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● *Technical Note*

BLINDED COMPARISON BETWEEN AN IN-AIR REVERBERATION METHOD AND AN ELECTRONIC PROBE TESTER IN THE DETECTION OF ULTRASOUND PROBE FAULTS

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Abstract—The aim of this study was to perform a blinded trial, comparing the results of a visual inspection of the in-air reverberation pattern with the results of an electronic probe tester in detecting ultrasound probe faults. Sixty-two probes were tested. A total of 28 faults were found, 3 only by in-air reverberation assessment and 2 only by the electronic probe tester. The electronic probe tester provided additional information regarding the location of the fault in 74% of the cases in which both methods detected a fault. It is possible to detect the majority of probe faults by visual inspection and in-air reverberation assessment. The latter provides an excellent first-line test, easily performed on a daily basis by equipment users. An electronic probe tester is required if detailed evaluation of faults is necessary. (E-mail: nick.dudley@ulh.nhs.uk) © 2017 World Federation for Ultrasound in Medicine & Biology. Published by Elsevier Inc. All rights reserved.

Key Words: **Ultrasound, Transducer, Quality assurance.**

INTRODUCTION

Ultrasound scanner quality assurance (QA) is recommended, and guidelines are provided, by professional bodies around the world (*e.g.,* American Institute of Ultrasound in Medicine [AIUM 2008; Goodsitt et al. 1998; Kollmann et al. 2012; Russell et al. 2010). QA is mandatory for some applications, for example, screening programmes in the United Kingdom (Dall et al. 2011; Hartshorne and Summers 2014; National Health Service [NHS 2016), and accreditation schemes requiring QA are in place in some countries (American College of Radiology [ACR] 2017; College of Radiographers, Royal College of Radiologists 2013).

The ultrasound probe is the most vulnerable part of the instrument, and there is evidence that compromised image uniformity is the most common fault observed. Hangiandreou et al. (2011) reviewed the results of a 4-y quality control programme in a single large radiology department, including more than 300 probes. Probe failure represented 88% of total failures, the remainder being scanner component failures. The most frequent failure was image uniformity (66%), assessed by looking for artefacts in images of a tissue-mimicking test object (TMTO) and the in-air reverberation pattern. A recent survey of the condition of 219 probes in 12 hospitals found that more than 1 in 3 probes were faulty and 1 in 8 probes were not fit for purpose (Dudley and Woolley 2016a).

Probe faults are therefore common and important to detect. Electronic probe testers such as FirstCall (Unisyn, Golden, CO, USA) and ProbeHunter (BBS Medical AB, Stockholm, Sweden) provide comprehensive results that both detect faults and indicate their likely origin (Martensson et al. 2009, 2010; Sipila et al. 2011).

Martensson et al. (2009) tested 676 probes using an electronic tester and found faults in 269 probes (40%), but did not state how many of these faults were visible by other means, for example, inspection of the in-air reverberation pattern. Sipila et al. (2011) tested 135 probes using an electronic tester and with a TMTO to assess image uniformity and made a physical inspection of each probe, finding a total of 52 faulty probes (39%). Twenty-one faults (40% of all faulty probes) were detected with the electronic tester, 20 (38%) with the TMTO and 34 (65%) by physical inspection. Three faults (6% of total faulty probes) were detected only with the electronic tester, 8 (15%) only with the TMTO and 21 (40%) only by physical inspection. Sipila et al. (2011) concluded that all tests, including the electronic probe tester, are necessary.

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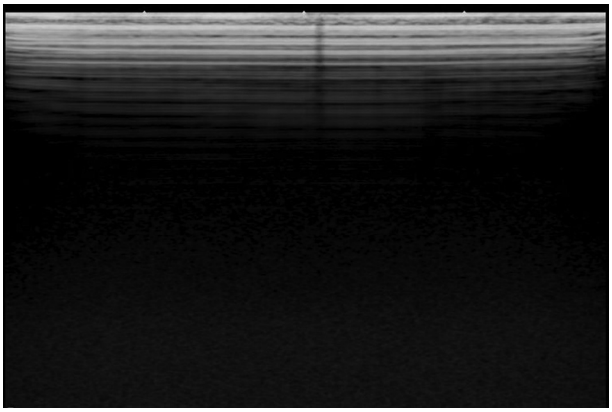

Fig. 1. Central dropout caused by a single element failure. The reverberation pattern also reveals signs of lens wear toward the ends of the array, indicated by reduced separation and intensity of reverberations.

Our experience using the FirstCall and comparing results with the in-air reverberation pattern is that the latter can detect a single non-functioning element, with appropriate adjustment of scanner settings. Figure 1 illustrates dropout caused by a single element failure. The "paperclip test" (Goldstein et al. 1989) and imaging of a TMTO may then be used to assess the severity and inform management of faults; for example, the paperclip test may or may not confirm element failure and a TMTO image may or may not reveal shadowing, but the physical origin of the fault may not be important unless considering a repair.

The aim of this study was to perform a blinded trial, comparing the results of a visual inspection of the in-air reverberation pattern with the results of an electronic probe tester.

METHODS

Multi-Medix carries a stock of used ultrasound probes from a range of manufacturers. Each probe is tested on arrival at the facility using a FirstCall electronic probe tester (Unisyn, Golden, CO, USA), with reports being stored in a database.

Electronic probe testing is performed by attaching the probe connector to a dedicated adapter. The probe is then mounted at the surface of a water bath with the probe face parallel to a steel reflecting plate. Three plates are available: a flat plate for linear and phased arrays, a plate with a large radius of curvature matched to typical convex arrays for abdominal use and a more tightly curved plate matched to typical endocavity probes. Under software control, each probe element, in turn, is driven by an excitation pulse; *via* the adapter, the returning echo is measured and the amplitude displayed. There is an initial alignment process, in which selected elements along the array are fired to allow multiplanar adjustment of the probe position until all elements are equidistant to the plate (achieved by timing of echo return). The entire array is then pulsed, one element at a time, and a sensitivity plot produced. The system then measures the capacitance of each element circuit and displays a capacitance plot; there are a number of probes for which FirstCall cannot measure capacitance. The capacitance results allow the user to determine whether low sensitivity is due to a short circuit, open circuit or damaged element. Additionally, the system provides plots of pulse width, centre frequency and fractional bandwidth for each element and pulse shapes and frequency spectra for three user-selected elements.

The FirstCall manual defines an acceptable probe array as having no more than four weak elements (40% to 75% of mean sensitivity), no more than two consecutive weak elements and no more than one dead element (<10% of mean sensitivity). For the purposes of this study a fault was defined as one or more dead elements, more than four weak elements or more than two consecutive weak elements to allow comparison between the methods in detecting element failure.

One of the authors (D.J.W.) managed routine probe testing; the other author (N.J.D.) was not involved in routine probe testing. For this study, D.J.W. provided N.J.D. with a selection of probes, some faulty and some without faults, across a range of manufacturers and probe types; N.J.D. was blinded to the FirstCall results. N.J.D. then connected the probes to appropriate ultrasound scanners and inspected the in-air reverberation patterns using the following settings. A clinical preset appropriate to the probe under test was selected; harmonics, beam steering, spatial compounding and any advanced image processing were disabled, and a single focus was moved close to the probe to minimise the width of the active aperture. Time gain compensation (TGC) was set to the default position where TGC slider controls are in the central position. Image scale, overall gain and transmit frequency were adjusted to optimise the display of any suspected anomalies in the reverberation pattern. Any suspected element failures were tested by running a paperclip or similar tool along the array, looking for a reduction in amplitude of the resulting "comet-tail" reverberation (Goldstein et al. 1989); the place where such a reduction was consistently observed was judged to represent one or more failed elements and recorded as a fault (dropout). Connectors were moved between ports to exclude connector/port faults as a cause of apparent element failure. Cables were manipulated in an attempt to identify cable faults as the source of element failure. In the absence of cable faults, isolated failed elements were recorded as non-specific element failure, that is, cause unknown, and multiple contiguous element failures were recorded as suspected array damage.

Where disruption of the reverberation pattern was seen, thought to represent delamination of the acoustic

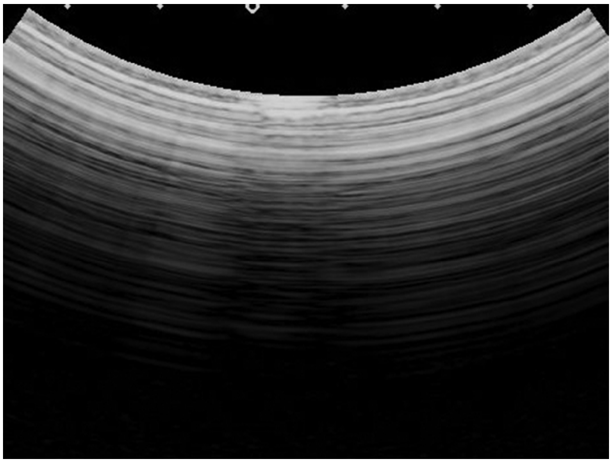

Fig. 2. Suspected delamination of the acoustic stack, indicated by disruption of the reverberation pattern.

stack, as illustrated in Figure 2, these were also recorded as faults. Delamination may be confirmed by applying pressure to the probe face; an image will be seen if the pressure restores contact between layers in the acoustic stack. The extent of each fault was recorded.

Phased arrays do not produce a parallel reverberation, because of beam steering, and so were tested using a modified version of the paperclip test (Dudley and Woolley 2016b), where the probe was operated in M-mode to turn off beam steering, with the M-mode line central in the image and a deep focus to ensure that all elements were active. The paperclip was then swept along the array and the image frozen. Any dark vertical bands in the M-mode display represent failed probe elements.

After testing in this way, the results were compared with FirstCall reports to assess agreement. Where faults were detected by inspection of the in-air reverberation pattern, FirstCall results were reviewed to assess whether useful additional information had been provided.

RESULTS

A total of 62 probes were tested: 32 convex abdominal arrays; 20 linear arrays; 8 transvaginal probes; and 2 phased arrays. Probes came from four manufacturers: 22 GE (GE Healthcare, Hatfield, UK); 12 Philips (Philips, Amsterdam, The Netherlands); 15 Siemens (Siemens Healthcare, Erlangen, Germany); and 13 Toshiba (Toshiba Medical Systems, Tokyo, Japan).

Table 1 summarises the results; a total of 28 faults were detected with the two methods (45% of probes). Table 2 summarises the results of a review of the five probes for which the methods disagreed, all confirmed by retesting.

Where faults were detected by both methods (23 probes) the in-air reverberation patterns were categorised and compared with the details of the FirstCall results. Table 3 summarises the findings; dead elements found by both methods were in the same area of the array in all cases. In 8 of 9 cases of non-specific element failure, the FirstCall result provided additional information regarding the location of the failure in the cable or the element. In 9 of 13 cases of suspected array damage, this was confirmed by the FirstCall results; in the remaining 4 cases, no capacitance result was available, but sensitivity loss revealed by the FirstCall matched that seen in the in-air reverberation pattern. In 3 of 4 cases of suspected cable faults, FirstCall results isolated the cause to element failure (1) or cable fault (2). The finding of a single case of suspected delamination was qualitatively consistent between the two methods, although no capacitance result was available for confirmation. In 6 of the 23 probes (26%), no capacitance measurement was possible so the fault was not isolated to cable or element.

DISCUSSION

Inspection of the in-air reverberation and the FirstCall detected 93% and 89% of total faults respectively, so neither can be considered the definitive method. However, review of the images and results indicates that amending the fault criteria for the in-air reverberation pattern to include suspected weak groups of elements may improve the fault detection rate, making this an excellent first-line test.

Sipila et al. (2011) found 15% of faults only by uniformity assessment, supporting the finding that some faults are missed by the electronic probe tester. In the 2 cases with acceptable FirstCall results but where dropout was seen in the reverberation pattern and confirmed using the paperclip test, the dropout was atypical. In cases of element failure, the dark axial band extends from the top of the image, or close to it, throughout the reverberation pattern. In one of these cases, the axial band was narrower than is usual in our experience, and in the other case, there was a relatively strong echo in the first reverberation (Fig. 3). A possible explanation for these cases and for the case of two suspected areas of delamination is that for in-air reverberation, a small non-uniformity in the lens or a very small area of delamination may lead to internal reflection away from the receive aperture. This may result in a reduced signal. When the lens is in full contact with a transmission medium, transmitted and received energy will be

Table 1. Faulty and non-faulty probes detected by FirstCall testing and in-air reverberation assessment

	First call		
Reverberation	Fault	No fault	Total
Fault	23	3	26
No fault	2	34	36
Total	25	37	62

Table 2. Five probes for which the methods disagreed

Probe	FirstCall	Reverberation
Transvaginal	Group of weak elements	Pass; review reveals weak reverberations matching weak elements
Phased	Three groups of weak elements	Pass but with asymmetry noted; review reveals weak reverberations matching weak elements
Linear	No fault found	Single small dropout
Linear	No fault found	Single small dropout
Convex	No fault found	Two small areas of suspected delamination

refracted along the same path and detected so that a signal is obtained by an electronic probe tester.

The electronic tester failed to provide additional information regarding the location of faults in 26% of cases as no capacitance measurement was possible for these probe models. Only probes for which electronic probe tester adapters and pin layout profiles are available were included in this study; adaptors and profiles are not available for all models of probe (Sipila et al. 2011). There will be a delay between release of a new probe model and the development of an adapter and profile to allow testing; if a new adapter is required, this is a significant expense. There is a further caveat that dead elements with reduced capacitance could be either damaged elements or broken electrical connections to the elements; if repair is to be attempted, the probe will have to be examined internally to determine the nature of the repair.

Table 3. Comparison between in-air reverberation faults and FirstCall results for 23 probes where both methods found a fault*

Reverberation pattern	FirstCall results
Non-specific element failure (9 probes)	Isolated dead elements (6 probes) Cable fault (2 probes) Failed element with no capacitance result
Suspected array damage (13 probes)	Matching loss of sensitivity with no capacitance result (4 probes) Block of dead elements (9 probes)
Cable fault (4 probes)	Single dead element, cable intact Failed elements with no capacitance result Cable fault (2 probes)
Suspected delamination (1 probe)	Suspected delamination (no capacitance result)

* Some probes had more than one fault. In the absence of a capacitance result, it was not possible to isolate the fault to element or cable.

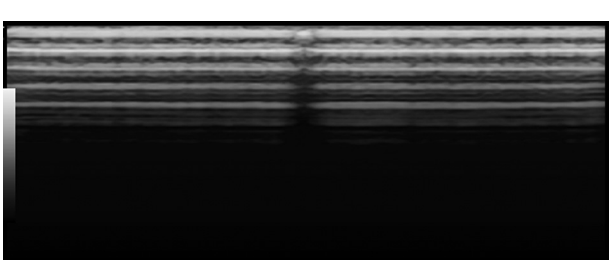

Fig. 3. Reverberation pattern revealing atypical central dropout where the FirstCall result indicated no fault. The dropout is atypical as the axial shadow does not extend to the top of the image.

Based on the 27% annual probe failure rate detected using FirstCall (Martensson et al. 2010), reliance solely on the in-air reverberation pattern for uniformity testing could lead to a 2% annual rate of undetected faults in a large probe pool. This may be improved by amending fault criteria as suggested earlier. In the clinical environment, there is a choice, therefore, between (i) the simple in-air reverberation method with 93% sensitivity in detecting faults demonstrated by the FirstCall and (ii) the more complex and expensive electronic probe tester that cannot be applied to all probes, with 89% sensitivity in detecting faults demonstrated by the in-air reverberation pattern.

In studies in clinical environments, more than 90% of faults were detected by physical inspection of the equipment and an assessment of uniformity (Hangiandreou et al. 2011; Sipila et al. 2011). It is very easy for equipment users to include a daily inspection of the in-air reverberation pattern with a visual inspection of the physical condition of the equipment, thus detecting most faults in a timely manner. Faults may then be risk assessed so that probes with only minor deterioration may remain in use and probes that are no longer fit for purpose may be replaced or sent for further assessment or repair. Probe testing and repair organisations should have access to an electronic probe tester, to ascertain the source of faults.

Minor deterioration may include a single failed element or minor lens wear as illustrated in Figure 1. Probes with large areas of dropout, multiple dropout or delamination should be considered not fit for purpose. There is evidence that two contiguous failed elements affect pulsed Doppler spectra (Vachutka et al. 2014; Weigang et al. 2003), so where the accuracy of Doppler velocity estimates is important, electronic testing of probes with single small dropout is prudent.

Where electronic probe testing is carried out in response to anomalies in the in-air reverberation pattern, it is reasonable that probes with subtle anomalies in the reverberation pattern, for example, suspected weak elements or small areas of dropout should be retained or repaired/replaced based on passing or failing electronic testing. A failed electronic probe test should be regarded as an indicator that a probe is no longer fit for purpose.

It should be noted that no matrix arrays were included in this study. These present a challenge, as single or small groups of elements will not present as dropout in an in-air reverberation image and the electronic complexity of the devices make design of electronic probe testers more difficult.

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