA) has been as an ultrasound phantom material approximately the same time as PAA. PVA is non-toxic, an industrial compound, which is often used in food packaging. Other applications for PVA are paper and textile sizing, adhesives, gal and composites. Polyvinyl alcohol is derived from polyvinyl acetate and the chemical structure of PVA is shown in Figure 24. In order to use PVA in the variety of application it must be cross-linked. The cross-linking of PVA can be done in three different methods. One is the cross-linking by using the difunctional crosslinking agents like glutaraldehyde, acetaldehyde and formaldehyde. Cross-linking agents cause a toxic residue. This can be avoided by using chemical or physical cross-linking. In chemical cross-linking an electron beam or γ-irradiation can be used. [31; 58; 63]



$$\left[\underset{\mathrm{OH}}{\underset{|}{\mathrm{CH}}} - \mathrm{CH_2} \right]_n$$

***Figure 22.** The chemical structure of polyvinyl alcohol. [54]*

When using the PVA as a phantom material, it is blended in water. By freezing and thawing the solution, the material is formed into a gel and the phase is then called cryogel [31]. The name cryogel is used for macroporous gels that are produced at subzero temperatures meaning under 0 °C. Cryogels are macroporous, physically and chemically stable and they have tissue like elasticity and biocompatibility. [64] When PVA-water solution is frozen and thawed, it begins to have rubber-like properties. Freeze-thaw cycles cause the material to cross-link through hydrogen bonding with hydroxyl groups on PVA molecules. PVA hydrogel can be prepared also by freezing and thawing the PVA. PVA gryogel (PVA-C) however differs from PVA hydrogel. Hydrogels cross-link chemically by the addition of compounds like aldehydes. Hydrogels have very low modulus and yield strength. Their appearance and strength are similar to common gelatin and therefore PVA hydrogels can't be used as a distensible phantom material. The number of freeze-thaw cycles effect on the mechanical and acoustical properties of PVA-C. Changing the number of freeze-thaw cycles the properties can be modified into wanted. The length of the freezing doesn't affect the properties. [65]

The common concentration of PVA used in tissue mimicking material is 10 %. The affect of different freeze-thaw cycles to the acoustical properties of PVA-C is shown in Table 6. The sound velocity of PVA-C increases when the number of freeze-thaw cycles increase. The same behavior is seen with the attenuation coefficient of PVA-C. The acoustical properties are similar to PAA. The sound velocity is close to the sound velocity of human soft tissue but the attenuation coefficient is significantly lower.

Table 6. *The effect of the number of freeze-thaw cycles on acoustic properties of PVA-C and PVA-C with 8% added enamel. Measurements are done at room temperature. [31]*

Material	Freeze-thaw cycles	c (m/s)	α (dB/cmMHz)
PVA-C	1	1526	0.08
PVA-C	2	1533	0.12
PVA-C	3	1535	0.21
PVA-C	4	1541	0.23
PVA-C + enamel	1	1521	0.11
PVA-C + enamel	2	1535	0.19
PVA-C + enamel	3	1536	0.26
PVA-C + enamel	4	1540	0.30

Sometimes the phantom must be constructed with components that are distinguishable by their color. Enamel paint as an additive can be used for this purpose. In Table 6, the affect of the addition of enamel paint to the material is shown. The sound velocity behaves similar with or without enamel, it increases when the number of freeze-thaw cycles increases. The attenuation coefficient with enamel paint also increases when the number of freeze-thaw cycles increases. Even though with or without enamel paint the attenuation coefficient of PVA-C is too low for tissue mimicking material.

Advantages of PVA-C as a phantom material are the low cost of PVA, high structural rigidity and quite long stability. Drawbacks are the low attenuation coefficient, manufacturing time and effort. Manufacturing may take several days depending on the number of freeze-thaw cycles and the lengths of freeze and thaw times. [13; 65]

3.1.6 Others

Several phantom materials have been created to mimic human soft tissue. In this chapter the materials, which are not studied as much as the previous ones, are introduced briefly. Materials like magnesium silicate, oil gel, open cell foam, polyvinyl chloride-plastisol (PVCP) and tofu are introduced here. Along with these material great number of other material composites are used as an ultrasound phantom material but they are not introduced in this thesis.

The magnesium silicate-based phantom material has good acoustical properties for the ultrasound phantom. Magnesium silicate is inorganic substance. It is mixed with tetrasodium pyrophosphate, n-propanol, water and graphite powder. The acoustical properties of this mixture are reported being the sound velocity 1458 m/s, which was able to increase up to 1520 m/s by adding more n-propanol. The attenuation coefficient was 0.85 dB/cmMHz, which is dependent linearly on graphite powder. Magnesium silicate is very stable at large temperature range (0 to 100 °C) and it is resistant to microbial invasion. A disadvantage of this material mixture is that it is not self-supportive and therefore it cannot be molded or sculpted into predefined shapes. Either the acoustical properties of this material needs more development to suit the ultrasound phantom. [13]

Oil gel-based phantoms are usually made of propylene glycol, gelatinizer (Dibenzylidenen D Sorbitol) and polymethyl methacrylate (PMMA) microspheres. The amount of propylene glycol has a direct affect on the acoustical properties. When the concentration of propylene glycol increases the acoustical properties increases. The oil gel-based phantom is immune to bacterial infection. The sound velocity of oil gel-based material was measured to be 1480 m/s and attenuation coefficient was 0.4 dB/cmMHZ for nonimpregnated gel (gel without PMMA). For impregnated gel (with PMMA) the sound velocity was 1580 m/s and attenuation coefficient 1.8 dB/cmMHz. Densities were 1040 kg/m^3 and 1060 kg/m^3 for nonimpregnated and impregnated gel irrespectively. [13; 55]

An open cell foam-based phantom is made of polyurethane foam and a salt-water solution. Salt is sodium chloride (NaCl). By varying the concentration of NaCl the sound velocity could be able to tailor wanted. The sound velocity of open cell-based material is 1540 m/s and the attenuation coefficient is 0.46 dB/cmMHz. The advantage of open cell foam material is that by removing the regions of foam before preparation the localized zones mimicking tissue pathologies or variation can be created within the material. The disadvantage is that the percentage of bubbles effect strongly to the attenuation coefficient and it might be difficult to control the amount of bubbles each time manufacturing the material. [13; 66]

The acoustical properties of two types of polyvinyl chloride-plastisol (PVCP) were studied and the affect of additives in material. PVCP is the suspension of polyvinyl chloride (PVC) particles. When particles are heated to 170 °C they dissolve and become a translucent and viscous liquid. Then the liquid is cooled below 60 °C resulting in a flexible plasticized material. Additive materials are graphite and PVC. Plastic PVCP without additives has the sound velocity of 1440 m/s and attenuation coefficient of 0.14 dB/cmMHz. Other type of PVCP is Super-Spoft PVCP and the sound velocity of it is 1431 m/s and attenuation coefficient 0.66 dB/cmMHz. Sound velocity of plastic and super-soft PVCP are close to each other's but like with other polymer-based tissue mimicking material it is lower than the value of human soft tissue. The attenuation coefficient of super-soft PVCP is similar to human soft tissue but plastic PVCP has lower value. 5 % of graphite powder was added to plastic PVCP and the sound velocity of material is 1439 m/c and attenuation coefficient 0.58 dB/cmMHz. Other additive material is PVC and it is added 8 % as powder to plastic PVCP and the sound velocity of the material is 1449 m/s and attenuation coefficient 1.09 dB/cmMHz. When both graphite (2 %) and PVC (8 %) were added to plastic PVCP the sound velocity is 1448 m/s and attenuation coefficient 1.16 dB/cmMHz. Additives do not affect significantly on sound velocity but attenuation coefficient increases. Adding graphite gives the attenuation coefficient closest to the value of human soft tissue. PVC and both, graphite and PVC, increases the attenuation coefficient too much. Advance of the PVCP material is its long stability but the sound velocity is slightly too low. [67]

Study has been made to investigate the acoustical properties of tofu for ultrasound phantom material. Tofu is a soy product, which is available in grocery stores. It is cheap and easy to get. Three different types of tofu were tested; soft, firm and extra-firm. The sound velocities of these tofu types were 1485, 1485 and 1485 m/s respectively. The attenuation coefficient for soft tofu was 0.74 dB/cmMHz, for firm tofu 1.0 dB/cmMHz and for extra-firm tofu 0.94 dB/cmMHz. Densities of soft, firm and extra-firm tofu were 1170, 1150 and 1100 kg/m^3 respectively. The sound velocity is low for tissue mimicking material and the attenuation coefficient on the other hand is too high. The major disadvantage of tofu is the poor stability and bacterial resistance. [68]

3.2 Comparison of phantom materials

In Table 7 all the materials described before are listed to compare the acoustical properties. First four materials in Table 7 are the commercially available ultrasound quality phantoms. The rests of the materials are hand made in a laboratory. In Table 7, the sound velocity (c), the attenuation coefficient (α), density (ρ), and cost of materials are listed.

From Table 7 can be seen that the sound velocity of most of the materials is good considering the requirements of the application they are designed for. The attenuation coefficient is near human soft issue only with gelatin, agar, nonimpregnated oil gel and open cell foam. The attenuation coefficients of other materials are either too low or high. Densities of different material don’t vary much.

Costs of commercially available phantoms are the average prices of different retailers. For some of the materials, the price per kilograms is presented in Table 7. The prices are the price of the pure material and they are collected only from the data of one supplier. Table 7 shows that the ultrasound phantom materials need more investigations to achieve ideal acoustical properties, stability and reasonable price for the phantom use.

Table 7. *The comparison of acoustical properties and cost of phantom materials.*

Material	**c (m/s)**	**α (dB/cmMHz)**	**ρ (kg/m^3)**	**Cost (€/kg)**	**Ref.**
CIRS (Zerdine)	1540	0.5 / 0.7		2870	[33; 36]
ATS Lab. (PUR)	1460	0.5 / 0.7	900	1650	[13; 35; 36]
Gammex (cond. Milk)	1540	0.5 / 0.7		1880-2710	[37; 38]
Kyoto Kagagu (PUR)	1440	0.57		1790	[36; 39]
Gelatin	1529	0.4		150	[47; 69]
Agar	1538	0.49	1030	465	[13; 16; 52; 55; 69]
PUR	1468	0.13	1130	13	[16; 55; 69; 70]
PAA	1546	0.074	1024	100-400	[7; 16; 60; 69]
PAA + BSA	1544	0.17	1044		[59]
PAA + egg white	1539	0.15	1000		[61]
PVA-C	1541	0.23		230-360	[16; 31]
PVA-C + enamel	1540	0.3			[16; 31]
Magn. silicate	1458	0.85		220	[13; 71]
Oil gel (nonimp.)	1480	0.4	1040		[13; 16; 55]
Oil gel (imp.)	1580	1.8	1060		[13; 16; 55]
Open cell foam	1540	0.46		low	[13; 66; 72]
PVCP plastic	1440	0.14			[67]
PVCP super-soft	1431	0.66			[67]
PVCP + graphate	1439	0.58			[67]
PVCP + PVC	1449	1.09			[67]
PVCP + graphate+ PVC	1448	1.16			[67]
Tofu (soft)	1485	0.74	1170	low	[68]
Tofu (firm)	1485	1.0	1150	low	[68]
Tofu (extra firm)	1485	0.94	1100	low	[68]

In Table 8 other properties like toxicity, bacterial resistance, complexity of preparation and stability are listed and compared with phantom materials.

Only clearly toxic material used in phantom materials is polyacrylamide (PAA). Polyurethane (PUR), polyvinyl alcohol (PVA) and open cell foam are irritating, which mean they are not toxic but can cause irritation reaction if contact with skin. The toxicity of other materials is low or they are not toxic at all. The bacterial resistance of materials is mainly poor. Magnesium silicate, oil gel, open cell foam and PVCP have good bacterial resistance.

Complexity of preparation of material is the ambiguous concept in Table 8. Even though the preparation of gelatin and agar is simple the recipe for these materials is not straightforward. Agar and gelatin based phantom materials are manufactured from many different ingredients and the content of each must be exact to achieve the wanted acoustical properties. Stabilities of commercially available ultrasound phantoms are the warranty times given by manufacturers. The stability times of other materials are estimates if the material is stored properly and there is no bacterial growth.

Table 8. *The comparison of phantom materials.*

Material	Toxicity	Bacterial resistance	Preparation	Stability	Ref.
CIRS (Zerdine)				4 years	[33]
ATS Lab. (PUR)				1-10 years	[35]
Gammex (cond. milk)				1 year	[37]
Kyoto Kagagu (PUR)					[39]
Gelatin	low	poor	simple	poor	[47]
Agar	no	poor	simple	2.5 years	[13; 16; 55]
PUR	irritant		complex	long	[16; 55; 70]
PAA	yes	poor	complex	months	[16; 55]
PAA + BSA	yes	poor	complex	months	[59]
PAA + egg white	yes	poor	complex	months	[61]
PVA-C	irritant	poor	moderate	months	[16; 31]
PVA-C + enamel	irritant	poor	moderate	months	[16; 31]
Magn. silicate	low	good			[13; 71]
Oil gel (nonimp.)	low	good	simple		[13; 16; 55]
Oil gel (imp.)	low	good	simple		[13; 16; 55]
Open cell foam	irritant	good			[13; 72]
PVCP plastic	no	good	simple		[67]
PVCP super-soft	no	good	simple		[67]
PVCP + graphite	no	good	simple		[67]
PVCP + PVC		good	simple		[67]
PVCP + graphite + PVC		good	simple		[67]
Tofu (soft)	no	no	simple	1 day	[68]
Tofu (firm)	no	no	simple	1 day	[68]
Tofu (extra firm)	no	no	simple	1 day	[68]

Additive materials are usually used to modify the acoustical properties of phantom materials or to improve the stability and bacterial resistance of materials. Sodium benzoate is used to eliminate the bacterial growth and to increase the bacterial resistance [47]. Acoustical properties can be modified with n-propanol, formaldehyde, graphite powder, glass beads, proteins (BSA and egg white), NaCl, PVC powder and by changing the concentration of solution.

N-propanol and formaldehyde are used to increase the sound velocity. NaCl is used in the same way to increase the sound velocity. [13; 47] Reinforcement materials like graphite and PVC powder and glass bead increase the attenuation coefficient but they don’t have that big impact on the sound velocity. They increase it a little but not as much as the attenuation coefficient. [13; 16; 34; 47; 51; 52] Proteins like BSA and egg white have the similar impact on the acoustical properties than reinforcements. They increase the attenuation coefficient. BSA doesn’t have any impact on the sound velocity and the egg white increases the sound velocity very little. [59-62] Temperature affects the sound velocity by increasing it to the certain point after the sound velocity is no longer increasing (Figure 20). The attenuation coefficient decreases until the certain point when temperature increases but after that point the attenuation coefficient starts to increase (Figure 21). [59; 62] The phantoms are used in room temperature due to the application it is used. The affect of temperature shouldn’t have a big affect unless the phantom needs to be stored in other temperature but room temperature.

The sound velocity and attenuation coefficient are not comparable with each other. Even though the sound velocity of a material is higher than other material the attenuation coefficient may be vice versa. This phenomenon can be seen in the Table 1 (in Chapter 2.1) and in Table 7. Neither the attenuation coefficient nor the sound velocity are comparable with density either.

4 MATERIAL DEVELOPMENT

First in the development of a new tissue mimicking material common silicone materials were prepared and tested because silicones are elastic, stable and their appearance is similar to skin. Bacteria don't grow easily in silicones, which is an important quality of material in the phantom application. Because in references macroscopic glass beads were used, the glass fiber powder and glass bead powder were added to one silicone material to study the affect of reinforcement to acoustical properties.

Experimental material solution with water was tested for tissue mimicking material. Materials components cannot be stated here due to the intellectual property right reasons. Materials and their preparation or manufacturing methods are described more detailed in Chapter 4.1.

4.1 Preparation of sample materials

Mold silicones were prepared from Wackes Chemie AG Elastosil silicones. In Figure 23 shows all the silicone samples and Table 9 lists the dimensions and densities of the silicone samples. Three different Elastosil silicone materials were used; M 4601 A/B, RT 601 A/B and RT 628 A/B [73-75]. RT 601 A/B silicone was mixed with glass fiber powder and micro glass beads. Kevra supplies glass fiber powder and micro glass beads [76]. They were used as reinforcement materials to see how they affect acoustical properties.

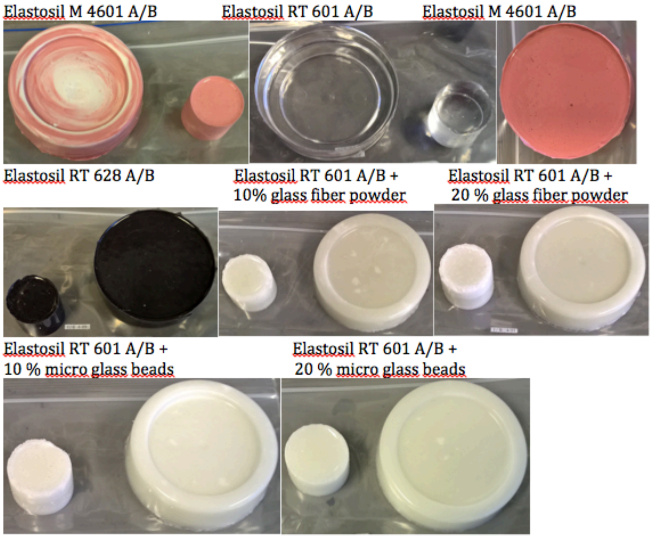


Figure 23. *The silicone samples.*

Table 9. *The dimensions, weight and density of silicone sample materials.*

Material	Thickness (mm)	Diameter (mm)	Volume (mm^3)	Weight (g)	Density (kg/m^3)
E 4601 small	22.2	28.7	14362	17.43	1214
E 601 small	22.6	29.0	14928	16.314	1093
E 601 large	17.1	71.2	72373	74.99	1036
E 4601 large	15.0	71.0	63369	74.12	1170
E 628 small	23.0	29.1	15297	19.094	1248
E 628 large	14.6	71.2	62626	79.61	1271
10% glass fiber small	20.0	29.0	13210	15.183	1149
10% glass fiber large	13.6	71.0	57849	66.05	1142
20% glass fiber small	21.4	29.0	14135	17.288	1223
20% glass fiber large	11.7	70.5	49774	61.39	1233
10% glass beads small	18.2	29.0	12021	14.143	1177
10% glass beads large	13.2	71.0	56881	63.50	1116
20% glass beads small	19.1	29.1	12703	15.399	1212
20% glass beads large	15.2	71.0	64904	78.27	1206

All the silicones used here are two-component silicone rubbers. They vulcanize in room temperature, which makes preparation easy. First the Elastosil part A is measured into a paper cup. After measuring the part A, the part B mass is calculated using the mix ratio of 9:1 for all silicones. Part B is then measured into the same paper cup as the part A. Two components are mixed properly with wooden stick to get the smooth mixture. Next step is to pour the material into the two different sizes of mold cups. Air bubbles are removed from the silicone samples tapping the cup against the table. After the removal of air bubbles, the samples are left to cure on the table. Next day the samples are removed from the molds and placed in the plastic bags to wait for the measurements. Pot life for these Elastosil silicones is 60 to 90 minutes. The laboratory temperature was 18 °C and the samples were cured over night approximately 20 to 24 h.

The silicone part of the samples, which include reinforcement, are manufactured the same way as described below. Silicone material is measured and mixed for each sample separately. After measuring and mixing the silicone part the mass of reinforcement is calculated. After calculation, the reinforcement is measured and added to the silicone material. The compound is mixed properly with wooden stick. After mixing, the paper cup and mixing stick is placed in the vacuum chamber to remove air bubbles. In 10 minutes, the mixture is taken out of the vacuum chamber and the material is poured into the molds. The molds are placed in the vacuum chamber to remove the remaining air bubbles. After 10 to 15 minutes, the molds are taken out of the vacuum chamber and leaved on the table to cure. Next day the samples are removed from the molds and placed in plastic bags to wait for the measurements. The curing time for reinforcement silicone samples was the same; 22 to 24 h over night in 18 °C temperature.

Experimental material is water based and concentration of the material in water was determined by removing the water from solution. Three samples were dried in an oven for 4 hours in 63 °C temperature. It occurred that the time wasn't enough to dry the water out of the samples. To dry the samples properly, they were placed in a vacuum oven for 20 hours over night. Table 10 shows the weight of samples and mass after drying. Concentration of the experimental material is about 4.0 % meaning the water content in the material is 96 %.

Table 10. *The measurements for determining the concentration of the experimental material.*

Sample	Weight of the sample (g)	Dry mass (g)	Concentration (%)
1	7.618	0.314	4.1
2	10.703	0.387	3.6
3	7.039	0.294	4.2

Experimental material was watered down to be able to measure the acoustical properties for different concentrations. The original concentration of experimental material was mixed with deionized water. Eight samples of different concentrations were made according to Table 11.

Table 11. *The concentrations of the experimental material samples made from the original concentration.*

Desired concentration	Sample mass (g)	Calculated amount of added water (g)	Real amount of added water (g)
100%			
90%	62.67	6.963	6.982
80%	59.524	14.881	14.892
70%	56.521	24.223	24.222
60%	52.539	35.026	35.052
50%	54.876	54.876	54.879
40%	34.884	52.326	52.358
30%	19.879	46.384	46.382

The amount of the original experimental material, shown in Table 11 in second column from left, was measured in a cup. To get the desired concentration, the calculated amount of water was measured and added to the cup. The second column from right in Table 11 shows the calculated amount of water amount and the last column right shows the real amount of added water. Added deionized water and experimental material was mixed with wooden stick to get homogenous solution. After the preparation of the samples, cups were sealed with decks and placed in a refrigerator to settle for a couple of days before measuring the acoustical properties.

4.2 Test procedure

The acoustical properties (sound velocity and attenuation coefficient) were measured at Aalto University first. In Aalto University, the measurements for acoustical properties were carried out with Olumpus Omniscan ultrasonic device (Figure 24) and the frequency of the transducer was 2.25 MHz. The sketch of the measurement system is drawn in Figure 24. To measure the sound velocity in material the pulse-echo method was used. The through transmission method could also be used to measure the sound velocity in the same way but with one transducer it was easier for user to hold the transducer still during the measurement. The Omniscan ultrasound device is designed to search defects in material and therefore the sound velocity should be known to measure the depth of defect. In this case the thickness of the material is known and the sound velocity is measured by trying to find correct sound velocity for material that gives the correct thickness for the sample material.

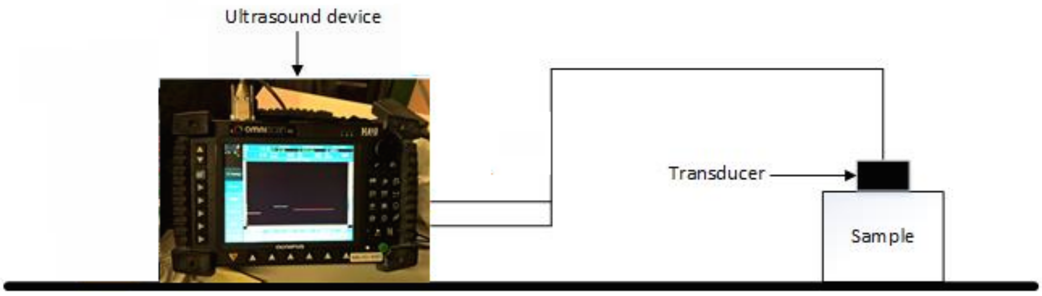


Figure 24. *Sketch of the measurement system used to measure sound velocity.*

To measure the attenuation coefficient of materials at the moment there was only a rough method for evaluating the attenuation coefficient. The attenuation coefficient was measured using the through transmission method in a water path. Because the attenuation coefficient of water is small in comparison of the materials measured, it can be ignored and the diameter between the transducers is irrelevant. The sketch of the attenuation coefficient measurement is shown in Figure 25. The backwall amplitude was set to 100 % of screen height and the amplitude value in this setup was measured to get the attenuation in used sample thickness.

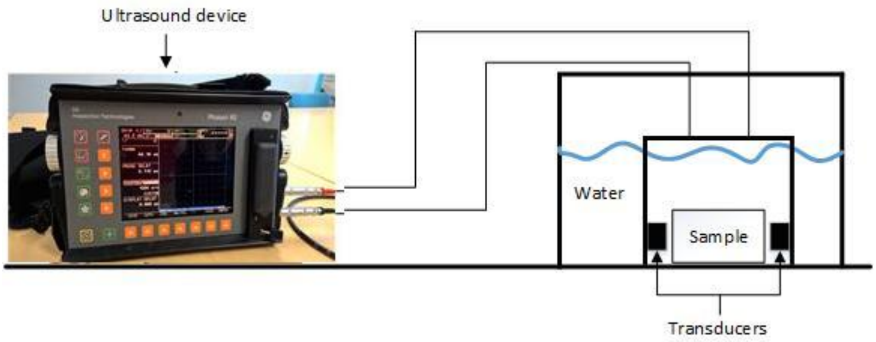


Figure 25. Sketch of the measurement system used to measure attenuation coefficient.

A problem of using the measurement system described above to measure the attenuation coefficient is that the interface between the sample and water causes two times an unknown factor that is the acoustical impedance between water and sample material. To measure the attenuation coefficient more accurately, an unknown factor must be eliminated. The attenuation of the material should be measured with two different thicknesses of sample materials to exclude the effect of acoustic impedance on the interface between two materials. Even more accurate value for the attenuation coefficient can be measured by connecting the transducers on the surface of the sample material. The attenuation measurement can be done either with a through transmission or a pulse-echo method.

Tampere University of Technology (TUT) has Olympus Phasor XS ultrasonic device (Figure 25). To get more accurate values for the attenuation coefficient of materials the measurements were done once more. In TUT, only a pulse-echo method was in use due to the transducer type they have. The acoustical measurements of silicone materials were done via method represented in Figure 24. The sound velocity measurements were also done once again even though the measurement method was the same as previously. For measuring the attenuation coefficient, the backwall amplitude is measured when the screen height is set for 80 %. The same measurement is done for two different thicknesses of samples to calculate the difference in amplitudes and thicknesses.

Silicone materials were firm materials and the transducer was placed on top of the surface of silicone. Water was used to get good contact between the sample and transducer. Experimental material is not solid and therefore cannot be measured the same way as the silicone materials. The transducer can’t be pressed on the surface because it will sink to the material and the thickness won’t be correct. For measuring the experimental material, a specific measurement setup was made. In Figure 26, the measurement setup is shown.

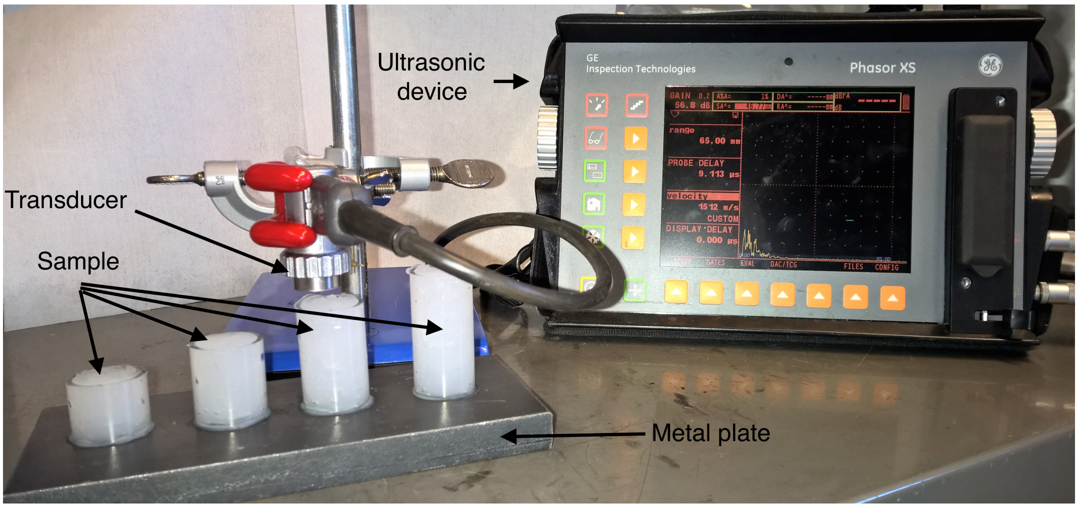


Figure 26. *The measurement setup for measuring the experimental material.*

The mold around the material is an acrylic tube, which has an inner diameter of 21 mm. The acrylic tube is glued on top of a metal sheet to get the reflection of the ultrasound wave. Four different heights of tubes were made. The exact thickness of sample material is measured with a caliper after setting the transducer in position with a stand.

4.3 Test results

The thicknesses of sample materials and backwall amplitudes, which were measured with the screen height of 100 % is presented in Table 12. Values in Table 12 were measured with Omnicsan ultrasonic device at Aalto Univercity. Two of the samples are E 4601. They are the same material only prepared separately into two different sizes of molds. Other materials are manufactured at once a one bigger portion of material, which was poured into two different molds.

Table 12. *Thickness and backwall amplitude of silicone materials measured with Omniscan ultrasonic device.*

Sample	**Thickness (mm)**	**Screen height (%)**	**Backwall amplitude (dB)**
E 4601	22.18	100	8.9
E 601	22.83	100	0.8
E 4601	14.80	-	-
E 628	23.10	100	25.6
10% glass fiber	19.94	100	37.1
20% glass fiber	21.65	100	62.1
10% micro glass beads	18.47	100	39.3
20% micro glass beads	19.39	100	55.8

In Table 13 the sound velocity and attenuation coefficient of silicone materials are presented. The sound velocity (c) is measured with ultrasound but the attenuation coefficient is calculated by dividing the backwall amplitude with the sample thickness (Table 12). This value is divided with frequency, which was 2.25 MHz.

Table 13. *Sound velocity and attenuation coefficient of silicone materials.*

Sample	c (m/s)	α (db/cmMHz)
E 4601	982	1.8
E 601	988	0.2
E 4601	921	-
E 628	962	4.9
10% glass fiber	982	8.3
20% glass fiber	1020	1.7
10% micro glass beads	994	9.5
20% micro glass beads	966	12.8

The measurements were done at TUT again with Phasor XS ultrasonic. Backwall amplitude was measured from several different spots on the surface of the sample to get more reliable test results. In Table 14, the measured backwall amplitudes and average values of them are shown. The samples, which included reinforcements like glass fiber powder (gf) and micro glass beads (mgb) could not able to be measured. Lines in Table 14 display the lack of the measurement result. This time also the experimental material (100 % concentration) was measured by using the simpler test method than was described in Chapter 4.2.

Table 14. *Measured backwall amplitudes with 80 % of screen height at TUT with Phasor XS ultrasonic device.*

Sample	Bac. amp. 1 (dB)	Bac. amp. 2 (dB)	Bac. amp. 3 (dB)	Bac. amp. 4 (dB)	Bac. amp. 5 (dB)	Bac. amp. AV (dB)
1. E 4601	97.6	89.6	94.4	92.4	-	**93.5**
2. E 4601	86.6	86.6	85.6	84.0	-	**85.7**
1. E 601	60.0	72.8	70.4	56.2	58.4	**63.6**
2. E 601	53.6	52.8	57.8	53.2	53.8	**54.2**
1. E 628	-	-	-	-	-	**-**
2. E 628	104.2	104.4	101.6	104.2	104.6	**103.8**
1. 10% gf	-	-	-	-	-	**-**
2. 10% gf	-	-	-	-	-	**-**
1. 20% gf	-	-	-	-	-	**-**
2. 20% gf	-	-	-	-	-	**-**
1. 10% mgb	-	-	-	-	-	**-**
2. 10% mgb	-	-	-	-	-	**-**
1. 20% mgb	-	-	-	-	-	**-**
2. 20% mgb	-	-	-	-	-	**-**
1. exp.mat.	52.6	-	-	-	-	**52.6**
2. exp.mat.	43.2	-	-	-	-	**43.2**

The thicknesses of the samples are measured with a caliper and the results are shown in Table 15. The amplitudes 1 and 2 are the average amplitudes from Table 14. Screen height for all the measurements was 80 % and frequency of the transducer was 4 MHz.

Table 15. *The acoustical properties of sample materials.*

Sample	Thickness 1 (mm)	Thickness 2 (mm)	Backwall amplitude 1 (dB)	Backwall amplitude 2 (dB)
E 4601	22.2	15.0	93.5	85.7
E 601	22.6	17.1	63.6	54.2
E 628	23.0	14.6	-	103.8
10% gf	20.0	13.6	-	-
20% gf	21.4	11.7	-	-
10% mgb	18.2	13.2	-	-
20% mgb	19.1	15.2	-	-
Exp.mat.	40	20	52.6	43.2

In Table 16, the calculated values for the attenuation coefficient and measured values for sound velocity are presented. Attenuation coefficient (α) is calculated by using equation (9).

$$\left(\frac{amplitude\ 1 - amplitude\ 2}{thicknes\ s1 - thickness\ 2}\right) \div frequency \tag{9}$$

The attenuation coefficient is reported in cm instead of mm because in the references the attenuation coefficients of the phantom materials and tissues are reported in cm. The acoustical properties of all the sample materials could not be measured and calculated as stated before.

Table 16. *The acoustical properties of sample materials.*

Material	c (m/s)	α (dB/cmMHz)
E 4601	992	2.7
E 601	1040	4.2
E 628	986	-
10% gf	-	-
20% gf	-	-
10% mgb	-	-
20% mgb	-	-
Exp. mat.	1474	1.7

The acoustical properties of different concentrations of the experimental material were measured. Each concentration was tested with four different sample thicknesses and each thickness was measured three times. Because of the great amount of measurement results, the test results of different concentrations of the experimental material are shown in separated tables. In Tables 17 through 24 are shown the thicknesses and backwall amplitudes of the sample materials. All the measurements were made in 21 °C temperature, which was the room temperature in the laboratory. The frequency of the transducer was 4 MHz and the screen height was 80 % in each measurement. Some of the tables have red numbers in them. The red and strikethrough numbers indicate the apparent measurement error that cannot be used in the attenuation coefficient calculations because it would give negative value for the attenuation coefficient.

Table 17. *Test results for 30 % concentration of experimental material.*

Sample	Thickness (mm)	Backwall amplitude (dB)
30 %	16.02	41.2
30 %	24.68	33.6
30 %	35.59	35.8
30 %	46.33	51.4
30 %	16.61	~~45.4~~
30 %	27.40	26.2
30 %	35.92	31.4
30 %	46.54	33.4
30 %	17.09	~~39.2~~
30 %	27.39	30.2
30 %	36.51	32.2
30 %	43.31	33.8

Table 18. *Test results for 40 % concentration of experimental material.*

Sample	Thickness (mm)	Backwall amplitude (dB)
40 %	16.85	43.0
40 %	24.61	24.6
40 %	34.84	47.2
40 %	45.87	53.8
40 %	17.29	36.2
40 %	27.48	31.6
40 %	36.23	37.2
40 %	45.94	40.2
40 %	16.35	37.0
40 %	26.62	41.0
40 %	37.42	33.8
40 %	44.91	43.4

Table 19. *Test results for 50 % concentration of experimental material.*

Sample	Thickness (mm)	Backwall amplitude (dB)
50 %	17.73	~~45.0~~
50 %	27.28	31.0
50 %	36.82	33.2
50 %	44.12	40.6
50 %	15.59	37.8
50 %	27.64	35.8
50 %	38.06	35.6
50 %	46.50	39.2
50 %	17.65	29.8
50 %	25.97	38.0
50 %	36.28	40.2
50 %	-	-

Table 20. *Test results for 60 % concentration of experimental material.*

Sample	Thickness (mm)	Backwall amplitude (dB)
60 %	15.34	37.6
60 %	24.80	28.4
60 %	33.60	48.4
60 %	46.50	51.4
60 %	14.97	39.0
60 %	24.83	31.4
60 %	34.38	54.8
60 %	44.09	60.0
60 %	15.03	35.8
60 %	26.74	28.2
60 %	35.68	42.4
60 %	43.54	46.2

Table 21. *Test results for 70 % concentration of experimental material.*

Sample	Thickness (mm)	Backwall amplitude (dB)
70 %	14.76	44.0
70 %	25.70	31.4
70 %	35.78	49.4
70 %	44.37	64.4
70 %	16.34	34.4
70 %	26.74	30.2
70 %	36.25	35.2
70 %	44.35	51.8
70 %	16.98	42.4
70 %	26.00	42.0
70 %	34.89	45.0
70 %	45.72	52.0

Table 22. *Test results for 80 % concentration of experimental material.*

Sample	Thickness (mm)	Backwall amplitude (dB)
80 %	16.47	35.0
80 %	26.61	53.2
80 %	34.88	-
80 %	43.51	67.4
80 %	15.65	43.2
80 %	26.74	46.2
80 %	35.98	52.2
80 %	46.92	52.2
80 %	17.56	43.6
80 %	25.83	30.6
80 %	34.17	59.8
80 %	44.54	60.8

Table 23. *Test results for 90 % concentration of experimental material.*

Sample	Thickness (mm)	Backwall amplitude (dB)
90 %	16.39	54.6
90 %	25.48	30.6
90 %	36.62	46.8
90 %	46.88	59.0
90 %	14.38	~~49.4~~
90 %	25.89	45.4
90 %	35.14	46.4
90 %	44.37	49.2
90 %	14.97	38.2
90 %	25.65	42.4
90 %	34.96	44.0
90 %	45.67	56.8

Table 24. *Test results for 100 % concentration of experimental material.*

Sample	Thickness (mm)	Backwall amplitude (dB)
100 %	15.59	47.8
100 %	22.82	63.2
100 %	34.93	57.6
100 %	44.07	62.6
100 %	14.95	41.0
100 %	24.72	60.8
100 %	36.19	70.0
100 %	43.10	72.0
100 %	14.74	39.4
100 %	25.17	51.2
100 %	34.48	59.8
100 %	43.94	61.2

The sound velocity of each concentration of the experimental material is shown in Table 25. The sound velocity was measured three times for each sample thickness like backwall amplitude. The last row in Table 25 is the average value for the sound velocity. The red numbers in Table 25 are the apparent measurement errors that are not included in the average calculations of the sound velocities.

Table 25. *The measured sound velocities (m/s) of different concentrations of the experimental material. The sound velocity of soft tissue is 1540 m/s.*

30%	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**100%**
1538	1592	~~1720~~	1464	1418	1576	1530	1480
1510	1512	1672	1516	1570	1622	1534	1394
1502	1470	1550	1414	1490	1444	1540	1456
1534	1518	1464	1526	1458	1474	1524	1444
1596	1652	1482	1444	1556	1624	1404	1432
1676	1686	1684	1486	1630	1522	~~1600~~	1496
1514	1512	1604	1456	1534	1530	1484	1502
1544	1520	1548	1438	1472	~~1702~~	1466	1432
1646	1570	1662	1442	1582	1586	1464	1428
1660	1622	1590	1622	1574	1428	1560	1502
1532	1582	1518	1500	1444	1466	1468	1460
~~1442~~	1488	-	1442	1516	-	1512	1456
1568	**1560**	**1577**	**1479**	**1520**	**1527**	**1499**	**1457**

The average sound velocities of different concentrations of the experimental material are presented in Figure 27. In Figure the regression line to average sound velocities is drawn and the coefficient of determination (R^2) is calculated to Figure 27. The R^2 value tells how well the regression line fits the test results.

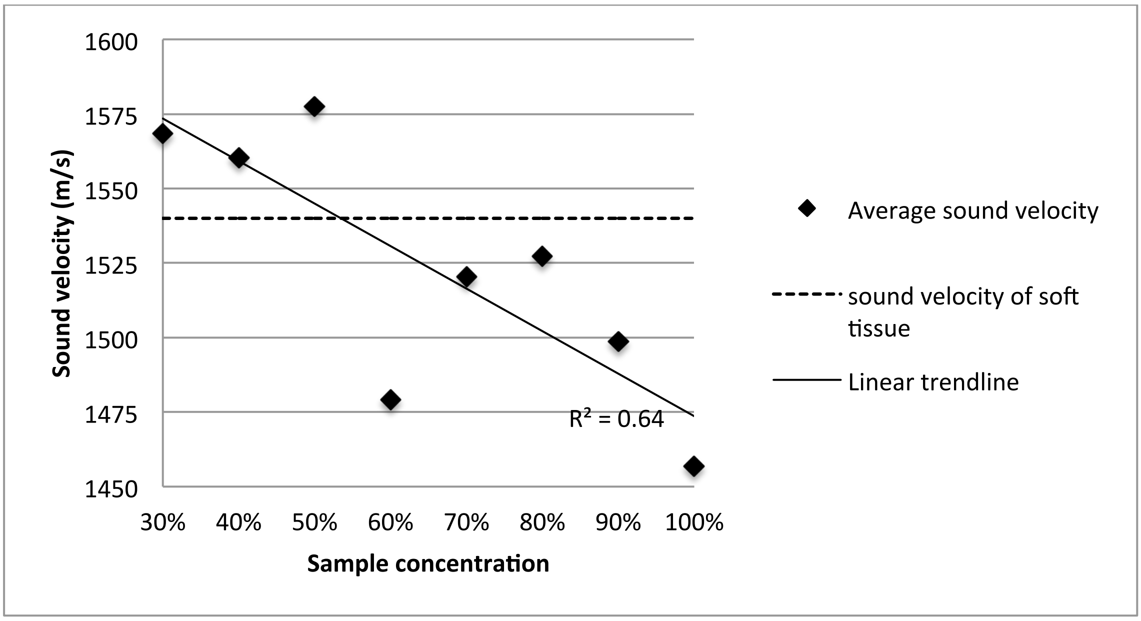


Figure 27. *Sound velocities of different concentrations of the experimental material.*

The attenuation coefficients in Table 26 are calculated using the equation (9). Different amounts of attenuation coefficient values in different samples result from apparent measurement errors, which are shown in Tables 17-24. The red numbers are again apparent measurement errors that are not included in the average values of the attenuation coefficient, which are calculated for the last row in Table 26.

Table 26. *Attenuation coefficients (dB/cmMHz) of different concentrations of the experimental material. Attenuation coefficient of soft tissue is between 0,5 and 0,7 dB/cmMHz.*

30%	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**100%**
0.8	0.6	~~0.1~~	1.5	0.6	4.5	0.4	~~5.3~~
0.5	0.9	1.4	1.1	1.7	2.1	3.6	1.3
~~2.1~~	~~5.5~~	2.5	~~5.7~~	4.5	2.1	~~6.9~~	1.3
~~3.6~~	~~3.4~~	~~0.1~~	2.7	4.4	0.7	3.0	1.4
1.5	1.5	0.5	0.6	4.4	1.1	0.3	~~5.1~~
0.9	0.1	1.1	2.0	~~0.1~~	0.7	0.5	3.4
0.5	0.4	2.5	1.8	1.6	1.6	0.8	2.8
0.6	1.6	1.4	~~6.1~~	1.3	0.7	1.0	2.0
0.6	1.2	0.5	3.2	3.1	~~0.0~~	0.7	~~0.2~~
0.6	0.8		1.3	5.1	2.4	1.5	0.7
	1.0		0.8	~~0.4~~	1.6	0.4	2.8
	0.6		0.9	0.8	~~8.8~~	1.8	2.6
	0.3		4.0	0.8	4.0	3.0	1.9
	~~3.2~~		2.7	1.3	~~0.2~~		2.3
			1.2	1.6			1.3
							~~0.4~~
0.7	**0.8**	**1.4**	**1.8**	**2.4**	**2.0**	**1.9**	**2.0**

In Figure 28, the attenuation coefficients of different concentrations of the experimental materials are shown. Like in Figure 27 also in Figure 28 the regression line is drawn and the coefficient of determination is calculated.

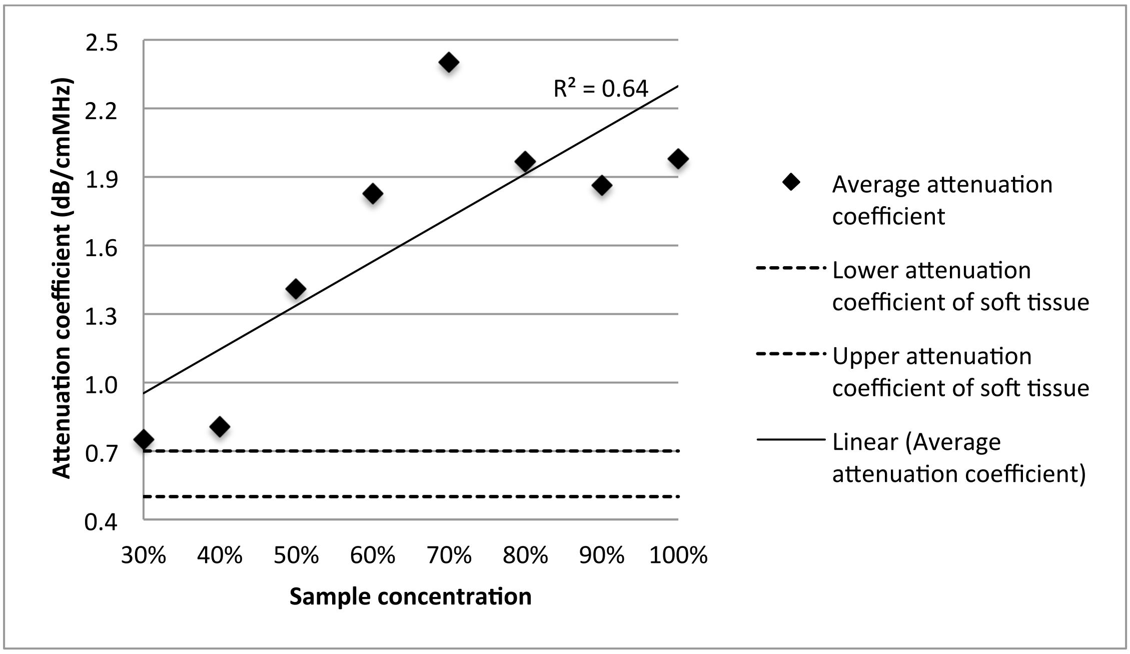


Figure 28. *Attenuation coefficient of different concentrations of the experimental material.*

5 DISCUSSION

Silicone materials have low sound velocity for ultrasound phantom application. Omnicsan ultrasonic device gave lower values for the sound velocity than the Phasor XS ultrasonic device. Omnicsan ultrasonic device is a more accurate measurement system because with Omnicsan the distance and sound velocity is possible to set digitally in the right position whereas with Phasor XS device the sound velocity must set to match the correct sound velocity manually in the diagram. Despite the small differences in test results, both devices give similar results for the sound velocity.

E 628 silicone has the lowest sound velocity of the silicone materials that was between 962 and 986 m/. E 601 has the highest sound velocity between 988 and 1040 m/s. The attenuation coefficient measurements done with Omniscan device are only rough estimations of attenuation coefficient of the materials. For E 601, the attenuation coefficient in Table 16 is only 0.16 dB/cmMHz, which is clearly error in measurements. The attenuation coefficient of E 4601 silicone is much lower than the attenuation coefficient of the two other silicone materials. This could be explained with measurement error or bad sample material. The sample can have air bubbles, which cause false results in the measurements because the ultrasound wave reflects from each interface in its way.

Silicones that have reinforcements added have higher sound velocity than E 601 silicone, which is the same silicone material without reinforcements. Samples with glass fiber increase the sound velocity when the glass fiber amount is increased. Samples with glass beads decrease the sound velocity when the amount of glass beads is increased. This is due to the measurement error and the fact that the measurements couldn’t be repeated with Phasor XS ultrasonic device. The ultrasound wave was not able to travel through the material. The reinforcement and silicone material form interfaces to the material, which causes the ultrasound wave to scatter before it reaches the bottom surface of the sample surface. Air bubbles can cause the same effect on the sample. The rough estimation of the attenuation coefficient is measured with Omniscan device. The attenuation coefficient increases rapidly when the amount of reinforcement is increased. The increase in the attenuation coefficient happens for both of the reinforcement materials. The effect of the reinforcement material on the acoustical properties should have been tested with lower amount of reinforcement. With lower amount of interfaces in the material, the ultrasound wave could have passed the material without reflecting so much than it did now.

Different concentrations of the experimental material were tested because the earlier measurement indicated that it could have proper acoustical properties for the ultrasound quality phantom application. The test results show that the acoustical properties are similar to human soft tissue. The sound velocity is close to 1540 m/s when the concentration of experimental material is between 50 and 60 %. The attenuation coefficient is nearly 0,7 dB/cmMhz when the concentration of experimental material is 30 %. The acoustical properties could be modified using suitable additives to lower the sound velocity in the low concentrations of experimental material. The attenuation coefficient could be modified correspondingly to lower with the higher concentration of additives.

In Figures 27 and 28, the coefficient of determination (R^2) was calculated. R^2 value was the same 0.64 for both the sound velocity and the attenuation coefficient measurements. If the R^2 value is 1.0, the regression line fits the data perfectly. In this case, the R^2 is 0.64, which indicates the regression line fits the data well but it could also fit it better. More accurate test method could result in better R^2 value for regression line to different concentrations of the experimental material.

Even though the measurement system was not the most accurate one, the test results show that the experimental material is worth more studies and could be suitable for the ultrasound quality phantom application. This experimental material has been kept in a refrigerator for over three years, which indicates good stability. The stability of the acoustical properties of the experimental material cannot be said with certainty because the acoustical properties haven’t been tested after preparing the experimental material.

The used measurement system was not very accurate. The Phasor XS ultrasonic device is four years old and the transducer is even older than the ultrasonic device. The transducer may be one of the causes for measurement errors. In Figure 29, the used transducer is shown. There can be seen that the surface of the transducer is rusty and scratchy. With a newer and a more accurate device the test results could be little different and more linear. Newer and not a scratched transducer should be used when carrying out the measurements in future. The transducer is meant to use in a testing of metal materials that have much higher sound velocities and attenuations than the materials were measured in this study. The frequency of the transducer should perhaps be little lower (2-2.5 MHz).

Figure 29. The surface of the used ultrasound transducer.

Other cause of the measurement errors is the air bubbles in the sample materials. The experimental material was stiff and air bubbles could not be removed in the vacuum chamber or in the ultrasound washing device, which vibrates the material. In Figure 30 are shown the air bubbles in sample material. The small concentrations like 30 and 40 % of experimental material were more fluid and the air bubbles were not a problem but with higher concentrations the material was stiffer and the removal of the air bubbles was difficult. Similar error than air bubbles can arise if the material is not mixed homogenously. Solid lumps in material cause interfaces into the material and the ultrasound wave is reflected on the interfaces.

Figure 30. *The air bubbles and solid lumps in sample materials.*

A measurer can cause repeating error. The measurer can also do measurements differently under each sample. The pressure the transducer is pressed on the sample can vary between samples and the point the measurement is taken can vary. When measuring the silicone materials, the transducer must be pressed against the surface of the material to get good contact between the sample and transducer.. This can cause distortion to the thickness of the sample if the transducer is pressed too hard on the sample material. In the other hand, the transducer must be pressed properly on the sample because otherwise between the transducer and sample can be air.

The measured thickness of samples may not be the same at the point the measurements are done. Sample shapes are such that thickness is not unequivocal to measure. Sample materials may include air bubbles. Air bubbles scatter the ultrasound wave, which effect on the results. The transducer may not be in the straight line against the sample. This causes the change in the thickness of the sample if the ultrasound wave doesn’t travel straight through the sample in perpendicular line against the surface of the sample.

6 CONCLUSION

In this thesis, the materials used as ultrasound quality assurance phantoms were studied and new materials for this application were tested. Phantom materials are usually water-based because human soft tissue is mainly water. Water has similar acoustical properties than the human soft tissue. The acoustical properties of the phantom material need to mimic the acoustical properties of the human soft tissue so that they can be used in the ultrasound quality application.

Nowadays the most common phantom materials are gelatin, agar and PVA-C. They have correct sound velocity for phantom application but the attenuation coefficient is usually too low. The acoustical properties can be modified with additives like n-propanol and formaldehyde to increase the sound velocity. Graphite or glass beads are used to increase the attenuation coefficient. Even though the acoustical properties of these materials are close to the values of the human soft tissue, the materials have problems in bacterial resistance and dehydration. Bacterial growth in material causes the contamination of the materials and they cannot be stored a long time even with the additives that prevent the bacterial growth. Dehydration causes changes in the acoustical properties of the materials. Dehydration occurs in longer time line than bacterial growth but is still a problem within a couple of year’s time. Commercially available ultrasound quality phantoms are stable longer time but they are expensive and need to be replaced within four years.

The study of new phantom material was based on the need for stable and cheaper material than what has been in use until now. The study was carried out by testing the silicone materials, which are very stable over time and easy to prepare. Adding the glass fibers into the silicone material and testing the acoustical properties the effects on reinforcement materials to the acoustical properties were studied. The sound velocities of silicone materials were too low and their attenuation coefficients were too high for the phantom application.

The acoustical properties of the experimental material were tested and they turned out to be promising for the application. Different concentrations of the experimental material were tested and the sound velocity of 50 to 60 % concentration seems to be the best and closest to the values of human soft tissue. The attenuation coefficient was suitable with the concentration of 30 % of the experimental material. These tests show the experimental material to be suitable for the ultrasound phantom material. More tests needs to be done to study the material in a better and more accurate manner.

In the future the exact concentration for the experimental material should be determined to get both values the sound velocity and the attenuation coefficient suitable for the ultrasound phantom. Additives may help to achieve the optimal acoustical properties. Now the material is stored in the refrigerator. If the experimental material is manufactured the way the storing is possible in the room temperature, it would ease the usage of the material as a ultrasound phantom material. Testing the material after several years or doing the ageing test for the material should be used to ensure the stability of the material. If the dehydration is a problem for this material, some kind of film is possible to build on top of the material to block the dehydration. After finding the optimal material, the phantom prototype can build and tested.

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