HL2029
Medical Engineering,
Advanced Course

On the investigation of transducer defects using programmable ultrasound systems

En utredning av defekter i ultraljudsgivare med programmerbara ultraljudssystem

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Summary

With the widespread use of medical ultrasound as a diagnostic tool, there is a constant need for ways of improving diagnostic confidence. One of them is to ensure the ultrasound system used is correctly and reliably functioning.

Quality assurance procedures can be defined for that purpose but, unless a systemic and thorough testing of the device is performed before each diagnostic procedure, it is not realistically possible to be 100% confident that the device is fully functional.
It could then be argued that, additionally to regular testing procedures, the person operating the device should be able to detect when the ultrasound transducer they are using is not functioning properly. As there are many factors influencing the overall quality of the image obtained when imaging a patient with an ultrasound system, this is something that proves to be difficult. Indeed, many kinds of artefacts can be introduced in the image, due to system settings, to the patient himself or to the way the transducer is used.

However, in the same way that transducer operators learn how to recognize and avoid such artefacts, there should be means of identifying when the quality of the image is affected by a defect in the transducer.

In this project, we investigated on the effects of transducer defects on image quality. Using the computer controlled Verasonics ultrasound system, we created a tool that simulates transducer defects, and allows the user to directly visualize the deteriorating effect on the ultrasonic image.

Acknowledgements

First and foremost, I would like to thank my supervisor, Dmitry Grishenkov, for his guidance and support. Having the opportunity to work on this project and getting familiarized with the work of the CEMIT research group has been an extremely valuable experience and will, I hope, serve me greatly for my master thesis project.

I would then also like to thank everyone from the CEMIT group, for advising me in my experiments and for sharing their progress, findings and successes over the past few weeks.

This Medical Engineering advanced course has given me a chance to greatly develop theoretical knowledge from previous courses and to directly apply it in a laboratory setting, making it an especially enriching course.

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Introduction

Ultrasound is one of the most commonly used diagnostic tool in healthcare. There are many reasons why it is favored over other imaging techniques: it is inexpensive and provides real-time information, and it is considered safe, particularly since it does not use ionizing radiations.
Furthermore, the technique's unique time resolution, in the order of milliseconds, combined with its high spatial resolution, in the order of millimetres, gives healthcare professionals the ability to obtain satisfactorily accurate measures.
The technique has seen continuous development over the past decades, and this has led to increasingly better quality of the ultrasound image.
In clinical use, image quality highly contributes to making accurate measurements and consequently obtaining a diagnosis.
There are several factors influencing the overall quality of the image obtained. One of them is of course the operator and their skill level. A poorly trained operator will most likely produce ultrasonic images of worse quality than a highly skilled and experienced one.
Human factor put aside, the ultrasound system itself and its various components (transducer, image processing, display, etc.) are yet the main factors determining the ultimate quality of the image.
The performance of each one of these components then becomes critical, and defects in their functioning will highly impact how reliably a diagnosis can be performed.

Motivation

In a study evaluating the function of 676 ultrasound transducers used in clinical departments in 32 different hospitals [1], it was shown that almost 40% of them exhibited a transducer error. This very high incidence of defective transducers poses a risk for incorrect diagnosis and shows that the testing protocols established in clinics are not enough to identify defective devices. It also raises the issue of ultrasound operators not recognizing that the transducer they are using is not functioning properly.
The importance of defining better protocols for testing clinically used transducers is obvious and undeniable. Giving appropriate training for operators to understand the relationship between image quality and transducer performance should also be considered and could improve the clinical efficacy and precision of ultrasound imaging.

Goal

The idea behind this project is to create a pedagogic tool that would allow the user to simulate and visualize transducer defects. By deliberately introducing errors in the functioning of the transducer, the user could then directly observe how the ultrasonic image quality is impacted and learn how to detect potentially defective transducer by simply looking at the image they produce.

For this tool, we wanted to use commercially available products and a programmable system, such as the Verasonics System, thus offering the possibility to develop further and improve the features of the tool.
We also wanted the tool to be user friendly, and to allow users to easily configure different models for defective transducers. Using a simple user interface, they should thus be able to, for example, simulate a specific defect on a specific element of a transducer.

Background

In order to simulate transducer defects, it is important to understand the different kinds of damages that can occur in a transducer, and what they mean for the functioning of the overall system.

How to identify these defects should also be discussed. There are several methods for detecting defective transducers, from very simple one such as the paper clip method, that allows to identify the presence of non-functioning elements, to more advanced and accurate testing devices, that measures different parameters for each single element of a transducer array.

Finally, as we are interested in evaluating the performance of transducers, we should define what parameters are relevant and of clinical importance.

Transducer errors

There are different potential defects that can affect the correct functioning of a transducer. Below, we define what they are.

Dead elements

If an element operates at less than 10% of the element with the highest sensitivity in the array, and if there is no delamination of the ultrasound lens, the element can be considered as dead.

Weak elements

If an element operates between 40% and 75% of the mean sensitivity value of the elements in the array, and given the array has no consecutive dead elements and no more than a total of 3 dead elements, the element is considered weak.

Delamination

Transducers are composed of 4 basic components: a backing layer, a piezoelectric plate, a matching layer and a lens. [2]

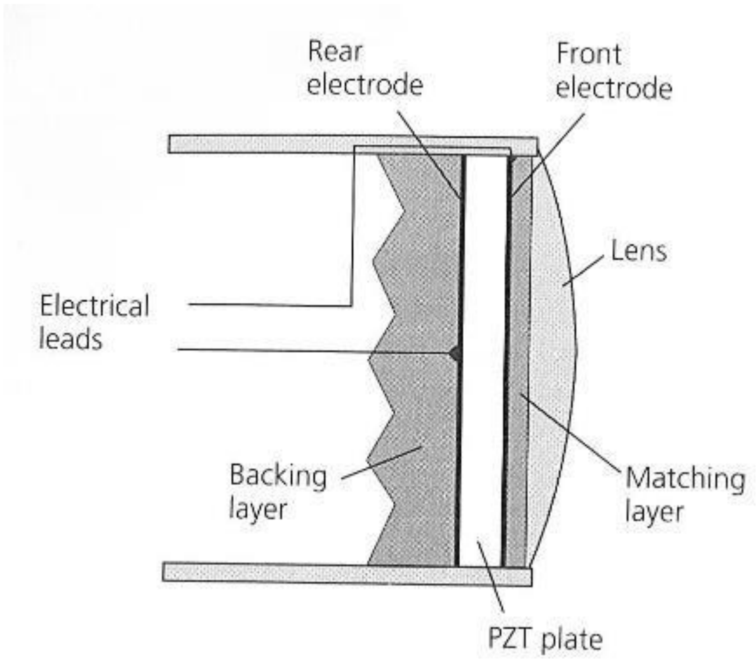


Figure 1 - Main components in a transducer

Delamination means that the ultrasound lens, the matching layer or the backing layer is detached from an adjacent component.

In case of delamination, the affected elements will have a lower sensitivity than normal but will preserve a normal capacitance value.

Broken cable
A break in the cable prevents the activation of the element it connects to, meaning the element's sensitivity value will be zero. The capacitance value will be lower, between 0 and 50% of its normal value depending on where the cable is broken.

Short circuit
In case of short circuit, the sensitivity will also be reduced to zero, but the capacitance value will be higher than normal.

Sonora FirstCall Test System

The Sonora FirstCall Test System is an ultrasound probe testing device developed by Sonora Medical Systems Inc. (Longmont, CO, USA) [3]. When connected to an ultrasound probe, the device pulses each element within the array and measures the relevant acoustic and electrical parameters to test for:

- Element sensitivity (volts p-p)
- Capacitance (pF)
- Pulse width (ns)
- Center frequency (MHz)

- Fractional bandwidth (%)
- Pulse shape

Figure 2 - Sonora FirstCall Test System

For this project, the FirstCall Test System was not used. Instead, we referred to the results from a clinical study carried out in 2014 [4], during which a total of 115 transducers were tested at the Karolinska Universitetssjukhuset, Danderyds Sjukhus, Södersjukhuset and Sankt Görans Sjukhus. Four pairs of identical transducer models were then selected, with each pair being composed of one functional and one defective transducer.

Two of those pairs were phased-array probes, one pair were convex probes and one pair were linear probes, model L7. Since we would be using a linear array transducer, model L7-4, for our experiments, the FirstCall data reported from the defective L7 transducer would be used as a reference to simulate such defects in a transducer, and to assess and compare the effect on the emitted acoustic field.

The defective L7 transducer had several failures spread over the whole array. There was delamination at both edges and towards the center of the array. Broken cables and short circuits were also identified at the center of the array. A total of 72 of the 128-elements array were damaged.

The following data was compiled from this transducer's test with the FirstCall Test System.

Element sensitivity

Element sensitivity measures the impulse response of each individual element within the array. Although variations in sensitivity are not uncommon, only minor variations in signal amplitude should be observed within a functional array.

The sensitivity is displayed as a bar graph of the returning echo intensity. A reduction of more than 20% in intensity indicates that the corresponding element is weak.

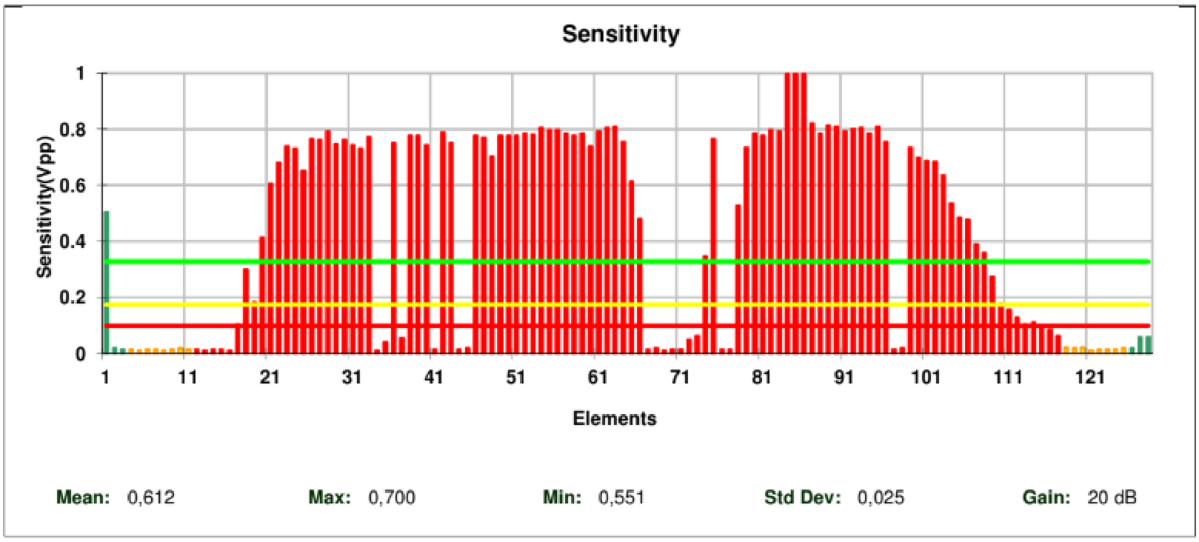


Figure 3 - Sensitivity histogram of defective L7 transducer

Capacitance

The capacitance value of an element measures its electrical performance. High frequency transducers generally have lower capacitance, whereas low frequency transducer have higher capacitance.

In comparison to the capacitance of the other elements of the array, a very high capacitance is the sign of a short circuit. A capacitance near zero is the sign of a break in the cable.

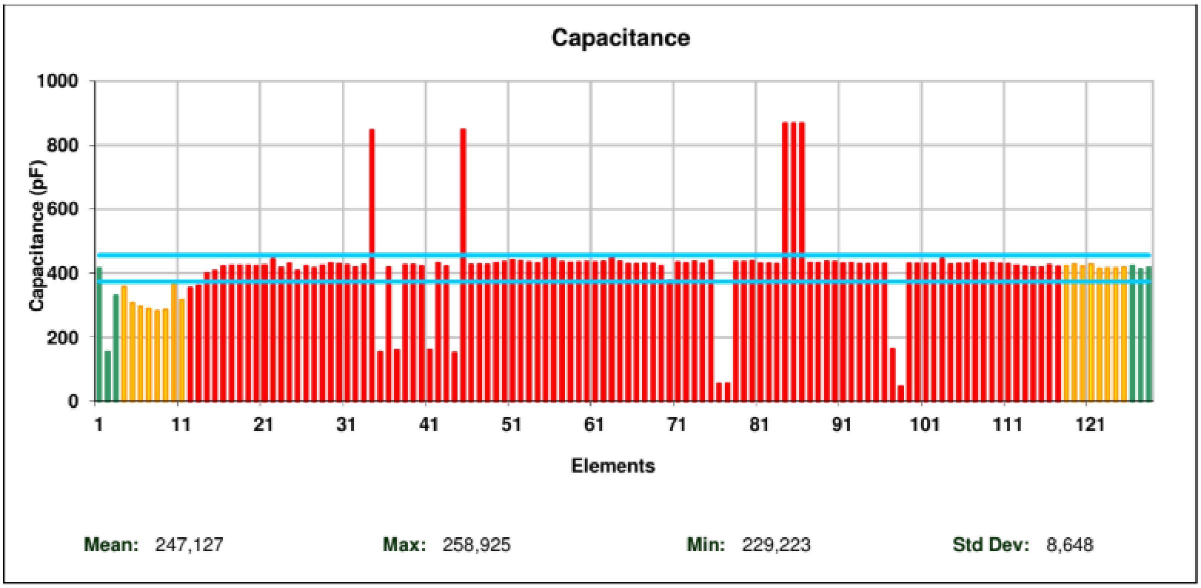


Figure 4 – Total capacitance histogram of defective L7 transducer

Pulse width

Pulse width is the length of the returned echo for each individual element. If a pulse length is longer than normal, it will often result in poor axial resolution. A very long pulse length is the sign of a dead element, since the transmit signal is not terminated.

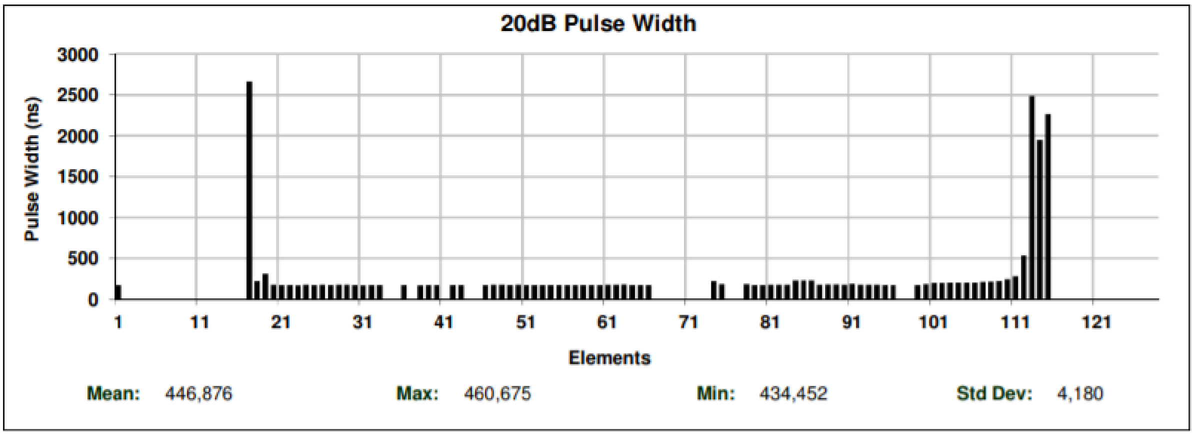


Figure 5 - Pulse width histogram of defective L7 transducer

Center frequency

The center frequency is the midpoint of the pulse spectrum and should be uniform across the transducer array.

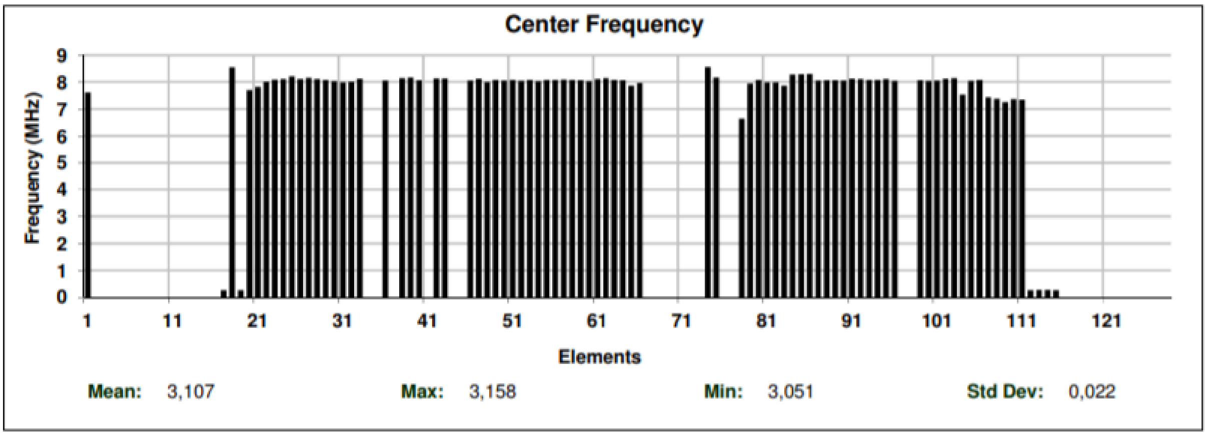


Figure 6 - Center frequency histogram of defective L7 transducer

Fractional bandwidth

The fractional bandwidth value is obtained by dividing the bandwidth by the center frequency. Most modern transducers have a fractional bandwidth above 50%. This parameter is closely connected to the overall dynamic range of the probe and a low value can often be attributed to a poor design of the probe.

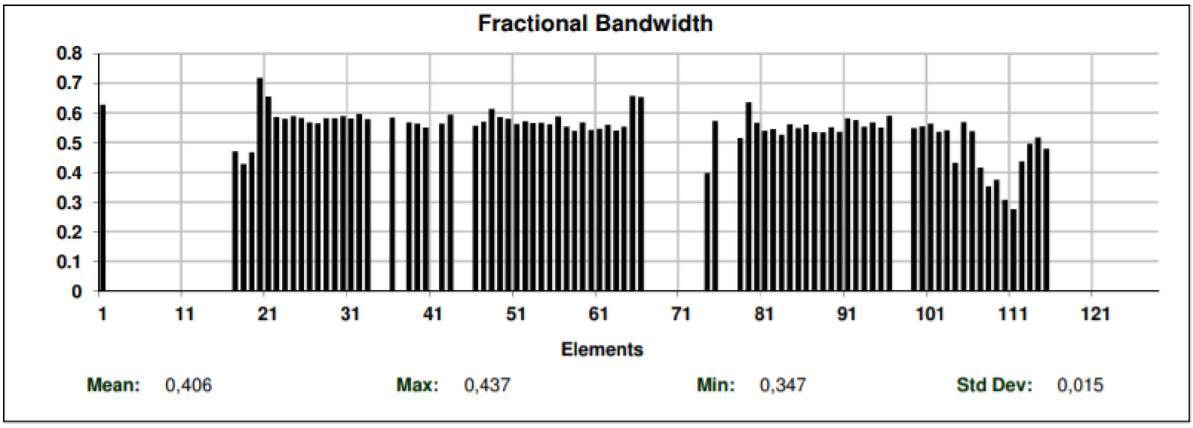


Figure 7 - Fractional bandwidth histogram of defective L7 transducer

Pulse shape

For each element in the array, a pulse is sent, and a graphical image of the magnitude frequency response curve is created.

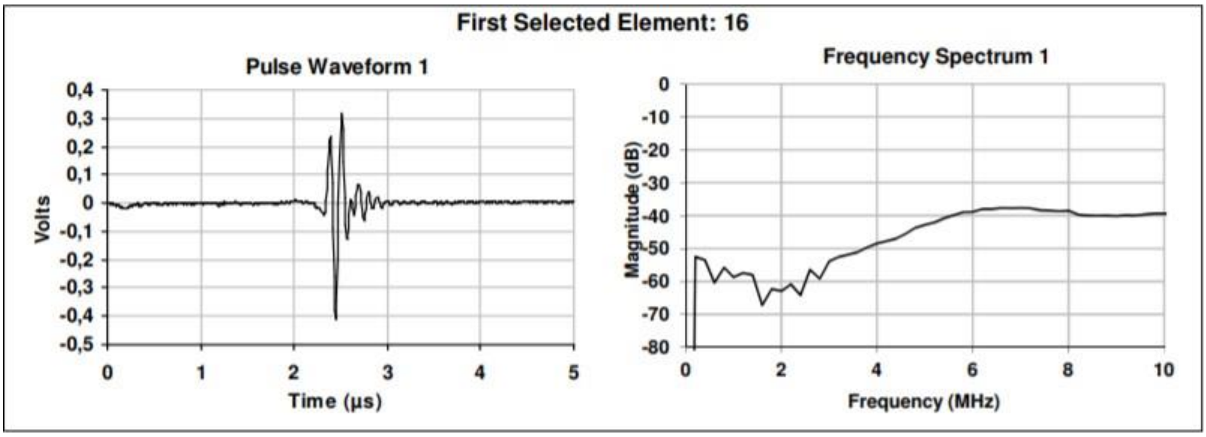


Figure 8 - Pulse waveform (left) and pulse spectrum (right) of a single element of defective L7 transducer

The two most important measurements from the Test System are the sensitivity and the capacitance [1], and observing even and correct values for both those parameters is considered enough to qualify a transducer as functional.

Performance parameters

The assessment of a transducer's performance should be based on specifically chosen parameters that contribute directly to image quality.
Quality assurance of ultrasound transducers is often performed by measuring the following set of parameters [3].

Axial and lateral resolution

Resolution is defined as the ability to distinguish between two objects located at different positions in space.

Axial resolution is then the ability to distinguish two objects located along the axis of the ultrasound beam, and lateral resolution is the ability to distinguish two objects located next to each other in the direction perpendicular to the beam.

Axial resolution is proportional to the length of the ultrasonic pulse, whereas lateral resolution is related to the beam width and will be at its best within the focal zone.

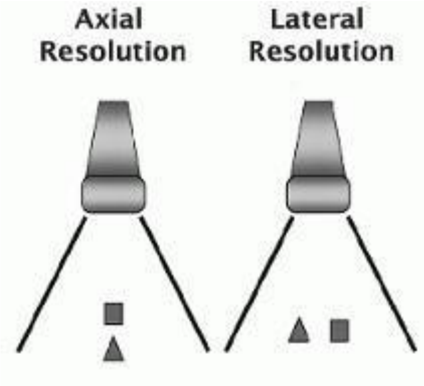


Figure 9 - Axial and lateral resolutions [5]

Penetration depth
The penetration depth, also called maximum depth of visualization, is the maximum distance in the phantom at which an echo can be detected. It is determined by the frequency of the transducer, the attenuation of the medium and the system settings.

Contrast resolution
Ultrasound displays tend to represent low-contrast structures smaller than they are and with irregular edges. This is called the fill-in effect.

Ideally, this effect should be minimal so that small-sized anechoic targets, such as small cysts, are correctly represented.

Grayscale contrast sensitivity
The dynamic range of an ultrasound system can be evaluated by looking at its ability to display targets with different grayscale contrast levels, representing cystic or hyperechoic masses.

Dead zone
Also known as “near field resolution”, the dead zone is defined as the distance between the front face of the ultrasound transducer to the closest identifiable echo. In this region, no useful information can be acquired.

Vertical and horizontal distance
Vertical distance is the distance along the axis of the beam, horizontal distance is the distance in the direction perpendicular to the axis of the beam. The accuracy of measurements can be determined by comparing the known distance between two targets aligned in the vertical or the horizontal direction to the distance measured on the display of the system.

Material and methods

The goal of our experiments is to simulate and observe transducer defects.

Using results from a previous study on defective transducers [4], and in order to test the accuracy of the modelled defects with the programmable ultrasound system, we also want to compare our observations on performance parameters to those made in that study.

Our first step is to create an interface that will allow the user to model a defective transducer. The interface should be user friendly and should clearly represent the model used.

For our reference comparison, we also want the interface to allow the user to set up the transducer so that it functions in the same way than the defective transducer that was used in the reference study.

Verasonics

The Verasonics V-1 System is a programmable ultrasound research tool. It can acquire, store, display and analyze data in a laboratory setting.
The system includes the Verasonics Hardware and the Verasonics Software.
The Verasonics Hardware consists of an acquisition module, with 256 transmit and 128 receive channels, each channel multiplexed to 1 of 2 transducer connectors.
The Verasonics Software consists of the Verasonics Matlab Simulator, a hardware abstraction layers and other supporting tools. Of greatest interest to us, the Verasonics Matlab Simulator uses the MATLAB environment to run ultrasound imaging sequences on the Verasonics Hardware. [6]

A transducer can be connected to the Verasonics Hardware, that will then acquire, process and transfer the ultrasound signals from the transducer to the host computer. The processed image is then rendered on the computer screen.

Transducer L7-4

The Philips ATL L7-4 is a linear array ultrasound transducer, with a frequency range of 7 to 4 MHz. It is composed of 128 elements and has a field of view of 38mm.

Figure 10 - L7-4 transducer from the Jonasson Centre for Medical Imaging

The transducer pictured above is the transducer used in our experimental setup and was connected to the Verasonics system.

Phantom

In order to evaluate the transducer performance, and more specifically the performance parameters described above, we need to be able to compare images obtained with a defective transducer to images obtained with a similar but functional transducer. For these comparisons to be accurate, we need to image an object that will be stable over time, and that mimics human tissue, since this is what would normally be imaged with the transducer. For this reason, we perform our tests on a phantom.

The phantom used in our experimental setup is the CIRS Model 040GSE Multi-Purpose, Multi-Tissue Ultrasound Phantom, a phantom designed for performance and quality assurance testing [7].

Figure 11 - The CIRS Model 040GSE [7]

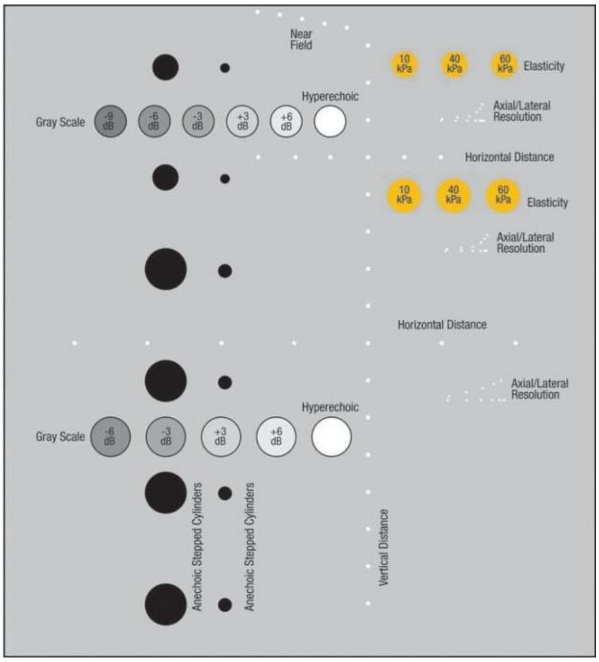


Figure 12 - Target groups in the CIRS Model 040GSE [7]

It allows evaluation of transducers ranging from 2 to 15 MHz and contains nine performance measurements:

- Dead Zone
- Horizontal Distance
- Vertical Distance
- Depth of Penetration
- Image Uniformity
- Axial Resolution
- Lateral Resolution
- Anechoic Mass Resolution
- Gray Scale Contrast Resolution
- Elasticity Image Evaluation

The phantom's background gel is a hydrogel polymer, CIRS's patented Zerdine®, a tissue mimicking material that is not affected by temperature changes.

Results

What can be controlled with the VSX System

When programming with the Verasonics System, a sequence program is written using Matlab. This program defines various system parameters and attributes as well as the sequences of events to be carried out by the hardware and software system.
Both the transmit event and the acquisition event are defined with a Matlab structure.
For the transmit event, the waveform used is defined using different parameters such as the number of master clocks in a half cycle, the number of half cycles in the waveform, or the initial polarity of the first half cycle.
A delay on the transmit time of each specific element can be set, thus allowing to choose between a plane wave excitation (when all elements transmit at the same time) or a focused excitation, with delays set so that elements further from the focus point are transmitted slightly earlier.
It is also possible to define which elements in the transducer arrays are active, and to specify a transmit apodization function for each active element.
The transmit apodization for an element is a float value between 0 and 1, where 0 turns the transmitter off and 1 means that the transmitter is on, operating normally.
By setting the apodization value to 0, it is then possible to simulate a dead element, and by setting the apodization to a value between 0 and 1, we can simulate an element with a reduced sensitivity.

This control then allows us to simulate delamination of a component of the transducer, as well as weak and dead elements.

However, we have seen from the FirstCall Test System that transducer defects such as a short circuit will lead to a higher than normal capacitance for the affected element, and this is not something that can be simulated using only the available system parameters.
Workarounds could certainly be used, for example manipulating the maximum high voltage limit, but this is beyond the scope of this project.

The User Interface

As mentioned before, it is important that the interface allows the user to easily and intuitively configure the transducer they want to test. Using clear color coding and simple inputs (buttons, sliders), the UI lets the user simulate defects on each single elements of the transducer array.

The different options provided by the UI are listed below.

Transducer elements
With the help of a slider, the user can choose how many elements the simulated transducer should have. The slider allows the number of elements to be between 1 and 128.

Figure 13 - Slider to adjust number of elements

Elements state
For each element of the transducer, one of three states can be set:
- functional, meaning that the element operates at 100% of its maximal sensitivity amplitude
- weak, meaning that the element operates at a sensitivity of 50%
- dead, meaning that the element has no sensitivity.

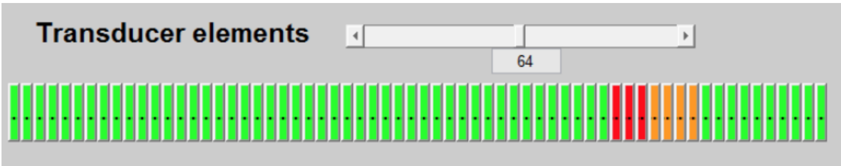


Figure 14 - UI representation of transducer elements

The element's state is visualized by its color on the UI, green representing a functional element, orange representing a weak element and red, a dead element.

Default transducer setup
To avoid the need for manually setting the state of the transducer that we want to simulate for our tests, two buttons allow the automatic setup of the following transducers:

- A fully functional L7 transducer, with 128 elements

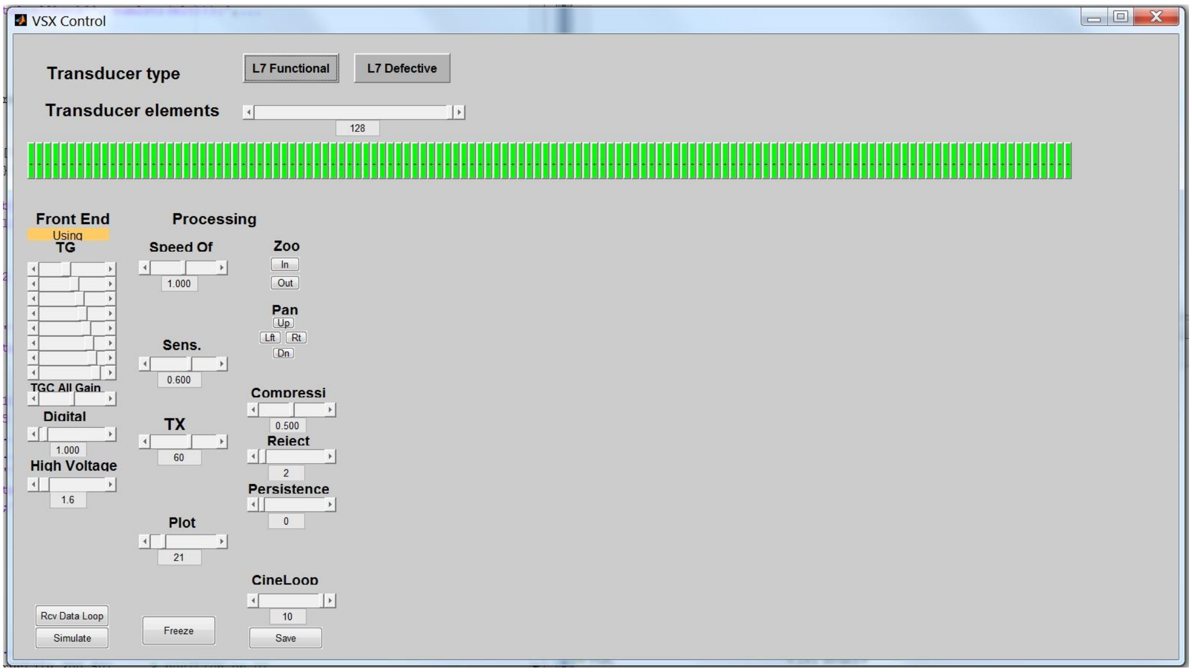


Figure 15 - VSX control window with functional L7 transducer selected

- A defective L7 transducer, with 128 elements, of which 72 elements are damaged.

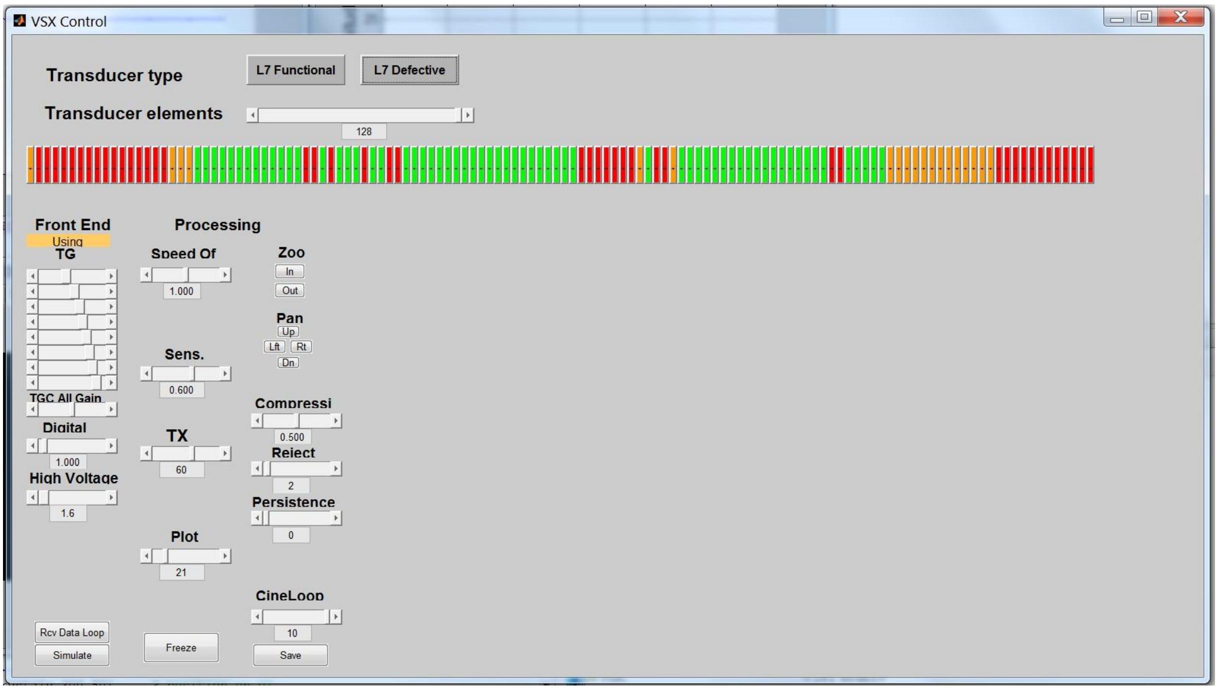


Figure 16 - VSX control window with defective L7 transducer selected

The sensitivity values for the defective elements of the transducer are deduced from the sensitivity chart produced from testing the actual transducer with the Sonora FirstCall test system.

Parameters affected

Once the transducer defects could correctly be applied to the transducer model, we could use the transducer on the phantom. The CIRS 040GSE Phantom comes with a testing procedure, that allows us to test for the different performance parameters.

We captured the images allowing us to evaluate each parameter following the procedure steps. These images were captured twice: once using the setup for the functional transducer, once using the setup for the defective transducer. As much as possible, we tried to keep the transducer immobile between those 2 captures, so that the images could be properly compared, but the human error should not be neglected during this comparison.

The following tests were performed:

- Depth of penetration testing
- Vertical distance measurements
- Horizontal distance measurements
- Axial and lateral resolution testing
- Contrast resolution
- Grayscale contrast sensitivity
- Dead zone assessment

For each of those tests, we compare the image obtained with the functional transducer (left image) to the image obtained with the defective transducer (right).
It should be noted that we here evaluate the relative performance of the defective transducer, in comparison to a functional transducer, rather than the absolute performance of both transducers.

Depth of penetration testing

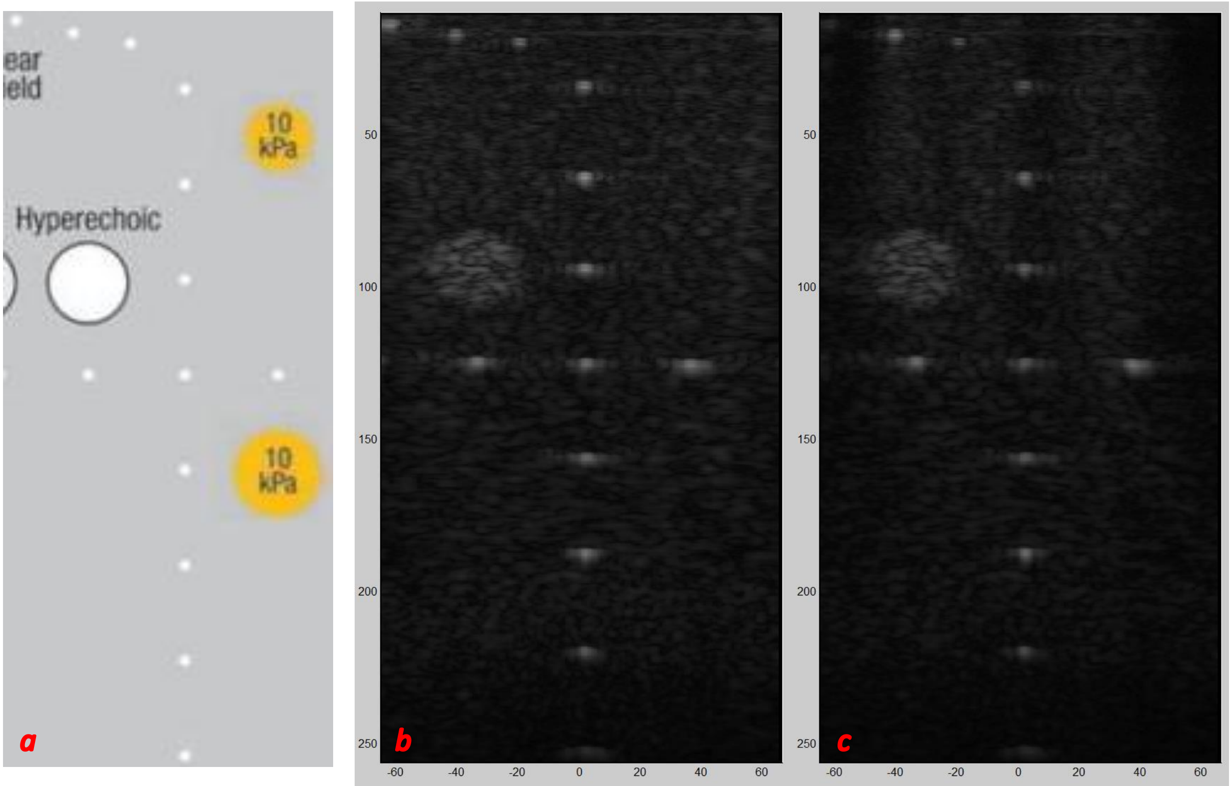


Figure 17 - Captures of the phantom's expected image (a), image from the functional (b) and defective (c) transducers to measure depth of penetration

Although on both images, the same vertical targets can be seen, the targets are being displayed with a lower intensity when imaging with the defective transducer.
It can also be observed that the depth of penetration is quite uneven with the defective transducer, with a shorter penetration at the edges of the image.

Vertical distance measurements

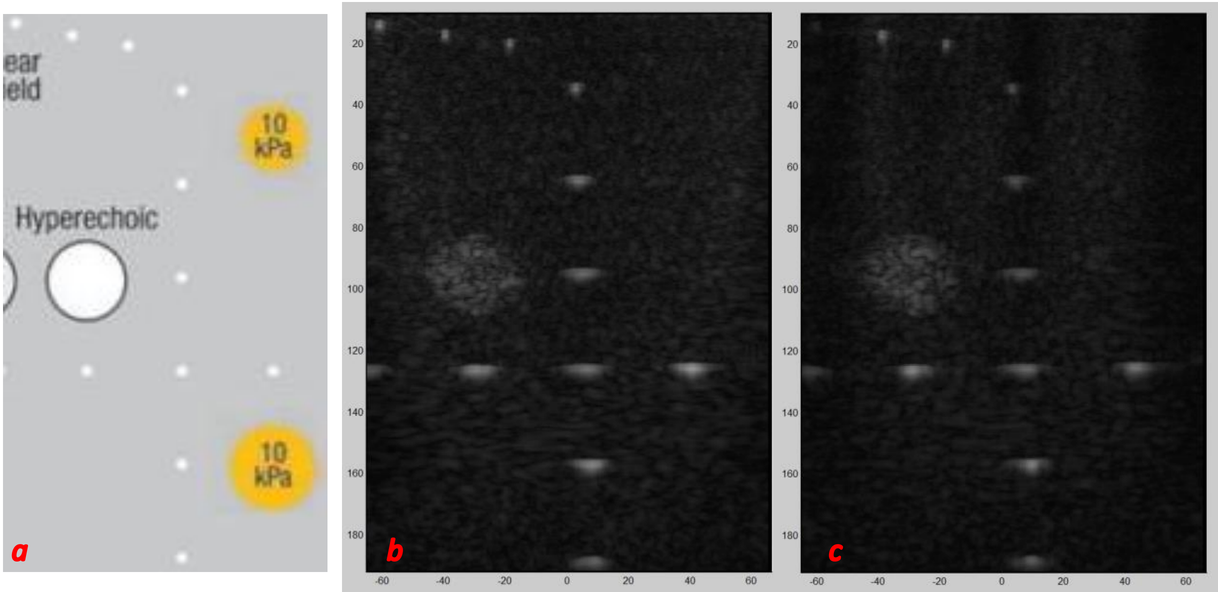


Figure 18 - Captures of the phantom's expected image (a), image from the functional (b) and defective (c) transducers to measure vertical distance

Although the quality of both images is quite poor, with the wires not being represented as dots, it can seen that the intensity with which they are represented using the defective transducer is visible lower. This lower intensity makes it more difficult to measure the distance between two wires and thus reduces furthermore the accuracy of the measurements. Measuring the distance between two wires at the different depths, it can be assessed the vertical distance measurements exceed the expected values by 3% in average, both with the functional and the defective transducers.

Horizontal distance measurements

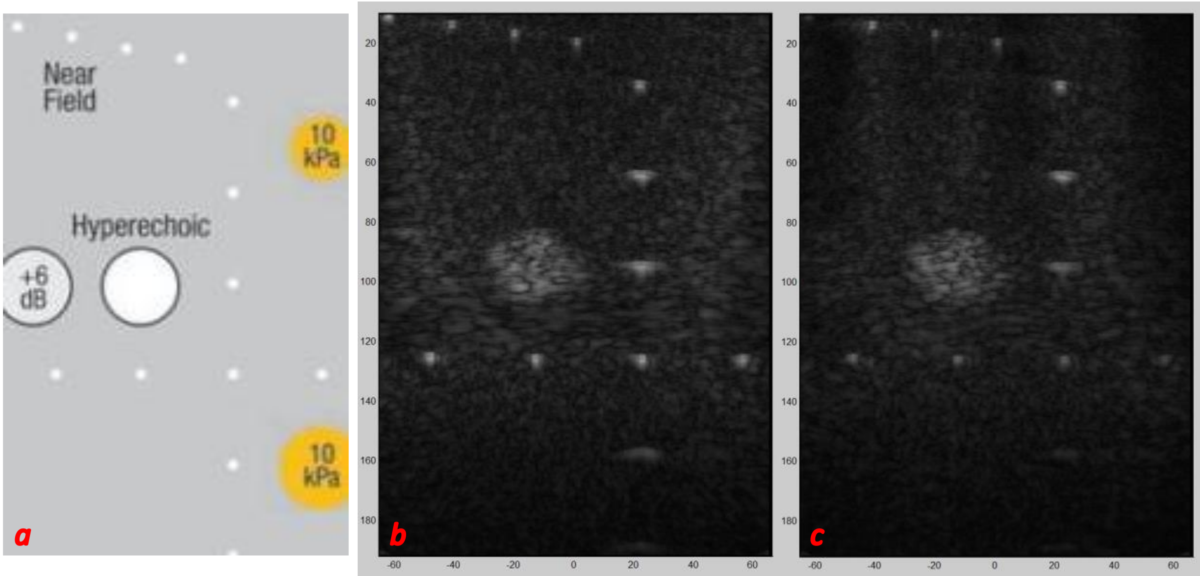


Figure 19 - Captures of the phantom's expected image (a), image from the functional (b) and defective (c) transducers to measure horizontal distance

As for the vertical distance measurements, the decreased intensity of the wires in the defective transducer's image could negatively affect the accuracy of horizontal measurements. Measuring the distance between the wires on the horizontal plane and calculating, it can be assessed that the margin of error in horizontal measurements is around 4% with the functional transducer, and around 4.6% with the defective transducer.

Axial and lateral resolution testing

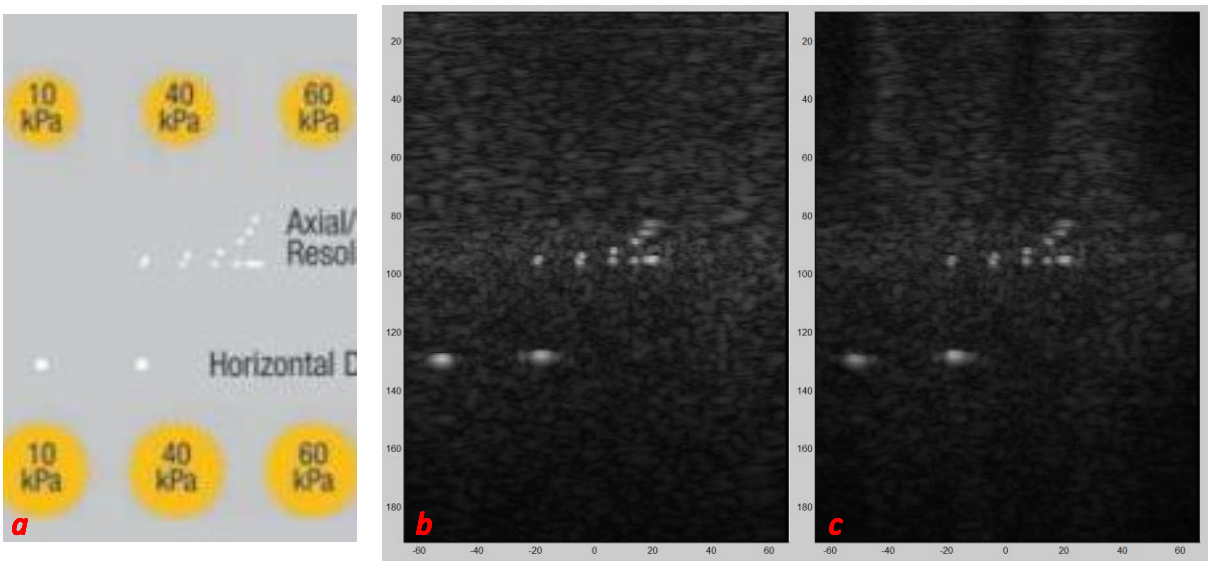
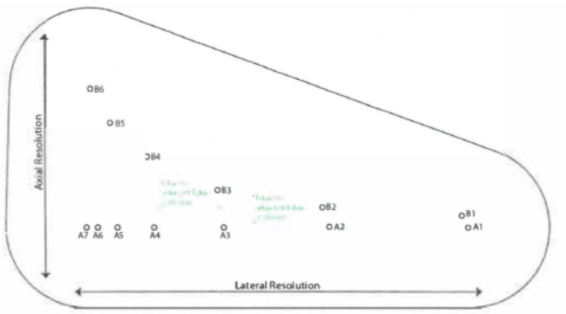


Figure 20 - Captures of the phantom's expected image (a), image from the functional (b) and defective (c) transducers to measure resolutions

To measure axial and lateral resolution, the focus is centered on the resolution target groups. Although many parameters can be tweaked to get the best possible image, it was difficult with this transducer to obtain an image where all targets would appear as dots (rather than lines).

As described in the testing procedure, lateral and axial resolution can be calculated determining the last pair of wires to be distinguished as two separate objects.



	Targets					
	A1-B1	A2-B2	A3-B3	A4-B-4	A5-B5	A6-B6
Axial Resolution (mm)	0.25	0.5	1.0	2.0	3.0	4.0
	Targets					
	A1-A2	A2-A3	A3-A4	A4-A5	A5-A6	A6-A7
Lateral Resolution (mm)	4.00	3.0	2.0	1.0	0.5	0.25

Figure 21 – Combined axial and lateral resolution targets (a) and table listing the distances between them (b)

Comparing the images captured, it is however visible that axial resolution is worse with the defective transducer. In particular, the pairs A2-B2 are harder to resolve due to being displayed with a lower intensity. Axial resolution with the functional transducer can be estimated to be around 0.5 mm, whereas it is closer to 1.0 mm with the defective transducer. Lateral resolution is, in both cases, estimated at 1.0 mm.

Contrast resolution

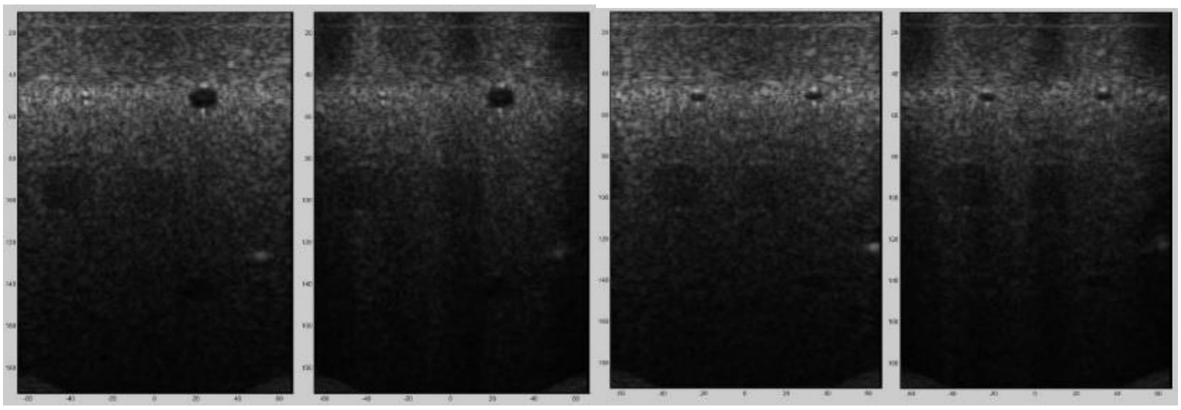


Figure 22- Captures of the phantom image to measure contrast resolution

On both images, the fill-in effect can be observed, especially on the smallest part of the cylinder. The cylinders are displayed with a similar width and height with both transducers, but the uneven quality of the image with the defective transducers makes it harder to resolve small sized targets.

Grayscale contrast sensitivity

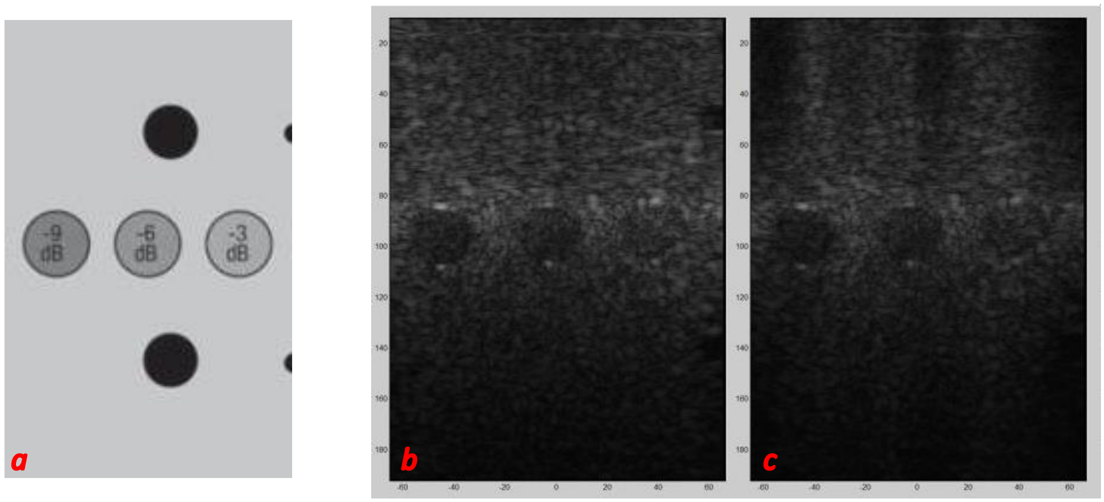


Figure 23 - Captures of the phantom's expected image (a), image from the functional (b) and defective (c) transducers to measure grayscale contrast with the -9dB, -6dB and -3dB contrast targets

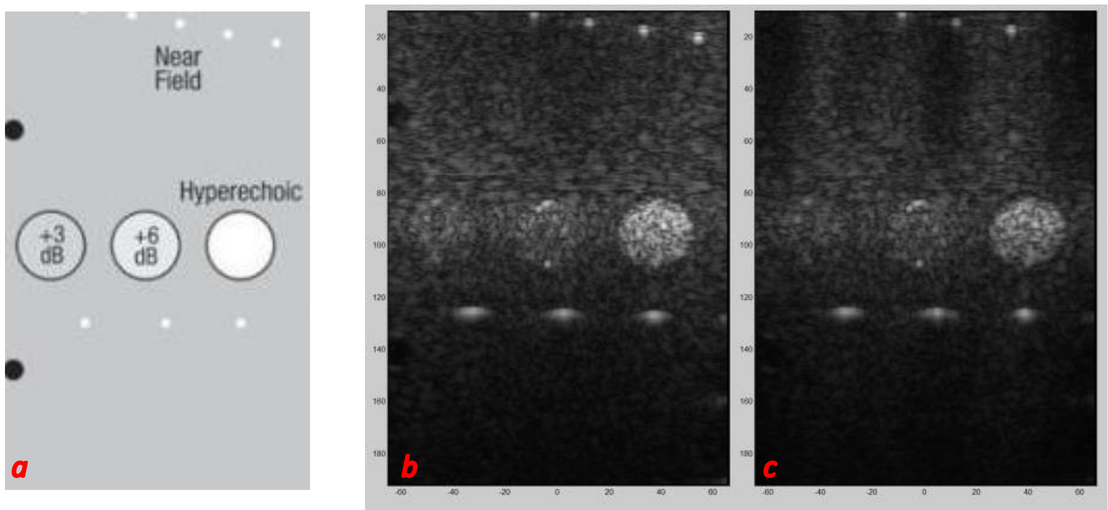


Figure 24 - Captures of the phantom's expected image (a), image from the functional (b) and defective (c) transducers to measure grayscale contrast with the +3dB, +6dB and hyperechoic targets

Grayscale targets with the lowest contrast (specifically the +3dB target) are more difficult to observe when imaging with the defective transducer.
Additionally, the targets edges are more uneven and blurry.

Dead zone assessment

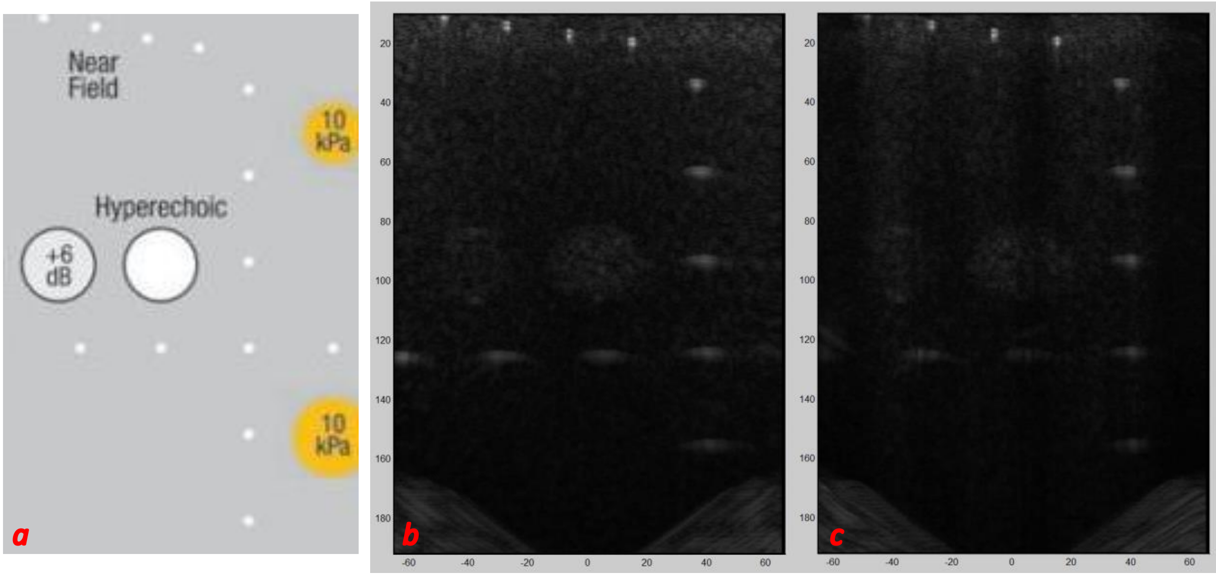


Figure 25 - Captures of the phantom's expected image (a), image from the functional (b) and defective (c) transducers to measure dead zone

The dead zone can be assessed by imaging the near field target group and observing the closest target that can be resolved. With the functional transducer, 4 out of the 5 near field targets can be seen, giving a dead zone distance of 2mm. With the defective transducer on the other hand, the 4th target is harder to resolve, hence increasing the dead zone distance to 3mm.

Discussion

In the reference study of the impact of defective transducers [4], although the defective L7-4 transducer was not tested with the phantom, physicians were asked to test the device on a patient and to compare its performance to a similar but functional transducer.
Their observations were unanimous and pointed out the lower quality of the images obtained with the defective transducer.
As we applied the phantom's testing procedures to our modelled defective transducer and compared it to the results obtained when no parameters of the transducer were modified, we could easily observe how the image quality was deteriorated due to these defects. We were also able to assess the transducer's axial and lateral resolution and could observe a deterioration in axial resolution with the defective transducer, with a reduction by a factor of 2.
Although errors in vertical distance measurements were similar with both transducers in our tests, the errors in horizontal distance measurement increased by about 15% with the defective transducers.
From those results, it can be assumed that the quality of the image is affected by the defects of the transducer both in the vertical and the horizontal plane.

Clearly, these observations are in no way surprising. Had the actual defective transducer been tested with the phantom and had the results from the test been presented in our reference study, a more thorough comparison could have been performed as part of this project.
It is then difficult to guarantee that the defects modelled with our program accurately reflect actual material defects.
Moreover, as mentioned before, there are transducer errors, such as short circuits, that could not be modelled with this program. Deeper investigations should be performed in order to be able to accurately replicate all possible transducer errors.

The tool that this program provides should however be considered as a pedagogic tool whose aim is visualize the effects of transducer defects on image quality.
Even for skilled ultrasound operators, performance-related problems often remain unnoticed [8]. Operators should be provided with ways of recognizing typical transducer defects. With simulation tools such as this one, they could themselves simulate defects, and figure out how the resulting image is affected. By being exposed to these kinds of results, it would become easier for them when performing clinical examinations to notice that a transducer's performance is deteriorating.

Conclusion

Due to its many advantages, ultrasound is one of the most widely used imaging technique in healthcare. Therefore, it is extremely important to ensure that this technique can provide with a reliable diagnosis.
Having strict and thorough quality assurance procedures, using test systems such as the Sonora FirstCall, clearly are a necessity, and should be part of all hospitals standards. Unfortunately, there is still today a high number of defective transducers being used in various clinical departments. The consequence of this is an increased risk of missed diagnosis, due to the ultrasound operator not being able to identify the impaired performance of the transducer they are using.

The fact that operators cannot identify such impairments is not a reflection of their skills as ultrasound operators, but a symptom of the absence of training around the effects of transducer defects on image quality.

With this project, we aimed to evaluate the possibility of creating a tool to model and observe transducer defects. Using a programmable system, we have been able to simulate various common defects: delamination of the transducer components, and weak or dead elements in the transducer array. Controllable via a simple user interface, the tool allows the user to specify the state of each and everyone of the elements of the transducer, and to directly observe the effect on the processed ultrasonic image.

References

[1] M. Mårtensson et al., "High incidence of defective ultrasound transducers in use in routine clinical practice", European Journal of Echocardiography, vol. 10, no. 3, pp. 389-394, 2009.

[2] P. Hoskins et al., "Diagnostic Ultrasound - Physics and Equipment", 2nd ed. Cambridge, United Kingdom: Cambridge University Press, 2010.

[3] Sonora Medical Systems Inc, "First call 2000™ Ultrasound Probe Testing System – Users Guide", Available : http://old.vtpup.cz/common/manual/LF_biofyz_Sonora_FirstCall2000_manual_EN.pdf [Accessed: October 2018]

[4] L. Eghbali, "The impact of defective ultrasound transducers on the evaluation results of ultrasound imaging of blood flow", 2014

[5] Thoracic Key, "Physics and instrumentation", Available: https://thoracickey.com/physics-and-instrumentation-2/ [Accessed October 2018]

[6] Ron Daigle, "Verasonics Sequence Programming Tutorial", 2012.

[7] CIRS, "Multi-Purpose Multi-Tissue Ultrasound Phantom", Available: http://www.cirsinc.com/products/all/67/multi-purpose-multi-tissue-ultrasound-phantom/ [Accessed: October 2018]

[8] B. Weigang, "The Methods and Effects of Transducer Degradation on Image Quality and the Clinical Efficacy of Diagnostic Sonography", 2003