Detecting failed elements on phased array ultrasound transducers using the Edinburgh Pipe Phantom

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Abstract

Aims: Imaging faults with ultrasound transducers are common. Failed elements on linear and curvilinear array transducers can usually be detected with a simple image uniformity or ‘paperclip’ test. However, this method is less effective for phased array transducers, commonly used in cardiac imaging. The aim of this study was to assess whether the presence of failed elements could be detected through measurement of the resolution integral (R) using the Edinburgh Pipe Phantom.

Methods: A 128-element paediatric phased array transducer was studied. Failed elements were simulated using layered polyvinyl chloride (PVC) tape as an attenuator and measurements of resolution integral were carried out for several widths of attenuator.

Results: All widths of attenuator greater than 0.5 mm resulted in a significant reduction in resolution integral and low contrast penetration measurements compared to baseline ($p < 0.05$).

Conclusions: Measurements of resolution integral and low contrast penetration both have the potential to be used as straightforward and inexpensive tests to detect failed elements on phased array transducers. Particularly encouraging is the result for low contrast penetration as this is a quick and simple measurement to make and can be performed with many different test objects, thus enabling ‘in-the-field’ checks.

Keywords

Quality assurance, image quality, Edinburgh Pipe Phantom, resolution integral, phased-array, cardiac imaging

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Introduction

Failed elements are a common fault on array transducers.¹ Failed or weak elements may result from faulty electrical connections, from manufacturing processes, delamination or mechanical damage. On conventional linear or curvilinear array transducers, failed elements can be detected using a simple uniformity test, as is recommended by the Institute of Physics and Engineering in Medicine Report 102 on the quality assurance of ultrasound imaging systems.² This test involves running the transducer in air, and passing a narrow, highly reflective object (such as a paperclip) across the array, coupled to the transducer with a small amount of ultrasound gel. An example of this test is shown in Figure 1. A bright reverberation pattern is seen on the image when the object passes over fully functional elements, while the brightness reduces when passing over failed elements, allowing them to be easily detected and located.

For phased array transducers, widely used in cardiac imaging where a small footprint is required, all elements are activated to form each scan line, unlike linear and curvilinear arrays, where only a subset of the array is active to form a single line. Consequently, detection of failed elements is more difficult and a simple test for failed elements on phased arrays therefore remains elusive. Commercially available automatic probe testing systems such as the Unisyn (Golden, Colorado, USA) FirstCall perform the task by electronically interrogating each transducer element, producing reports on the

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Figure 1. Example images showing the detection of failed elements using the simple uniformity test for a linear array transducer. As the narrow object passes over functioning elements, a bright reverberation pattern is seen (left). The brightness is much reduced when passing over failed or weak elements (right).

relative sensitivity of each element and the location of any failed elements on the array.³ This requires an adaptor and configuration file for each transducer type, one or both of which may not be available for new or uncommon models. Such systems are also relatively expensive and portable operation can be impractical, requiring the transducer to be removed from clinical service and relocated to a laboratory environment for testing.

The aim of this work was to assess whether measurement of the resolution integral using the Edinburgh Pipe Phantom could be implemented as an alternative, inexpensive test for detecting failed elements on phased array transducers.

The Edinburgh Pipe Phantom and the Resolution Integral

The concept of the resolution integral (R) was first proposed by Pye et al. in 2004 as a figure of merit for assessing the technical performance of ultrasound imaging systems.⁴ R is defined as the ratio of the beam penetration to the beam width. For focussed ultrasound beams, the variation of beam width as a function of depth is accounted for by the integral

$$R = \int_0^{\infty} L(\alpha) d\alpha$$

where α is the reciprocal of the effective beam width, and $L(\alpha)$ is the axial distance over which the effective beam width is $< 1/\alpha$.⁵ The parameters depth of field L_R and characteristic resolution D_R can also be defined

such that $R = L_R/D_R$ and a line joining the origin and the point $(1/D_R, L_R)$ bisects the area under the curve defined by $L(\alpha)$. This is effectively the penetration and width of an equivalent collimated beam. These concepts are illustrated in Figure 2.

The Edinburgh Pipe Phantom consists of a block of agar-based tissue mimicking material (TMM)⁶ containing a series of wall-less fluid-filled cylinders (pipes) of varying diameter (0.5, 0.7, 1.0, 1.5, 2.0, 3.0, 4.0, 6.0 and 8.0 mm), inclined at 40° to the vertical. A measurement of R is made by recording the depth range over which each pipe can be resolved on the image and plotting the length as a function of α . The plot forms a closed integral with the area under the curve equal to R . The measurement of low contrast penetration (LCP) is the intercept of the curve with the y-axis. A detailed description of the measurement of R using the Edinburgh Pipe Phantom has been given by Moran et al.⁷

Methods

A Siemens P10-4 paediatric phased array transducer was used in this study in conjunction with an Acuson Antares Premium ultrasound system (Siemens Healthcare, Erlangen, Germany). This transducer has 128 elements and active length of 13.1 mm, according to the manufacturer's datasheet,⁸ giving an element pitch of approximately 0.1 mm. Failed elements were simulated by covering the transducer face with strips of attenuating material. Three materials were trialled: expanded polystyrene (3 mm thickness), layered polyvinyl chloride (PVC) tape (19 mm width by 0.13 mm thick

Figure 2. The graph (left) shows a plot of L versus α for an ultrasound beam (right) with low contrast penetration L_0 and minimum beam width D_0 . α is the reciprocal of effective beam width. The graph (left) also illustrates depth of field L_R and characteristic resolution D_R . The area under the dashed curve joining L_0 to $1/D_0$ is equal to the resolution integral R .

electrical insulation tape (Advance Tapes, Leicester, UK)) and air-filled polythene strips, manufactured in-house using 125 μm low-density polythene lay flat tubing (Dow Chemical Company, Michigan, USA). The individual suitability of each material to create an image which approximated one generated from a transducer with failed elements was qualitatively assessed by sequentially applying each material to the face of a conventional linear array transducer (Siemens VF13-5). The transducer was then used to scan the echogenic wires of a Gammex 405 test object (Gammex, WI, USA). Images obtained using all three attenuating materials demonstrated a reduction in image brightness corresponding to the area beneath the attenuator, compared with that imaged with the uncovered areas of the transducer. The most effective material was PVC tape in three layers (combined thickness 0.4 mm). This was used as an attenuator to simulate failed elements for subsequent measurements using the phased array transducer. The attenuation of the tape was estimated by measuring the change in the LCP with and without the tape applied to the surface of the P10-4 transducer. The LCP measurements were performed on the Edinburgh Pipe Phantom where the TMM has an attenuation of $0.5 \text{ dB cm}^{-1} \text{ MHz}^{-1}$. Measurements were made with and without the tape covering the entire transducer. The gain and time gain compensation (TGC) were optimised to view the lowest speckle possible in each case, with the distance to this point measured to be the LCP using the callipers. The difference in LCP was used to calculate the attenuation, given the phantom attenuation, and assuming the distance was double for the

full pulse travel. The attenuation was estimated to be 14 and 24 dB at 4.4 and 7.3 MHz, respectively.

Baseline measurements of resolution integral were performed using the P10-4 phased array with no attenuating material applied, with three repeats used to confirm the repeatability of the measurements in relation to previous data obtained by several trained operators.⁵ Testing was performed using fundamental imaging only (harmonic imaging mode switched off), but frequency, depth and focus position were varied in order to separately image the most superficial and deepest parts of the pipe, to measure the range of depth over which the pipe can be resolved. LCP was measured as a fundamental component of the resolution integral (a detailed description of the measurement of resolution integral using the Edinburgh Pipe Phantom can be found in previously published work⁵). The distance to the lowest visible speckle was taken as the LCP, with the frequency adjusted to optimise this, which in practice meant using the lowest selectable frequency of 4.4 MHz. Measurements were repeated with strips of attenuator of 0.5, 1, 2, 3 and 5 mm in width. The results for each width of attenuator were compared with the baseline, with statistical significance checked using paired sample t-tests. The attenuator was cut to size using a scalpel, and the strips were adhered to the centre of the transducer face, perpendicular to the scan plane. Figure 3 shows a schematic of the transducer with the 5 mm width of attenuator applied. The narrowest width of attenuator which could be reliably produced was 0.5 mm. The width of tape cuttings was estimated to be accurate within $\pm 0.1 \text{ mm}$.

Results

The calculated values of R , L_R and D_R for each width of attenuator are shown in Table 1, along with measurements of the LCP. Figure 4 shows a plot of change in R and LCP with width of attenuator, with L versus α plots shown in Figure 5. There is a dependence of R value on the number of covered elements, with greater widths of attenuator giving lower R values. Similar results were obtained for attenuator width and LCP measurements. All widths greater than 0.5 mm give a statistically significant reduction in R ($p < 0.05$) compared with the baseline measurements. All widths of attenuator greater than 0.5 mm also showed a significant reduction in LCP value compared with the baseline ($p < 0.05$). A similar trend is observed for L_R and D_R .

Figure 3. Schematic of 5 mm PVC tape applied to the P10-4 transducer. Additional tape was applied to the sides to ensure the tape would not detach during measurement.

Discussion

The results demonstrate that both R and LCP are sensitive indicators of the presence of simulated failed elements in a phased array transducer. Particularly interesting is the result for LCP, as this is a quicker measurement to perform than that of R . Moreover, measurement of LCP can be carried out with a range of tissue mimicking test objects, not just the Edinburgh Pipe Phantom. Using a portable test object to perform LCP measurements would provide a quick and easy in-the-field test for failed elements on phased arrays. The full measurement of R is generally more sensitive to failed elements, as shown by a greater change in percentage from baseline for a given width of attenuator covering. This suggests that the full measurement of R would still be useful in detecting failed elements and quantifying the degradation caused by the defect, as R is indicative of overall imaging performance. The measurement of R could also be used to assess whether a known defect results in a degradation in image quality which is sufficiently significant to warrant removal from clinical service.

To use the measurement of either R or LCP as a test for failed elements, it would be necessary to have acquired an accurate baseline measurement for that model of probe or when the particular probe was functioning correctly. This could practically be done by incorporating the measurement into acceptance testing.

It is not surprising that lower R and LCP values were seen for a covering of 5 mm, since this equates to 50 failed elements – over a third of the width of the array. Of greater interest are smaller numbers of elements, although the smallest studied here – 0.5 mm of attenuator, equating to five failed elements – showed no statistically significant difference in R value compared to baseline (uncovered) values. However, the position of the elements relative to the placement of the tape was unknown. The tape was unlikely to cover a number of elements exactly, rather it was likely to partially cover

Table 1. Numerical results showing variation in measured parameters versus baseline values for different widths of attenuating covering (i.e. different numbers of simulated failed elements)

Parameter	Baseline	Repeatability as % of baseline (95% CI)	Value % versus baseline				
			5 mm	3 mm	2 mm	1 mm	0.5 mm
R	62.2	2.6	−30	−16	−14	−9.9	−2.7
L_R	88.9 mm	5.5	−10	−5.4	−3.3	−1.1	−7.0
D_R	1.43 mm	6.6	+27	+13	+12	+9.6	−4.5
LCP	115 mm	2.8	−14	−8.5	−6.6	−6.0	−2.8

Figure 4. Plot of R and LCP compared with baseline values against width of attenuator (error bars show 95% confidence interval).

Figure 5. Plots used to determine R (the area under the curve) for each width of attenuating covering.

those at the edges of the tape (e.g. for 0.5 mm of covering, this may leave three or four 'failed' elements and two partially covered elements). Furthermore, though the signal is attenuated by up to 24 dB at 7.3 MHz, there is still some penetration through the tape covering. By increasing the number of layers it would be possible to produce further attenuation, although this causes greater intrusion at the scanning surface, and increases the portion of the beam that is only partly attenuated by the covering. For these reasons, it is recommended that further work is carried out to assess the sensitivity of the tests for truly failed elements, rather than simulated; that is, elements disconnected electronically. Multiple phased array transducers from different manufacturers should also be studied to assess whether the test performance is consistent across all scanners and models, as well as phased array probe type (e.g. TOE, cardiac, etc.).

This investigation only simulated multiple adjacent failed elements that were located centrally on the array and did not consider spatially separated failed elements. It is possible that less image degradation will occur if the elements are spread out compared with the same number located contiguously on the array. It was hypothesised that a centrally located region would provide the worst image degradation. Changing this location closer to the periphery of the array may result in less pronounced changes in the R and LCP values making it more difficult to detect. However, this was not assessed as part of this study. In addition, dead-zone measurements may have been artificially high due to the reverberation resulting from the presence of the tape.

Conclusion

This work has shown that both the resolution integral R measured using the Edinburgh Pipe Phantom, and the LCP, are both sensitive to the presence of simulated failed elements on phased array transducers. Both the full measurement of R and LCP alone have potential to be used as quick and inexpensive tests for failed elements on phased arrays, provided type test and/or baseline measurements are available for comparison.

Declaration of Conflicting Interests

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Ethical approval

Not applicable

Guarantor

SDP

Contributorship

SDP and SI conceived the study. DW carried out the experimental work and analysis on which SI and SDP advised and assisted. DW produced the manuscript first draft. All authors reviewed and edited the manuscript and approved the final version of the manuscript.

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