Abstract

As ultrasound is the most common method for medical imaging, a lot of money could be saved if the equipment were cheaper. A problem is that the cheaper available scanners are less documented.

To evaluate a scanner bought for the institution of applied physics, three categories were pondered. The resolution, contrast and safety of the scanner was of most interest.

In order to provide results several measurements were performed. Screws of different dimensions were used for evaluating the resolution, whereas different materials were observed for the contrast. A method to investigate safety was tried by applying the ultrasound probe to water and measuring the transferred heat.

Results of the measurements ended up showing that the resolution was about four times lower when comparing with a commercial scanner. The contrast has a large dependence on the difference of acoustic impedance between object and medium. Lastly, a groundwork for investigating the safety was made.

Eftersom ultraljud är den vanligaste metoden för medicinsk avbildning så skulle mycket pengar kunna besparas om utrustningen inte var så dyr. Ett problem är att billigare scannrar har mindre dokumentation.

För att utvärdera en scanner inköpt hos institutionen för tillämpad fysik, så begrundades tre olika kategorier. Upplösningen, kontrasten och scannerns säkerhet var av störst intresse.


Resultatet av mätningarna påvisade att upplösningen var ungefär fyra gånger lägre än hos en kommersiell scanner. Kontrasten visade sig ha ett stort beroende av skillnaden av akustisk impedans hos objekt och omgivande medium. Slutligen lades en grund för att undersöka säkerheten av scannern.
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1 Goal of the Study

The goal of this study was to investigate the resolution, contrast and safety of a Chinese ultrasound scanner.

These properties are of interest in the scope of comparing cheaper alternatives to the modern, but very expensive, ultrasound machines of today.

The evaluation focused on the limits of the machine and compare these to a more expensive version on the market. These limits were approximated by the help of the Rayleigh Criterion which will be explained in Section 3.1, and different ways of measuring safety, described in Section 3.3.

2 Introduction

The most common method of medical imaging is performed using ultrasound. Such examinations are quick and easy to perform. Although good performance, a downside is that the most commonly used ultrasound scanners are expensive. There are cheap alternatives, but with mostly undocumented image qualities such as resolution and contrast.

Evaluation of image qualities is a difficult task. This is due to lack of concrete detection data, as well as the unavailability of the signal handling to form images.

To investigate the cheaper alternatives, a less expensive ultrasound scanner from a Chinese vendor, was purchased at the department of applied physics at the Royal Institute of Technology. In order to evaluate the image qualities, a number of samples were examined. Different materials and dimensions were taken into consideration.

Previous examinations of this subject has been made, where different aspects of the performance were evaluated. Most focus was then on whether such scanners can be used for simple examinations on humans. However, this project will mainly handle the axial- and lateral resolution of the imaging as well as its contrast and safety, where the following guidelines will be used.

- Is the resolution comparable with that of a modern ultrasound scanner used for medical imaging?
- How does the contrast depend on the medium observed and objects within that medium?
- Is it plausible that the cheaper ultrasound scanner is safe to use on humans?
3 Theory

3.1 The Rayleigh Criterion

The Rayleigh criterion describes how diffraction is a limiting factor when it comes to resolution. Since the aperture is finite, the light passing through it can be considered to move through slits, and will therefore, due to the wave-nature of light, interfere with itself. This will cause an interference pattern where two close but separate points can be perceived as one. The criterion for the smallest distance $\Delta l$ from the normal line is given by Equation 1.

$$\Delta l = \frac{1.22 F \lambda}{D}$$

Where $F$ is the distance to the object, $\lambda$ is the wavelength and $D$ is the diameter of the lens. $\Delta l$ can also be thought as the radius of the smallest spot the lens can perceive.

3.2 Resolution

3.2.1 Lateral Resolution

The lateral resolution of an ultrasound machine describe its ability to detect objects lying parallel to the transducer according to Figure 1. The smallest circular object it can theoretically perceive is given by the Rayleigh criterion, explained in the previous section.

3.2.2 Axial Resolution

Axial resolution is a way to denote the ability to distinguish two objects along the axis, i.e. parallel to the propagation of the ultrasound wave. An estimation of the limit is given by Equation 2.

$$\Delta x = \frac{T c}{2} = \left\{ \text{half the spatial distribution of the pulse, } T = \frac{1}{f} \right\} = \frac{c}{2f}$$

Where $c$ is the propagation speed through the medium and $f$ the frequency of the ultrasound pulses [4]. Given this estimation, which is inversely proportional to the frequency, a higher frequency gives a higher resolution, i.e. one may distinguish smaller
structures from each other. There is though a trade-off since higher frequency also leads to higher absorption in the medium, this means a lower penetration depth.

![Diagram of axial resolution](image)

**Figure 2: Axial resolution [4]**

### 3.3 Safety

Safety is always of utmost importance when experimenting with new devices. To be able to use the ultrasound scanner in a proper way, it is much needed to learn about the safety beforehand. Furthermore, it is appropriate to define the words hazard and risk in the context of ultrasound scanning. Hazard is the nature of the threat, whereas risk on the other hand is the possible outcomes of the hazard. Chemicals in a laboratory can be used to exemplify hazard and risk. On a can of chemicals, a warning for burning corresponds to the hazard. However, risk is the outcome of the burning, i.e. burn damage. Knowing this, it is convenient to move onto the ultrasound specific risks and hazards.

#### 3.3.1 Hazard

The primary threat of ultrasound is thermal hazard. Secondly tissue may be subject to mechanical hazard. Ultrasound is a longitudinal pressure wave, causing a point to cyclically increase and decrease its pressure. The phenomenon is caused by absorption of some wave energy by the tissue. The absorbed energy is then converted to heat and this gives rise to the increase of temperature in the tissue. Considering though that ultrasound is merely mechanical vibrations it may also contribute to non-thermal effects. One such is acoustic cavitation which refers to the response of gas bubbles in a liquid under influence of an acoustic wave.

It is known that about 70% of most soft tissue in the human body consists of water. A big difference between water and tissue though is that tissue absorbs more ultrasound. It has thus been found that the energy absorption rate per unit volume, \( q_v \), depends on the amplitude absorption coefficient, \( \alpha_0 \), of tissue, acoustic frequency, \( f \), and the intensity \( I \) as

\[
q_v = 2\alpha_0 f I
\]

where the factor 2 arises because the intensity absorption coefficient is twice the amplitude absorption coefficient [2]. With proper models one can predict temperature increase, but it has been preferred to make measurements of tissue phantoms instead due to uncertainties of the models.
Bone is highly absorbent and so areas where bones are present during examination are commonly more temperature elevated. So before moving on to the risks of the hazards, three different thermal indices (TI) will be defined. The TI is an estimate of the temperature rise, so a TI of 2.0 means an expected rise of 2.0 deg C. The different thermal indices are defined for three distinguished applications.

- TIS Soft-tissue Thermal Index
- TIB Bone-at-focus Thermal Index
- TIC Cranial Thermal Index.

3.3.2 Risk

Duration of temperature elevation and the specific sensitivity of the tissue must be had in mind when assessing risk. Having defined the main hazards of ultrasound it is easier to explain the risks. The risk of the thermal hazard arises as soon as the temperature of tissue rise over natural habitats. But the question is, will there be remaining biological damage? It all comes down to dependence of the nature of the examination and the use of the ultrasound scanner.

In the focus of the ultrasound wave, the rate of heat loss due to conduction to nearby regions will nearly cancel out the rate of energy absorption after about 30 seconds. Meaning that the temperature rise in these regions might be quick, but still reaches its maximum temperature rather fast as well. In areas with a wider spread of the ultrasound, where the temperature rise is more uniform, conduction will not be as apparent causing the temperature to keep increasing at the same rate over a longer period of time. This can be seen near the transducer. Another significant effect is the transducer itself. Considering it generates the ultrasound it will itself heat up and conduct into nearby tissue. After several minutes the temperature in the tissue near the transducer may well exceed the focal temperature. It is sometimes argued that the blood flow in tissue conducts all the heat, but this is misleading [2]. Most of the temperature rise happens during the first minute of exposure, and though blood flow surely is a contributing factor of conduction, it is not safe to assume that it will limit the temperature rise to risk-free levels.

A change of temperature affects the rate of occurrence of a process and also the equilibrium positions between competing reactions. The range of normal core temperature is about 36-38 °C and a temperature of 42 °C is largely incompatible with life. A further complication is the denaturing of enzymes and larger molecules, which may be apparent at temperatures higher than 45 °C. Even so, a locally exposed region of a human body may generally recover. Some regions, where the tissue sensitivity is higher, are not as tolerant though. Examples of such regions range from reproductive cells, unborn fetus to the central nervous system. Especially the examination of fetuses during pregnancy is a sensitive issue due to the amount of scans being performed.

Gas filled cavities in the body are an important factor when assessing the risk of non-thermal hazard. One such risk is inertial cavitation, which is when the liquid surrounded bubble of gas rapidly collapses and hence produces a shock wave. This has lead to the introduction of a mechanical index (MI), contrary to the previous TI, which instead estimates the effect of the mechanical oscillations. Physical conditions can probably not support bubble growth and collapse at a MI< 0.7, where bubble implicates a gas formation. Exceeding this level does however not mean that there will be any mechanical bio effects caused by the cavitation, but simply gives an estimate of where the risk might be at a limit.
Another risk of non-thermal hazard is stable cavitation. Stable cavitation occurs when small gas bubbles are formed at fairly low intensities and oscillate about some equilibrium for many acoustic cycles. Thus, the resulting shear stress may rupture cell membranes. This is how destruction of blood cells is executed. Another effect is that gaps may open in the membranes and enable larger molecules, such as DNA, to pass through.

Inertial cavitation can be caused by short ultrasound pulses, which causes the bubble to undergo very large size variations. Under the inertia of the surrounding liquid the gas bubble may collapse. Inertial cavitation is potentially more violent and destructive than stable cavitation. Micro-vascular damage may often result from exposure of gas-filled contrast to pulsed ultrasound at pressures less than 1 MPa, well within diagnostic range. Hence, the safety criteria for the use of contrast is of high priority in safety discussions.

There is no independently shown evidence that ultrasound would cause remaining biological effects when used on diagnostic levels. However, a note of caution, no studies have been made of exposure to pulsed Doppler or Doppler imaging, i.e higher levels of intensity and power. Consistent occurrences of alveolar hemorrhages when examining smaller mammals have though been observed, even at diagnostic levels of ultrasound. Similar small bleedings have also been seen in other tissues related to gas presence. The cause is unclear, but it shows that diagnostic levels of ultrasound may cause damage to fragile tissue while adjacent to gas bodies. Similar occurrences has not yet been observed on humans [2] and might indicate that humans have less sensitive or thicker membranes. Many studies have been made on effects of fetus’ in utero exposure, such as weight, malignancy, neurological-development or speech, but no remaining differences has been concluded.
4 Method

Laborations were performed at AlbaNova, Roslagstullsbacken 21, Stockholm, at the institute of applied physics. All measurements were performed in the same room at roughly the same temperature, using the settings explained in the following section. For measurements on solid mediums a coupling gel was used for enhanced contact with the probe.

4.1 Ultrasound Scanner and Settings

During all of the labs in this report a B-Ultrasound Diagnostic System CMS600B3 was used. The settings were chosen beforehand to give the most consistent result. All the relevant settings are shown in Table 1.

<table>
<thead>
<tr>
<th>Setting</th>
<th>FREQ</th>
<th>FPIN</th>
<th>FR</th>
<th>POWER</th>
<th>FMAVG</th>
<th>BGAIN</th>
<th>DR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>7.5 MHz</td>
<td>1 D0</td>
<td>71 LO</td>
<td>100 %</td>
<td>0.45</td>
<td>30/62</td>
<td>64</td>
</tr>
<tr>
<td>Setting</td>
<td>GY</td>
<td>IM</td>
<td>BRT</td>
<td>CC</td>
<td>Probe</td>
<td>Depth</td>
<td>Focus</td>
</tr>
<tr>
<td>Type</td>
<td>0</td>
<td>2</td>
<td>12</td>
<td>0</td>
<td>L3-1/7.5 MHz</td>
<td>40 mm</td>
<td>30 mm</td>
</tr>
</tbody>
</table>

Where FREQ is the frequency of the transducer, FPIN is the focus number, one or two focal points. FR describes the scan line density, the higher FR the lower image frame rate. FMAVG is the frame size and BGAIN is the gain of the current image to real-time single B mode used. DR, GY and IM are related to the dynamic range. BRT and CC describes the brightness of the picture. L3-1/7.5 MHz is the probe which came with the scanner.

4.2 Tissue Phantom

Tap water, salt water and gelatin structure, grilled chicken and a fresh chicken breast were the four tissue phantoms used for evaluation of the resolution of the ultrasound scanner. For evaluation of the contrast the materials wood, metal and two different plastic objects were used.

The tissue phantom of salt water and gelatin was made by boiling 1 liter of water and 2/5 dl of salt in a pot on a kitchen stove, then 65 g of gelatin powder was added to the salt water mixture. After dissolving the gelatin, the mixture was taken off the stove for cooling. When moderately warm, the solution was poured into a plastic box and put into the refrigerator for further cooling. After several hours the tissue phantom was a solid gelatin structure, which was divided into four uniform pieces for later evaluation.

4.3 Resolution

As described in Section 3.2 the resolution of a ultrasound scanner can be explained by two characteristics, axial- and lateral resolution. To evaluate the quality of the resolution, measurements on subjects of well known size can be made.

4.3.1 Measurements with screws

Imaging with ultrasound often observes small parts of the human body. Hence, modeling can be made using screws with varying size. The screw thread is the distance from the
inner diameter to the outer diameter of a screw. The thread gradient is the distance between threads after one revolution. By using screws with decreasing size a limit of the distinguishable distance can be found. In the purpose of finding axial- and lateral resolution screws with the properties of Table 2 were used. The size of the screw thread was used for evaluating the axial resolution whereas the thread gradient was used for evaluating the lateral resolution.

Table 2: Screws, in order of descending size, used for measurements.

<table>
<thead>
<tr>
<th>Screw [#]</th>
<th>Screw thread [mm]</th>
<th>Thread gradient [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.1</td>
<td>2.8</td>
</tr>
<tr>
<td>2</td>
<td>1.8</td>
<td>2.3</td>
</tr>
<tr>
<td>3</td>
<td>1.4</td>
<td>2.2</td>
</tr>
<tr>
<td>4</td>
<td>1.0</td>
<td>2.2</td>
</tr>
<tr>
<td>5</td>
<td>0.8</td>
<td>1.7</td>
</tr>
<tr>
<td>6</td>
<td>0.8</td>
<td>1.5</td>
</tr>
<tr>
<td>7</td>
<td>0.7</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Measurements were performed on all of the different tissue phantoms, using the defined settings under Section 4. For the cases where the phantom was solid a coupling gel was used on the probe for enhanced visuals.

The screws were placed one at a time 3 cm away from the surface being scanned. Thereafter the probe of the scanner was used to focus on the screws in the phantoms and images were saved onto the ultrasound scanner. Later on the images were exported to a computer. This procedure was repeated at different occasions, for the different tissue phantoms.

4.4 Contrast

Contrast of the ultrasound scanning can be seen by the difference of gray scale between certain objects or tissue. In order to see which materials cause a higher contrast, scanning of several materials as well as on bone was performed. For most purposes water was used as observed medium because of the low acoustic impedance, meaning a lower absorption. Thus differences between surrounding and object can be observed more clearly. However some images were made of other mediums to evaluate the influence of the surrounding.

4.4.1 Measurements with Different Materials

Using a plastic box filled with water, four different objects were submerged one at a time into the liquid and images were taken. The four different objects used were an aluminum whisk, a wooden scoop, a plastic scoop and a plastic seal.

4.4.2 Measurements with Bone

For the resemblance of a human body, measurements using bone was also performed. Images of the bone was taken in four different environments, in water, the gelatin structure described in Section 4.2, a grilled chicken and a fresh chicken breast. The images were saved to show differences of the contrast.
4.5 Safety

As previously stated in Section 3.3.1, the primary threat of ultrasound is thermal hazard. To be able to assess the risk of using ultrasound on humans, without directly applying it to test subjects, one has come up with methods to replace human tissue for examination.

4.5.1 Thermal Absorption

In this study a bath of 0.35 liters of water was used as a replacement for human tissue. A laboratory stand was used to keep the transducer in place and a thermal imaging camera, Flir C2 Digital Camera, was to measure the temperature change over time. The setup is shown in Figure 3.

Figure 3: Absorption Setup
Results

5.1 Lateral Resolution

Screw 6 and screw 7 can be seen in Figure 4. Images were saved from measurements according to Section 4.3.1. The thread gradient decreases from 1.5 mm, Figure 4 (A), to 1.1 mm, Figure 4 (B). One can see that the distinct revolutions vanishes somewhere in this range.

![Figure 4: Screws number 6 and 7 respectively in water for measuring lateral resolution. (A) Thread gradient is 1.5 mm. (B) Thread gradient is 1.1 mm.](image)

5.2 Axial Resolution

Results from the experiment described in Section 4.3.1 are shown in Figure 5. Here one can see that the ragged surface of the screw in Figure 5 (A) showing the screw thread disappears as the thread is decreased from 0.8 mm to 0.7 mm.

![Figure 5: Screws number 6 and 7 respectively in the phantom for measuring axial resolution. (A) Screw thread is 0.8 mm. (B) Screw thread is 0.7 mm.](image)

5.3 Contrast

From the result of the experiment with different materials described in Section 4.4.1, the most distorted image was given by the metal in Figure 6 (A). Furthermore gave the plastic
a more clear image and one can see the contours of almost all the object in Figure 6 (B) and 7 (A). The wood and the chicken bone gave a mixture of both the results as they were blurrier than the plastic but more clear than the metal.

Figure 6: Rod of metal and a rod of plastic. Similar dimension but different materials produce different kind of images. (A) Metal. (B) Plastic.

Figure 7: Plastic clamp and a wooden rod in water. (A) Plastic clamp. (B) Wooden rod.
Figure 8-9 are the results of the models corresponding to tissue which better resembles the human body. A chicken bone was placed according to Section 4.4.2. In the last figure the contour of the chicken bone has been marked by a red arrow in order to clarify the result. The last environment in which the chicken bone was observed was in a grilled chicken. However, these images were completely blurry and thus left out from the results.

![Figure 8: A bone from a chicken in water and in the tissue phantom. (A) In water. (B) In the tissue phantom.](image)

![Figure 9: A chicken bone marked in red within a fresh chicken breast.](image)

### 5.4 Thermal Absorption

The results from the thermal absorption lab described in Section 4.5.1 is presented in the Figure 10. Where the red line is the mean value over all the data points and the blue lines are measurements.

A linear fit describing the thermal changes of the water in the room with transducer is shown in Figure 11. The cooling gradients were found to be $-0.004996$ and $-0.005427$. 

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6 Discussion

Although satisfactory results of the measurements were obtained, certain improvements of the method could be made. Having used the same settings for all of the measurements results in a loss of generality. E.g. experimenting with different depth of focus of the scans, changing the frequencies, and applying real-time scans could have been made to further investigate the qualities of the ultrasound machine.

Regarding the tissue phantom, more effort could have been made when calculating the salinity to better represent the human body. Having more time, several phantoms of different salinity could be made for further investigating the contrast difference for varying mediums. The tissue phantom could also be improved by adding a skin-like layer of silicon.

6.1 Resolution

Theoretical limit values of the lateral- and axial resolution are obtained by Equation 1 and 2 in Section 3. The theoretical value for the lateral resolution is found to be approximately 0.31 mm. In Equation 1 we used the focal length 30 mm, the wavelength of the ultrasound calculated with frequency 7.5 MHz and speed of sound in water as 1482 m/s [1]. The diameter of the probe is 47 mm. Furthermore, for the axial resolution the theoretical value is found to be 0.099 mm, where the speed of sound in the medium $c_{\text{water}} = 1482$ m/s and the frequency 7.5 MHz were used in Equation 2.

Seeing as the screw gradient vanishes in the range between 1.1-1.5 mm one can conclude that it is somewhere within this range that the lateral resolution lies. A similar conclusion

![Figure 10: Mean value of collected data with (A) and without (B) the transducer.](image)

$R^2 = 0.912$

\[ C = -0.004996 \cdot t + 36.47 \]

![Figure 11: Linear fit of the data with and without transducer.](image)

$R^2 = 0.936$

\[ C = -0.005427 \cdot t + 36.57 \]
can be drawn for the axial resolution where the screw threads instead vanishes in the range between 0.7-0.8 mm. The results of the resolution in Section 5.1-5.2 were within the magnitude of the theoretical values and thus very satisfactory.

Furthermore, the values found for the ultrasound scanner can be compared with the resolution of a more expensive and larger scanner used for medical imaging. Such a scanner is the Vevo 3100 [3] which has a minimal resolution of 30 µm at 50 MHz frequency. Extrapolating this value to our used frequency, 7.5 MHz, (since according to Equation 2 the smallest perceivable distance is inversely proportional to the frequency) results in an axial resolution of 0.2 mm. Thus, the expensive scanner can distinguish objects one fourth the size.

6.2 Contrast

Contrast can be discussed using results found in Section 5.3. The metal rod is very distinct, however disturbance can be seen on its sides. This is probably due to the reflection of the ultrasound pulses. The same goes for the wooden rod, although the cut is not as distinct as for the metal. Observed plastic materials has the least disturbances but also the lowest contrast difference between object and medium. Since distinction relates to acoustic impedance, which in turn is proportional to the density, this might partly explain the difference of contrast.

Regarding the chicken bone, similar occurrence of disturbances are visible in Figure 8. However, when placed in water the cut of the bone is highly distinguishable whereas the bone in the tissue is more difficult to observe. This may be due to air bubbles which surround the bone, resulting from the insertion of the bone into the tissue phantom. Both of these cases compared to the bone in the fresh chicken have a remarkable difference. In the fresh chicken one can barely point out the bone placed within and there is a lot of disturbance in the background. Considering that the fresh chicken was previously frozen, it is plausible that some crystalized water remained in the tissue and hence affected the image.

For the last case, the laboration of the grilled chicken, no images were saved for evaluation. This was due to the indistinguishable images observed. A probable reason for this is that the grilled chicken might have had a large amount of air within, which diminishes the homogeneity of the tissue and thus worsen the contrast.

6.3 Safety

When evaluating the safety of the scanner, the chosen method was to look at how the temperature changed depending on whether the transducer was applied to a bath of water or not. The bath was heated to a temperature of 36.5 °C to resemble the human body. Furthermore, the bath was around 15 °C warmer than the room and rapidly started to cool down. Measurements could therefore be improved by thermally isolating the water bath to single out the energy applied by the transducer.

From Figure 11 (A) and (B), the resulting linear fit is shown from the cooling with and without the transducer. The quotient of the two cooling gradients is 0.92. This result cannot be interpreted solely as the effect from the transducer since the heat camera was somewhat unreliable, since calibration occurred at seemingly random times and fluctuated between values. Furthermore the water was swirling in the bath and disturbed the measurements. This can probably explain the fluctuation in the cooling seen in Figure 10. If there were more time and resources, the experiment would be remade in a more controlled environment with a different camera.
7 Conclusions

During this study an evaluation of a cheap ultrasound machine was made. There are less areas of usage for the cheaper scanner since the resolution of the more expensive machine was about four times as high. If one wants precision in the images, as in medical imaging, a more expensive scanner is preferred. However, for cases where less precision is needed the cheap alternative could be sufficient.

Since the contrast sharply decreased as the medium became less homogeneous, one can maybe conclude that if the medium observed contains a variety of tissues, e.g. the human body, the images will have less quality. Furthermore, it is preferable to avoid scanning dense materials, since they give rise to disturbances in the images.

The health risk associated with the scanner was tried to be evaluated by exposing water to ultrasound. Comparing the final temperature difference, with and without applied ultrasound, it is too small and the error sources too many for any justified conclusions. For a complete evaluation more data and more exact measurements are thus needed. Hence, further investigation is needed to know whether or not the scanner is safe to use on humans.
References


