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Technical note

A simple uniformity test for ultrasound phased arrays

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ABSTRACT

Purpose: It is difficult to test phased array ultrasound transducers for non functioning elements. We aimed to modify a widely performed test to improve its ease and effectiveness for these arrays.
Methods: A paperclip was slowly moved along the transducer array, with the scanner operating in M-mode, imaging at a fundamental frequency with automatic gain and grey scale adjustment disabled. Non-functioning elements are identified by a dark vertical line in the image. The test was repeated several times for each transducer, looking for consistency of results. 2 transducers, with faults already shown by electronic transducer testing, were used to validate the method. 23 transducers in clinical use were tested.
Results: The results of the modified test on the 2 faulty transducers agreed closely with electronic transducer testing results. The test indicated faults in 5 of the 23 transducers in clinical use: 3 with a single failed element and 2 with non-uniform sensitivity. 1 transducer with non-uniform sensitivity had undergone lens repair; the new lens was visibly non-uniform in thickness and further testing showed a reduction in depth of penetration and a loss of elevational focus in comparison with a new transducer.
Conclusions: The modified test is capable of detecting non-functioning elements. Further work is required to provide a better understanding of more subtle faults.

1. Introduction

Many years ago Goldstein et al. [1] introduced a linear array test tool that was shown to be useful in testing for non-functioning elements in a linear array transducer. The similarities between linear and curved array transducers mean that the test is simple and effective for any array transducer without beam steering. The test is, in theory, also suitable for phased arrays but is difficult to perform effectively as the pattern produced from the test tool covers the entire field of view (see Fig. 1). The test has been recommended in guidelines for ultrasound quality assurance (QA) [2] and is often known as the "paperclip test".

Non-functioning elements can be due to cable faults, faulty connections or element damage and may cause axial streaking in both in-air and clinical images (drop out), the severity and importance of which may be assessed by the clinical user. It is more difficult for the user to identify the impact on Doppler performance and it has been shown that non functioning elements can have a significant effect on both pulsed wave and colour flow Doppler [3,4].

Studies have reported a high incidence of element failure. Martensson et al. [5] tested 676 transducers using an electronic transducer tester and found non-functioning or weak elements in 90 transducers (13%) but did not state how many of these faults were visible by other means, e.g. inspection of the in-air reverberation pattern. Hangiandreou et al. [6] found 124 image uniformity faults over a 4 year period, using the in-air reverberation pattern and a tissue mimicking test object (TMTO), where the number of transducers in service grew from 267 to 322. This represented 66% of all detected faults and 98% of all image quality faults detected during testing.

Transducer faults are therefore common and important to detect in order to avoid compromising clinical diagnostic quality. There is evidence to show that electronic transducer testers such as FirstCall (Unisyn, Golden, CO 80403, USA) and ProbeHunter (BBS Medical AB, Stockholm, Sweden) provide comprehensive results that both demonstrate faults and indicate their likely origin [5]. However, many transducer faults can be detected simply by inspection of the in-air reverberation pattern using appropriate scanner settings; Fig. 2 shows drop out and delamination (separation of layers within the transducer). The paperclip test and imaging of a TMTO may then be used to assess the severity and inform management of faults, but the physical origin of the fault may not be important unless considering a repair. Good repair facilities will have access to an electronic transducer tester.

Goldstein et al. [1] performed their test using a thin metal rod with circular cross-section held across the short axis of the

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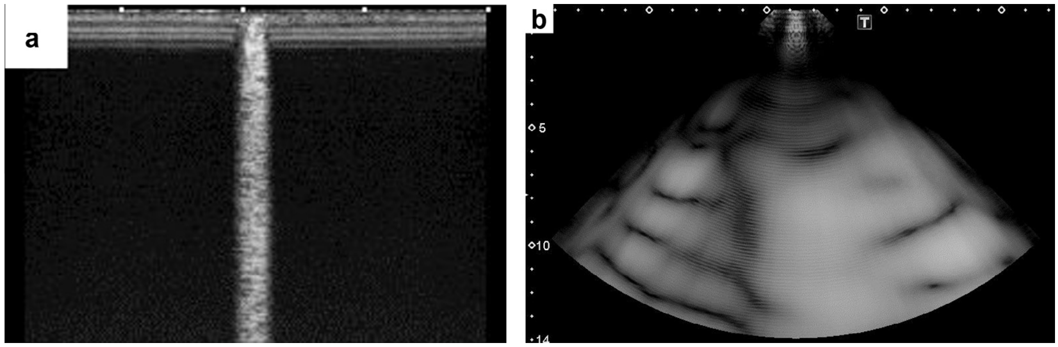

Fig. 1. The paperclip test in B-mode for (a) a linear array and (b) a phased array. Note that the reverberation pattern from the paperclip occupies the whole field of view for the phased array.

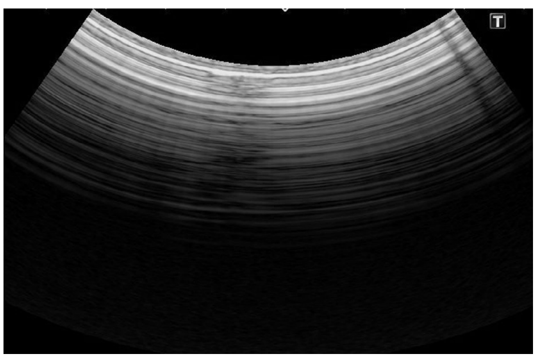

Fig. 2. Drop out (axial streak on the right) and delamination (disrupted reverberation pattern to left of centre) on a curvilinear array.

transducer face and slowly moved along the array. They found that the rod had to be rigid but sufficiently thin to make contact with a single transducer element at a time and chose an 18 gauge needle with diameter 0.73 mm. A size 1 paperclip has a diameter of approximately 0.8 mm and is suitable for this test.

The test is performed by slowly moving the paperclip along the face of the transducer, taking care to hold it perpendicular to the long axis of the transducer. A very thin film of water on the face of the lens may be used, if necessary, to reduce friction. In order to provide good control over the movement of the paperclip we pull the short edge and middle away from the long edge of the paperclip to form a triangle, and then grip the paperclip between forefinger and thumb at the apex of this triangle, using the long edge to perform the test.

For linear and curved arrays (without beam steering) a reverberation pattern appears (Fig. 1a), showing that the element in contact with the paperclip is both transmitting and receiving ultrasound. When the paperclip is held along a non-functioning element the reverberation pattern will dim or disappear, demonstrating the fault. A superficial transmit focal depth should be used to narrow the transmit aperture and the resulting reverberation pattern.

Without expensive and bulky equipment, drop out remains difficult to detect in phased arrays [7]. Our aim was to develop a modified version of the paperclip test to improve its ease and effectiveness for these transducers.

2. Methods

For phased arrays the paperclip test is difficult as the whole of the array is active for each beam line and the beam is steered, so that the reverberation pattern becomes indistinct and occupies the whole field of view (Fig. 1b). We modified the test as follows.

We performed the test using a fundamental frequency (not harmonics) and with any automatic gain or grey level adjustment disabled. A range setting of at least 10 cm and a mid-image focal depth were used to ensure that the whole array was active. Phased arrays often use only the central portion (approximately 50%) of the aperture when set to short ranges and/or a superficial focal depth. This can be checked by holding the paperclip on the transducer face in the outer 10% of the transducer array and increasing the range setting if no signal is seen. We then switched to M-mode, setting the M-mode cursor to the central axis of the image, to disable the beam steering. Each M-mode line then shows reverberations from the paperclip at a single location on the array. The paperclip was then swept slowly and steadily along the array. On reaching the end of the array the image was frozen immediately. The display then showed the reverberation pattern from each part of the array as a line in the M-mode display. The ideal sweep would match the paperclip speed to the scanner's pulse repetition frequency (PRF) so that each M-mode line represented a single element, but in our experience the PRF is faster than the motion of the paperclip between elements so that each element is represented by more than 1 M-mode line. Fig. 3 shows the pattern achieved from a normally functioning array.

The paperclip sweep was repeated several times for each transducer, also changing direction, until consistent results were achieved. Results were regarded as consistent when several sweeps showed no reproducible anomalies, or where several sweeps showed a vertical dark stripe appearing in the same location. We ignored horizontal banding in the images as this varied between sweeps and does not indicate faults. Once competent in

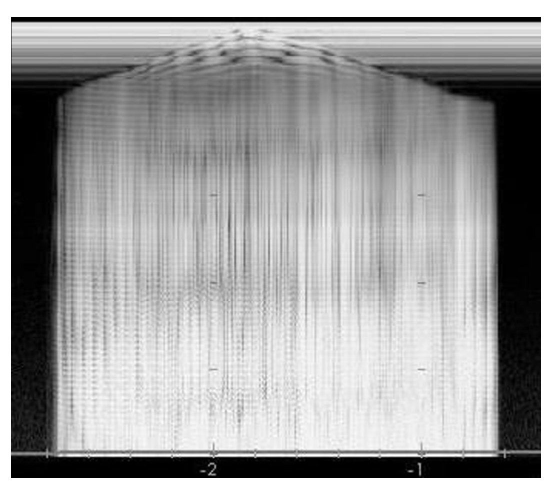

Fig. 3. M-mode reverberation pattern from a normally functioning phased array.

performing the test we recommend a minimum of 3 sweeps to ensure consistency.

To validate the method two transducers with known faults detected by sensitivity measurements made with a FirstCall transducer tester were used to compare the findings with the modified paperclip test. 23 transducers in clinical service were tested; at the same time at least one clinical user for each scanner was shown the test and invited to perform it.

The FirstCall has been designed to allow testing of transducers independently of the ultrasound scanner. An adapter specific to each transducer model is provided allowing transducer elements to be excited one at a time, sequentially along the array. Echoes are received from a metal plate in a water bath and the echo amplitudes for each element are plotted as a measure of sensitivity. Any non-functioning elements will show zero sensitivity.

Where no drop out was demonstrated but there were other anomalies in the paperclip test, e.g. non-specific non-uniformity, results were compared with TMTO testing where available. TMTO images were analysed using the Nottingham US QA software [8] to provide measurements of penetration depth, lateral, axial and elevational resolution. Penetration depth was reported as the depth at which the speckle signal falls to twice the noise level. Resolution was measured as the full width half maximum of the profile of a nylon filament target; elevational resolution used the Skolnick method, where the transducer is rotated through 45° [9].

3. Results

Results for the transducers with known faults are shown in Figs. 4 and 5; these were a GE 3S and a GE 3S-RS respectively (GE Healthcare, Amersham, UK). Fig. 4a and b show the M-mode reverberation pattern and the FirstCall sensitivity results for a phased array with a single non-functioning element. Fig. 5a and b show the M-mode reverberation pattern and the FirstCall sensitivity results for a phased array with known poor imaging quality due to cable damage.

23 transducers in clinical use were tested; there were 20 GE transducers (GE Healthcare, Amersham, UK), two Toshiba (Toshiba Medical Systems Ltd, Crawley, UK) and one Philips (Philips Healthcare, Guildford, UK). 5 transducers (all GE) showed anomalous results. Three transducers had a single area of drop out similar to that shown in Fig. 4a. One of these transducers was under warranty and was replaced. One transducer is still in use following confirmation of a single failed element using the FirstCall and a risk assessment. The other transducer was replaced by a third party supplier with a transducer that had been repaired with a replacement lens. The lens was visibly non-uniform in thickness and the results of the paperclip test are shown in Fig. 6; sensitivity appears non-uniform. Image quality tests using a TMTO (180 mm depth) and the Nottingham US QA software [8] showed low sensitivity (penetration depth 160 ± 7 mm versus >180 mm for a new transducer) and poor elevational focusing (full width half maximum at the focus 5.6 ± 0.9 mm versus 3.2 ± 0.5 mm for a new transducer). Following these tests the third party supplier supplied a new transducer. A further transducer appeared to have non-uniform sensitivity, as shown in Fig. 7. It was not possible to test all of these faulty transducers on the FirstCall, but multiple paperclip sweeps showed consistent results.

Clinical users who were shown the test and invited to repeat it obtained results in agreement with the authors in all cases.

4. Discussion

We have shown that the modified paperclip test is capable of detecting a single non-functioning element and that for multi-element failure the M-mode image agrees well with sensitivity measurements. Clinical users were able to perform the test after minimal training, with consistent results. We have provided limited evidence that the test also has potential to identify other, more subtle faults. There is a risk where a third party supplier replaces a lens that the lens material and shape may not match the original design specification. Using the modified paperclip test on such a probe we have identified non-uniformity that, on further investigation, had significant consequences for image quality. Future work will focus on comprehensive testing of transducers with non-uniform sensitivity, including FirstCall testing and TMTO

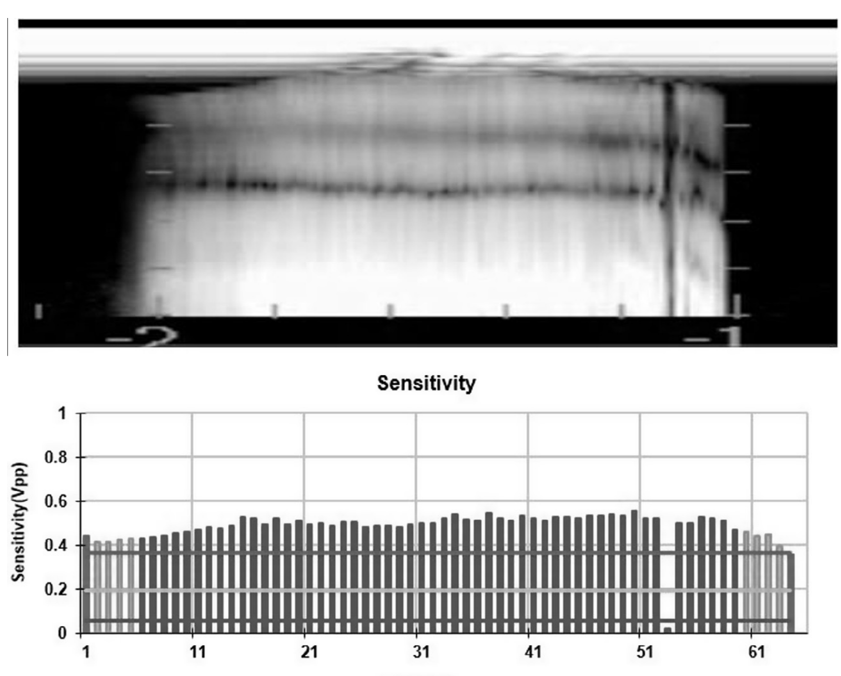

Fig. 4. M-mode reverberation pattern (a) and sensitivity measurements (b) for a phased array with non-functioning element 53.

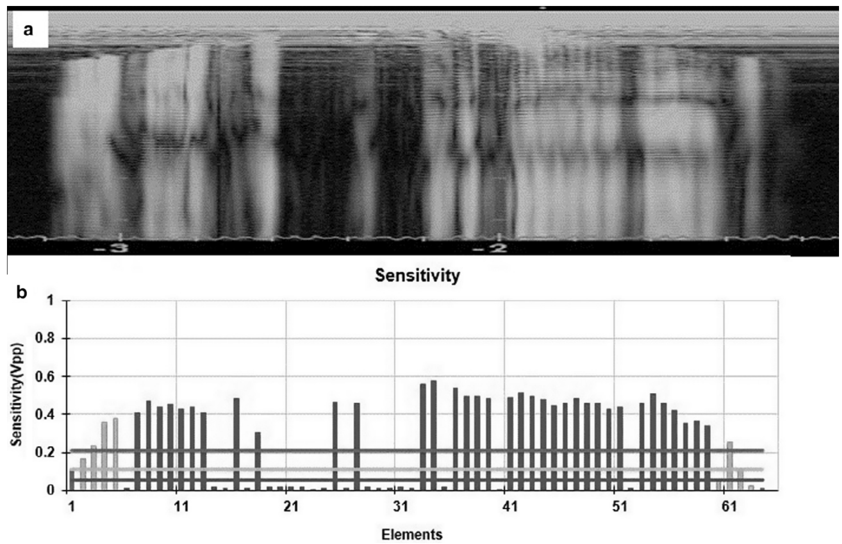

Fig. 5. M-mode reverberation pattern (a) and sensitivity measurements (b) for a phased array with very poor imaging performance due to a cable fault.

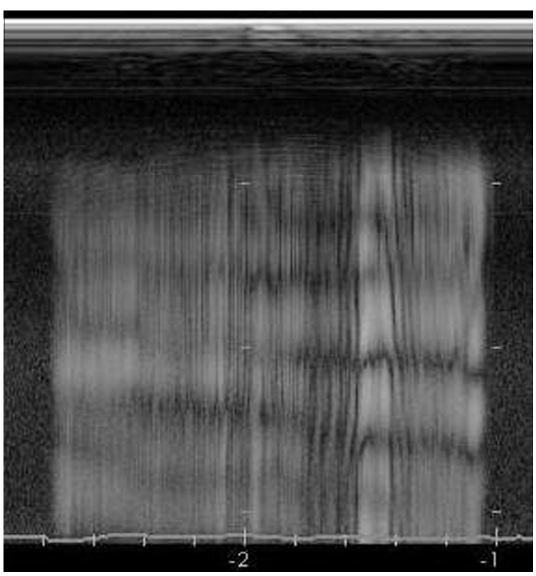

Fig. 6. M-mode reverberation pattern for a phased array with a replacement lens, showing non-uniform reverberation amplitude.

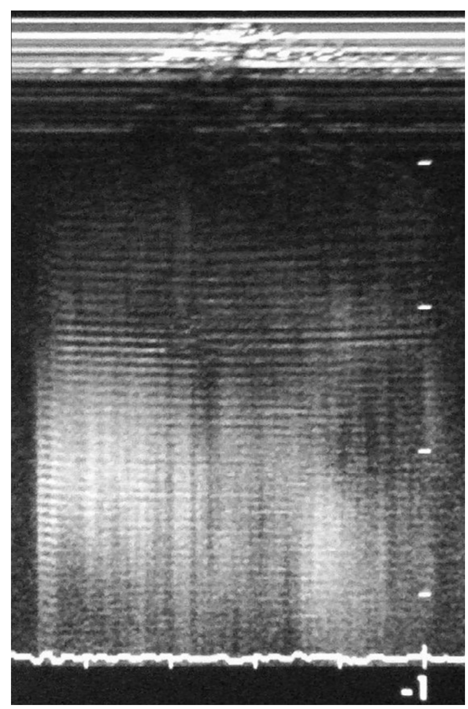

Fig. 7. M-mode reverberation pattern for a phased array showing apparent non-uniform sensitivity.

imaging, to attempt to provide a better understanding of more subtle faults.

Further work is also required to assess the clinical significance of faults detected using this method. In a phased array, typically using over 50 elements to form each beam, it is unlikely that image quality will be affected by failure of a single element. Weigang et al. [3] showed clinically significant changes to Doppler spectra and a 35% reduction in acoustic output power with 6 consecutive elements disabled at the centre of a phased array (they did not test a phased array with fewer elements disabled). Their study also showed clinically significant changes to Doppler spectra and a 17% reduction in acoustic output power with 2 consecutive elements disabled at the centre of a linear array. Vachutka et al. [4] disabled 1–10 elements at the centre of a phased array of 64 elements and showed a loss of Doppler power of approximately 7% per disabled element and that their phased array was more sensitive to disabled elements than their linear array in terms of changes to Doppler spectra. It would be prudent, therefore, to carry out further testing in cases of element failure to include sensitivity, e.g. B-mode depth of penetration, and accuracy of Doppler maximum velocity estimation, in order to assess the potential clinical impact.

5. Conclusion

We have developed a simple, modified paperclip test capable of detecting single element failure in phased arrays. The test also has potential to identify more subtle faults but this requires further investigation. Faults found using this test, unless grossly abnormal, should prompt further testing to assess their clinical significance.

Conflicts of interest

None

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None.

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