

An assessment of medical ultrasonic field measurement methods:
final technical report for EC contract no. MAT1-CT940064

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ABSTRACT

This document is the final report for EC contract no. MAT1-CT940064, entitled *An Assessment of Medical Ultrasonic Field Measurement Methods*.

The aim of the project was to carry out a European intercomparison of measurements on two reference devices, an NPL check source and a Dynamic Imaging diagnostic medical ultrasound scanner, in accordance with IEC 1157, 1993, *Requirements for the declaration of the acoustic output of diagnostic ultrasound equipment*. This standard is already being used by European manufacturers of medical ultrasound equipment as one means of demonstrating compliance with aspects of the Essential Requirements of the EC Medical Devices Directive which came into effect on 1 January 1995 (93/42/EEC). The project was organised radially, with the co-ordinator, NPL, taking a central rôle. A total of ten participants from seven EC countries have made measurements to IEC 1157 on the check source and scanner, with NPL carrying out the co-ordination, stability tests and inter-participant checks on the reference devices, and final analysis and reporting of the results.

The participants have carried out measurements on a modern, portable diagnostic scanner whose radiated fields pose a substantial challenge even to the most up-to-date measurement technologies. It appears that the single most important factor which contributes to differences between the results reported by participating laboratories is the range of different hydrophone and amplifier systems used. The measurements which were required on the NPL check source were extremely helpful in identifying effects arising from the different measurement systems. The report concludes with recommendations for possible future work identified as a result of undertaking this project.

This three-year project was funded partly by the Directorate-General for Science, Research and Development of the Commission of the European Communities, and partly by the United Kingdom's Department of Trade and Industry, as well as by the participating laboratories.

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Approved on behalf of the Managing Director, NPL
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1. INTRODUCTION

This is the final report for EC contract no. MAT1-CT940064 entitled *An Assessment of Medical Ultrasonic Field Measurement Methods*. The aim of this European collaborative project is to assess the ability of metrology laboratories and other relevant organisations to apply the measurement procedures set out in the International Electrotechnical Commission standard IEC 61157: 1993, *Requirements for the declaration of the acoustic output of diagnostic ultrasound equipment*. (Note that since 1996 the numbering of IEC standards has been changed so that all numbers are prefixed with the digit “6”. This practice is followed throughout this report.) This standard is already being used by European manufacturers of medical ultrasound equipment as one means of demonstrating compliance with aspects of the Essential Requirements of the EC Medical Devices Directive which came into effect on 1 January 1995 (93/42/EEC). The project is co-ordinated by the National Physical Laboratory (United Kingdom) and requires participating laboratories to carry out acoustic output measurements on two reference devices, one of which is a medical diagnostic ultrasonic scanner.

This report identifies the participating laboratories by name and appendix 2 sets out the address of each laboratory and the name of the relevant staff member or members at that laboratory. However, the results themselves are presented anonymously, so that each laboratory in tables, graphs and discussion of results is referred to only by a letter of the alphabet (laboratory A, laboratory B and so on). It should be noted that the order in which letters have been allocated does not follow the order in which names have been listed in section 2 of this report.

2. THE PARTICIPATING LABORATORIES

Ten laboratories representing seven E.C. countries took part in the project. They are listed below in alphabetical order based on the name of the organisation. Details of laboratories' addresses and staff involved in the project are given in appendix 2.

Department of Electrical Measurements, Lund Institute of Technology
Lund, Sweden

Institut für Biomedizinische Technik und Physik
AKH Wien, Austria

Instituto de Acústica del Consejo Superior de Investigaciones
Científicas, Madrid, Spain

National Physical Laboratory
Teddington, United Kingdom

Physikalisch-Technische Bundesanstalt,
Braunschweig, Germany

Regional Medical Physics Department, Newcastle General Hospital
Newcastle-upon-Tyne, United Kingdom

Technologie in Medizin und Gesundheitswesen eV (TIMUG)
Bonn, Germany

TNO Prevention and Health
Leiden, Netherlands

Wessex Regional Medical Physics Service, Royal United Hospital
Bath, United Kingdom

VTT Automation, Medical Device Technology
Tampere, Finland

3. THE REFERENCE SOURCES

Measurements were required on two ultrasound sources: an NPL pulsed check source and a portable diagnostic ultrasound scanner.

3.1 Check source

The first reference source for measurement by the participating laboratories was an NPL-designed ultrasound check source supplied by Gammex-RMI. This is a self-contained system which provides a stable acoustic output from a 13 mm diameter circular single-element transducer connected to electronic circuitry housed within its casing. The front panel provides a power-on switch, a choice of high and low amplitude settings and a trigger point. For the purposes of the intercomparison only the high output setting was used.

The participating laboratories were asked to make a limited set of measurements on the check source at a specified transducer-to-hydrophone separation (52 mm). The purpose of these measurements on a relatively simple acoustic source was to provide an indication of the possible problems which might arise in the measurements on the scanner owing to hydrophone or amplifier bandwidth limitations, for example.

3.2 Dynamic Imaging diagnostic ultrasound scanner

The main reference source which was circulated to laboratories for characterisation in accordance with IEC 61157 is a diagnostic medical ultrasound scanner, a Dynamic Imaging ConceptMC scanner with a 5 MHz linear array internal veterinary probe. This probe was chosen because it can be fully immersed in water without damage and its output is equivalent to that of probes used on humans. The scanner is a small portable device with a limited number of controls which are capable of varying its acoustic output. It nevertheless presents a substantial challenge to the capabilities of many ultrasound measurement systems as it is able to deliver very high acoustic pressures with small beam-widths, and to generate in water highly shocked wavefronts with rich spectral content. The scanner was modified by the manufacturer to provide two external BNC sockets for triggering purposes.

4. MEASUREMENT PROTOCOL

A measurement protocol document was prepared for circulation to each participating laboratory with the check source and scanner. The protocol identified for the laboratory the measurements which were to be made on each of the two devices and set out instructions on reporting results of the measurements.

The measurements had to be conducted in two stages. The first stage required the participant to identify the scanner settings in B mode and M mode which produced the highest values of the pulse-pressure-squared integral and of the spatial-peak temporal-average intensity. The laboratory was also required to provide a copy of the acoustic waveform obtained from the check source at the setting and transducer-to-hydrophone separation identified in the protocol. Following receipt of the stage one results by NPL, the laboratory was instructed to continue to a more detailed characterisation of the two devices at the settings identified in stage one and at any additional settings required by NPL.

The second stage of the measurement programme for each laboratory required measurements at one specified setting on the check source and the characterisation of the scanner in accordance with the standard IEC 61157, except that in order to limit the amount of work required from each laboratory only B and M mode measurements were requested, so that the laboratory was not required to investigate combined B+M mode or B+A mode. In addition, if it was found that the settings which give the maximum pulse-pressure-squared integral and the spatial-peak temporal-average intensity were different, then in the case of the spatial-peak temporal-average intensity, it was only necessary to report its value, the transducer-to-hydrophone separation and the settings which gave that value. The protocol included a suggested format for the reporting of the stage two results.

A copy of the protocol is included as appendix 4 of this report.

5. ACCEPTANCE TESTING OF CHECK SOURCE AND SCANNER AND RESULTS OF STABILITY TESTS

5.1 Acceptance testing of check source

The stability of the check source both in the short and long term was assessed at the beginning of NPL's experimental work on the project.

5.1.1 Short term stability tests

Short term stability tests were carried out using both the NPL Beam Calibrator and the NPL beam plotting facility. These were performed over a period of approximately three hours by measuring a limited range of acoustic parameters, peak-positive and peak-negative acoustic pressure and spatial-peak temporal-average intensity, every few minutes after the check source had been switched on. Accounts of the operation of the NPL Beam Calibrator and the NPL beam plotting tank can be found in Preston (1988) and Preston, Bacon and Smith (1988).

For the purposes of this section of the report, the results of a limited set of measurements of the acoustic output of the check source as obtained using the NPL beam plotting tank are given in table 1.

The transducer was totally immersed in a tank of freshly degassed, deionised water. Measurements were obtained at the 52 mm transducer-to-hydrophone separation using a coplanar hydrophone with an active element of diameter 0.5 mm and a membrane thickness of 9 μm . The hydrophone and amplifier were connected to a waveform processing oscilloscope (Tektronix 2430A). The sensitivity of the hydrophone and amplifier combination at the arithmetic mean acoustic working frequency was 12.25 nV Pa⁻¹.

In order to achieve consistent presentation of results, peak-negative acoustic pressure will be expressed as a positive number throughout the text and tables of this report. This follows the guidance in IEC 61157, paragraph 3.34.

TABLE 1:CHECK SOURCE - RESULTS OBTAINED DURING STABILITY TESTS	
Transducer-hydrophone separation 52 mm - indicate how measured	Time delay
Total power	3.63 mW ($\pm 4\%$)
Peak-negative acoustic pressure	1.20 MPa ($\pm 8\%$)
Spatial-peak temporal-average intensity	88.5 mW cm ⁻² ($\pm 16\%$)
-6 dB beam-width : perpendicular	2.56 mm ($\pm 6\%$)
parallel	2.37 mm ($\pm 6\%$)
Acoustic working frequency	3.60 MHz
Pulse repetition rate	1738 Hz
Temperature of water during measurements	20 $\pm$ 1 °C

The measurement uncertainties quoted in table 1 were assessed according to the NAMAS document NIS 3003, Version 7, entitled "The Expression of Uncertainty and Confidence in Measurement". They are for a confidence probability of not less than 95%.

The systematic uncertainties were estimated by combining the various contributions from a number of different sources. One major source of systematic uncertainty equal to $\pm 7\%$ at 3.5 MHz is in the determination of the hydrophone sensitivity. Additional contributions arise from spatial averaging over the finite size of the active element of the hydrophone, the amplifier gain, the digitisation of the hydrophone signal and the scan truncation level.

The random uncertainties were assessed from a number of repeat measurements recorded during the 200-hour acceptance testing of the check source. No evidence of instability of output from the check source was noted during the acceptance tests, provided that at least 30 minutes was allowed to pass after power-up and before commencing measurements.

5.1.2 Long term stability tests on check source

The long term stability of the check source was monitored by leaving its transducer in position and switched on for 200 hours in the beam plotting tank. Regular measurements of the peak-positive and peak-negative acoustic pressures and the spatial-peak temporal-average intensity were made throughout this period at the 52 mm transducer-to-hydrophone separation. During this period 55 determinations of the three acoustic parameters were made. Their mean values and standard deviations (randoms only) were:

Peak-positive acoustic pressure	2.565 MPa ($\pm 3\%$);
Peak-negative acoustic pressure	1.201 MPa ($\pm 3\%$);
Spatial-peak temporal-average intensity	88.3 mW cm ⁻² ($\pm 4\%$).

It was decided to use these values for stability testing of the check source following its return to NPL after each participating laboratory's measurements, the requirement for

acceptance being that the values of the three acoustic parameters on return should be within one standard deviation of those measured during the 200-hour stability test.

5.1.3. Stability tests over the 3-year course of the project

The results of these regular tests which took place over the three years of the project after the reference devices were returned to NPL by each laboratory show that the check source can be regarded as reasonably stable. The mean values of the three parameters for the nine measurements (one for each participating laboratory other than NPL) and their associated standard deviations expressed as a percentage are:

Peak-positive acoustic pressure	2.987MPa ($\pm 9.1\%$);
Peak-negative acoustic pressure	1.188 MPa ($\pm 3.2\%$);
Spatial-peak temporal-average intensity	90.21 mW cm ⁻² ($\pm 4.8\%$).

Note that the mean peak-negative acoustic pressure and spatial-peak temporal-average intensity values are within the test ranges determined during the long-term stability tests, but that the peak-positive acoustic pressure is higher and shows a greater variation. There are two possible reasons for this. It is difficult to obtain good repeatability of peak-positive acoustic pressure measurements in a shocked field such as that generated by the check source. The second is that the original tests measurements were carried out with a 0.5 mm diameter coplanar membrane hydrophone, whereas the later measurements were made with a 0.2 mm diameter bilaminar membrane hydrophone.

5.2 Dynamic Imaging diagnostic ultrasound scanner

5.2.1 Long term stability test of scanner

Following initial receipt of the scanner at the National Physical Laboratory, it was necessary to test its long term stability. This was done by mounting the transducer in water in a beam plotting tank and monitoring the output over a period of 200 hours. During this time regular measurements were made at one particular scanner setting. Whereas the scanner's transducer was kept switched on and immersed in water during the acceptance testing, the hydrophone was removed from the tank every evening. In addition, measurements were also made at other positions and settings in between acceptance test measurements. These two factors introduce elements of variability into the acceptance test measurements associated with aligning and positioning the hydrophone and with the warm-up time for the hydrophone amplifier and digitising oscilloscope.

The setting chosen for the acceptance test was the central scan line in B mode, 3 times magnification, focal zone 1, skin line 4, wide screen 160 scan lines, with a transducer-to-hydrophone separation of 22 mm. The hydrophone employed for the test was a 9 μ m thickness pvdf bilaminar device with a 0.2 mm diameter element. The means and standard deviations (expressed as a percentage of the mean) of the three chosen acoustic parameters, uncorrected for measurement uncertainties, were:

Peak-positive acoustic pressure	11.3 MPa ($\pm 1.8\%$);
Peak-negative acoustic pressure	2.94 MPa ($\pm 2.9\%$);
Spatial-peak temporal-average intensity	7.07 mW cm ⁻² ($\pm 3.5\%$).

It should be noted that for this test the spatial-peak temporal-average intensity includes only the contribution from the central scan line and not from any overlapping scan lines.

During the 200-hour acceptance test the temperature of the water in the scanning tank varied from 21.0 °C at the start to 19.8 °C at the end. The initial temperature of 21 °C was the highest during the test. The lowest temperature, 19.5 °C, was observed over the period from 53 hours to 141 hours after switch-on.

It was decided to take the settings and values obtained during the 200-hour acceptance test as those which would be used to verify the stability of the scanner following its return from each participating laboratory. The criterion would be that the uncorrected measured values on return should be within one standard deviation of the mean measured values during the acceptance test. It should be noted that the purpose of the stability tests during acceptance was to establish the overall stability of acoustic output. The question of the time needed to reach stable output conditions when switching between modes of the scanner was not investigated during the acceptance tests.

5.2.2. Stability tests over the 3-year course of the project

The results of these regular tests which took place over the three years of the project are tabulated below where the mean values of the three parameters for the nine measurements (one for each participating laboratory other than NPL) and their associated standard deviations expressed as a percentage are:

Peak-positive acoustic pressure	11.67 MPa ($\pm 3.8\%$);
Peak-negative acoustic pressure	3.04 MPa ($\pm 4.1\%$);
Spatial-peak temporal-average intensity	7.29 mW cm ⁻² ($\pm 6.7\%$).

For each of the nine measurements the same hydrophone and amplifier was employed as was used for the stability tests at the start of the project (0.2 mm diameter active element, 9 µm thick pvdf film). It should be noted that although the measurements of all three parameters overlap, given their associated error ranges, all three of the parameters showed higher mean values than those measured during the 200-hour stability test. All measurements were made after the scanner had been placed in the measurement tank and had been switched on for at least one hour. In addition, the hydrophone was also in place for at least one hour, with its pre-amplifier and digitiser on. It may be that the acoustic output of the scanner varies slightly over time scales of several hours. In addition a wider range of spatial-peak temporal-average intensities (from the same single scan line) was observed when the scanner returned from the final three laboratories taking part in the project than had been observed after the measurements in the first six laboratories. Some participating laboratories included comments on the stability of the scanner when switching between modes and the lack

of any requirement to establish the stability of the acoustic output of scanners in the IEC 61157 standard. These comments will be highlighted in a later section of this report.

6. PRESENTING THE RESULTS OF THE MEASUREMENTS

The remainder of this report sets out the results of each participating laboratory's measurements on the check source and the scanner, includes information on the measurement system employed by each laboratory and summarises key additional observations from laboratories' measurement reports. Given the large amount of data collected during the work described here and the comprehensive nature of many of the reports, it is not possible to include the full text of each laboratory's report and it has been necessary to summarise and standardise information.

In the main body of the report results are either summarised briefly or presented graphically. More detailed tabulations of check source data are included as an appendix.

7. RESULTS OF CHECK SOURCE MEASUREMENTS

This section of the report presents the results of each laboratory's measurements on the check source. As explained earlier, the purpose of these measurements was to allow an assessment of the performance of the measurement system employed by each participating laboratory. The main findings of each laboratory will be presented graphically, with more detailed information being included in appendix 1.

7.1 Measurement systems used for check source measurements

The participating laboratories employed a range of measurement systems both for the check source and scanner measurements and a brief summary of the apparatus used is given below, based on the information provided in each laboratory's measurement report.

Laboratory A

NP-1000 pvdf needle probe hydrophone with 0.5 mm diameter active element, bandwidth 20 MHz, and an HP-2130 30 dB gain amplifier with a bandwidth of 500 kHz to 40 MHz.

Laboratory B

NPL Beam Calibrator with GEC-Marconi pvdf multi-element hydrophone, 0.4 mm diameter active elements spaced 0.6 mm apart.

UBC SN0002E amplifier module, with 23 MHz -3dB bandwidth for the combined hydrophone-amplifier system.

Laboratory C

Force Institute pvdf needle probe hydrophone with 0.5 mm diameter active element, bandwidth 20 MHz.

Total power measured using a radiation force balance, namely a Sartorius 4401 microbalance with 60 mm diameter absorbing and reflecting targets, the results being averaged).

Laboratory D

GEC-Marconi 25 μ m thickness pvdf bilaminar shielded membrane hydrophone with 0.5 mm active element, type Y-34-3598 and a GEC-Marconi type Y-33-9724 amplifier of 17 dB gain; 23 MHz bandwidth for combined hydrophone-amplifier system.

Laboratory E

GEC-Marconi 25 μ m thickness bilaminar membrane hydrophone with 0.5 mm diameter active element, 25 MHz bandwidth and 75 MHz bandwidth GEC-Marconi Y-34-6527 type amplifier.

Laboratory F

GEC-Marconi 9 μ m thickness pvdf coplanar membrane hydrophone with a 0.5 mm diameter active element and bandwidth greater than 60 MHz with -7.5 dB gain amplifier of bandwidth greater than 60 MHz.

For the check source, power measurements were made by planar scanning.

Laboratory G

Force Institute 9 μ m thickness pvdf needle hydrophone type MHA9-4 0.4 mm diameter active element with wide bandwidth amplifier (bandwidth of combined hydrophone-amplifier system greater than 60 MHz).

Total power was measured with a radiation force balance with an absorbing target in addition to power measurements made with this hydrophone.

Laboratory H

NPL Beam Calibrator with GEC-Marconi pvdf multi-element hydrophone, 0.5 mm diameter active elements spaced 1 mm apart. Bandwidth of combined hydrophone-amplifier system 23 MHz.

In addition to the Beam Calibrator measurements, total power was also measured using a radiation force balance. For information concerning the design and construction of this kind of balance see Perkins (1989).

Laboratory J

GEC-Marconi 25 μ m thickness pvdf bilaminar shielded membrane hydrophone with 0.5 mm active element, type Y-34-3598 and a GEC-Marconi type Y-33-9724 amplifier of 17 dB gain and 23 MHz bandwidth for combined hydrophone-amplifier system.

Time-averaged intensity was measured with an electronic power meter giving a real-time analogue output (Martin, 1988)

Total power was measured with a radiation force balance with an absorbing target.

Laboratory K

Force Institute pvdf needle probe hydrophone with 0.4 mm diameter active element and a wide bandwidth amplifier. Bandwidth of combined hydrophone-amplifier system 60 MHz.

7.2 Main results of measurements on check source

In this section of the report the main check source measurement results for each laboratory are presented graphically. The 95% confidence interval for each measurement is indicated on each bar in the chart, the quoted uncertainty (where this has been provided) being that reported by the laboratory in question. The caption to each graph gives the arithmetic mean of the values reported by the laboratories together with its associated standard deviation. However, in a study such as that undertaken for this European Commission project, it is important not to attach too great a significance to the mean value. The aim of the project is not to establish or to agree "true" values for the acoustic parameters being measured, but to investigate how laboratories apply the measurement procedures set out in the IEC 61157 standard. The check source measurements act as an indicator of the performance of individual laboratories' measurement systems. It is likely to be the case that the main source of differences between laboratories' reported values for a particular parameter is the performance of the measurement system employed by each laboratory. As section 7.1 of this report demonstrates, some laboratories used membrane hydrophones, while others used needle probes. Two laboratories used multi-element membranes. In addition, a range of active element sizes was employed. Differences in hydrophone and amplifier bandwidth and in spatial-averaging by the hydrophone are likely to be the main contributors to variation in the results. Note that for the check source all measurements were performed at a transducer-to-hydrophone separation of 52 mm.

Figures 1 and 2 present the results for peak-negative and peak-positive acoustic pressure respectively. Figure 3 shows the total power output results and figure 4 sets

out the findings for spatial-peak temporal-average intensity (I_{spta}). Figure 5 summarises the reported values for pulse-pressure-squared integral (p.p.s.i.) and figure 6 shows the results for mean values of the -6 dB beam width.

It was pointed out above that differences between laboratories are likely to be due to differences in system bandwidth and in spatial-averaging effects. One way of comparing these effects across laboratories is to calculate the ratio of peak-positive acoustic pressure to peak-negative acoustic pressure for the check source, although this does not account for frequency-dependent effects. However, differences due to absolute sensitivities of hydrophone and amplifier systems, and their associated uncertainties, are removed from the comparison. Figure 7 shows the values for this ratio. The check source results for laboratory A appears to be out of line with those of other laboratories. Peak-negative acoustic pressure for the check source is a more stable acoustic parameter than peak-positive acoustic pressure, and is more easily measured, owing to the fact that the waveform is substantially shocked. The peak value of such shocked wavefronts can be difficult to detect in the presence of noise or jitter. In addition, if the hydrophone possesses a resonance within the bandwidth of the acoustic signal there may be a tendency to overestimate peak-positive acoustic pressures. Note that in figure 1, excluding laboratory A, peak-negative acoustic pressure shows variations not exceeding 0.22 MPa between laboratories, whereas in figure 2 peak-positive acoustic pressure varies by more than 1.1 MPa between laboratories.

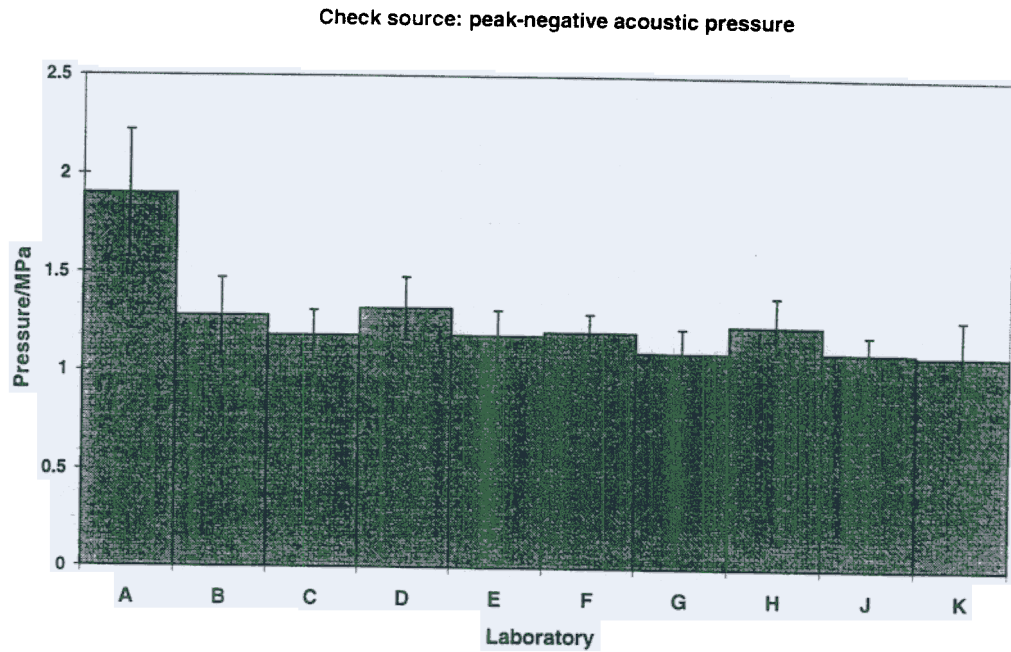


Figure 1: Check source: absolute value of peak-negative acoustic pressure reported by each participating laboratory with associated 95% confidence limits; mean value: 1.26 MPa $\pm$ 19% (1 standard deviation).

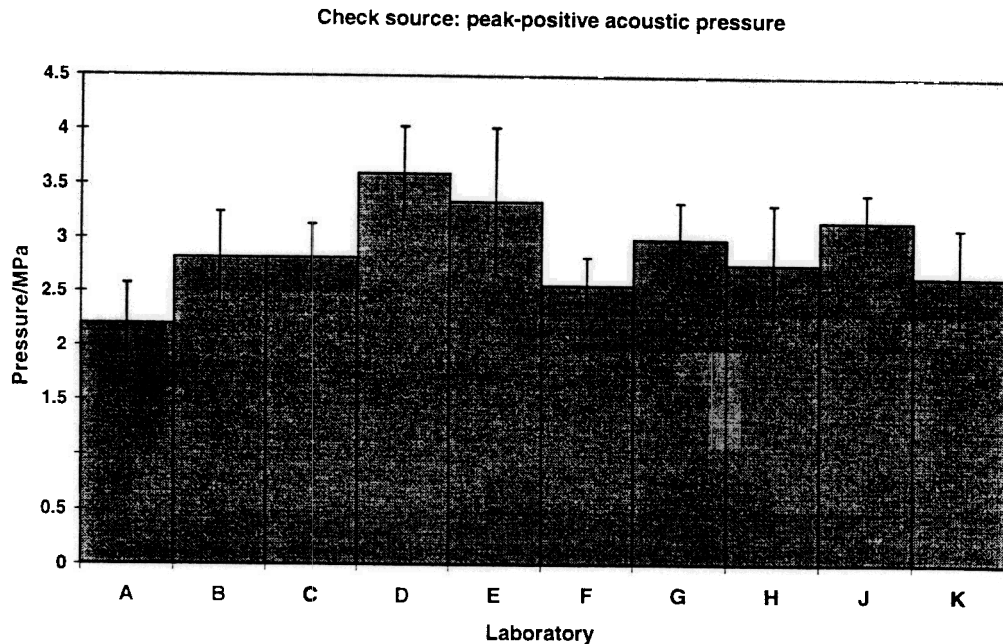


Figure 2: Check source: peak-positive acoustic pressure reported by each participating laboratory with associated 95% confidence limits ; mean value: 2.89 MPa $\pm$ 14% (1 standard deviation).

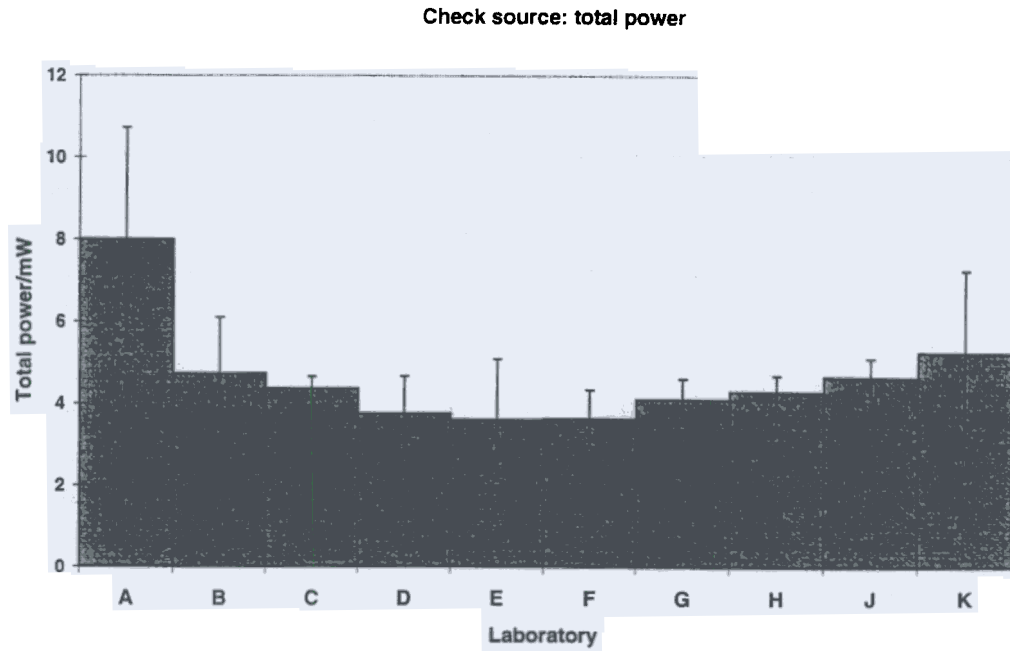


Figure 3: Check source: total power output reported by each participating laboratory with associated 95% confidence limits where reported; mean value: $4.65 \text{ mW} \pm 28\%$ (1 standard deviation).

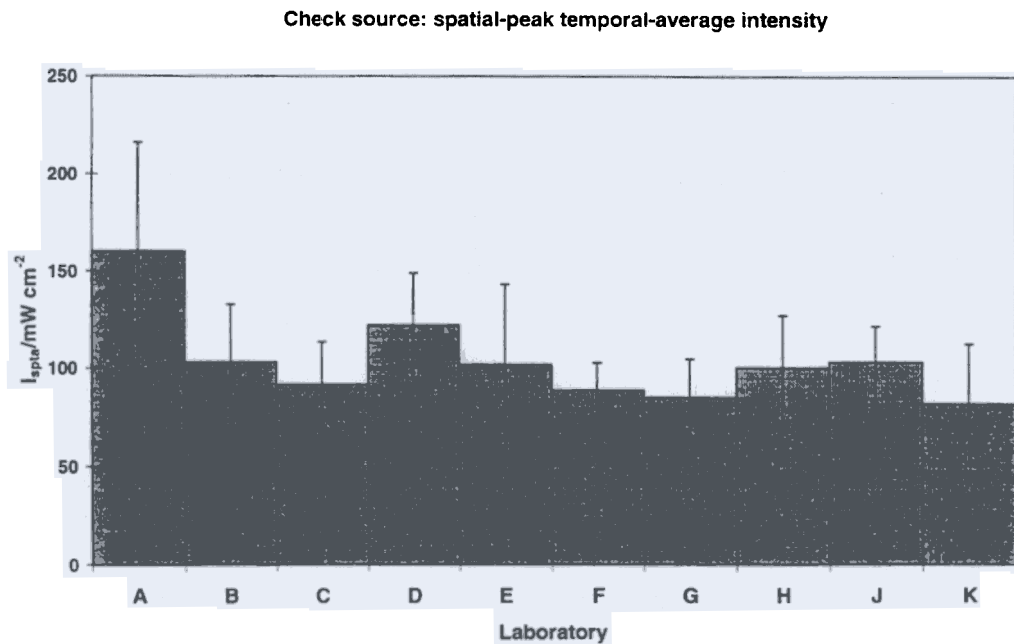


Figure 4: Check source: spatial-peak temporal-average intensity reported by each participating laboratory with associated 95% confidence limits; mean value: $103.7 \text{ mW cm}^{-2} \pm 22\%$ (1 standard deviation).

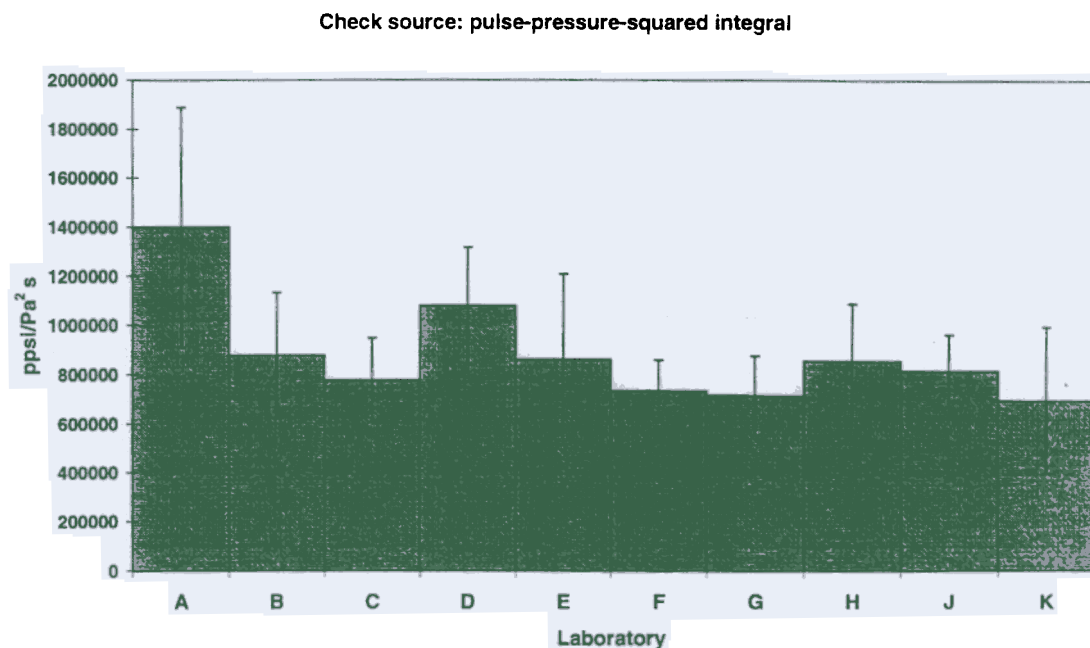


Figure 5: Check source: pulse-pressure-squared integral reported by each participating laboratory with associated 95% confidence limits; mean value: 882,780 Pa² s $\pm$ 24% (1 standard deviation).

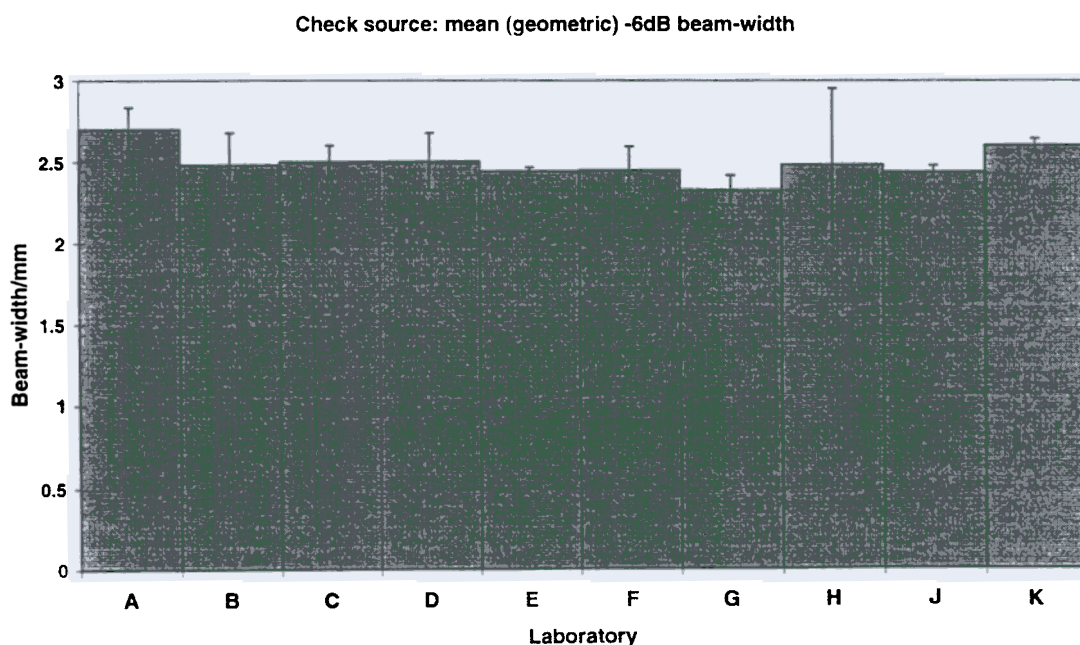


Figure 6: Check source:-6 dB beam-width (geometric mean of parallel and perpendicular measurements) reported by each participating laboratory with associated 95% confidence limits; mean value: 2.49 mm $\pm$ 5% (1 standard deviation).

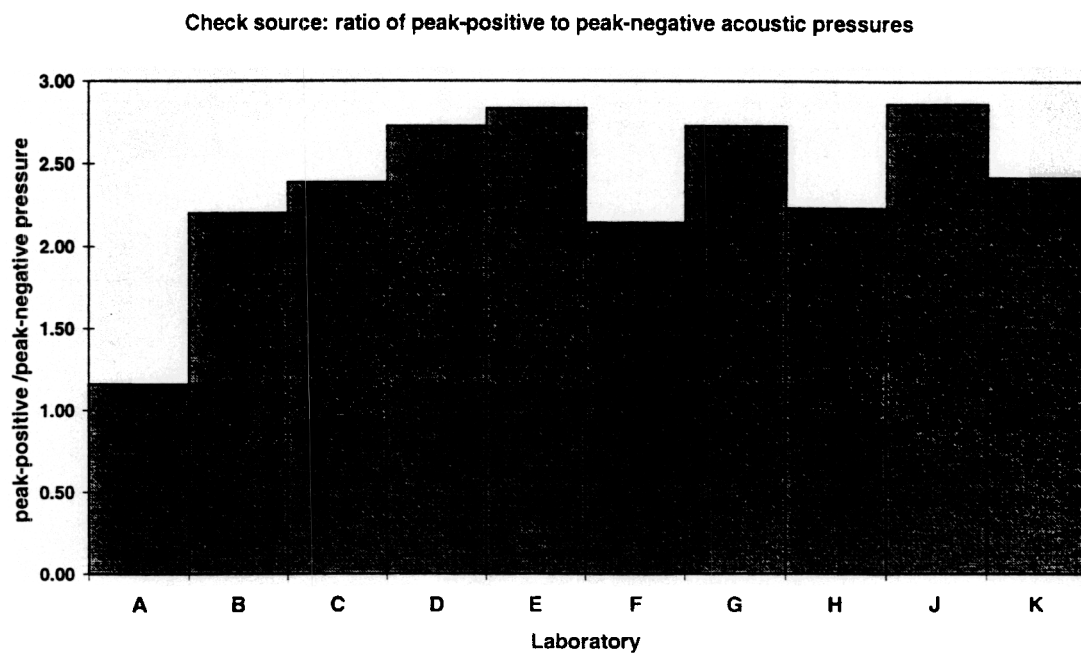


Figure 7: Check source: ratio of peak-positive to absolute peak-negative acoustic pressure for each participating laboratory.

7.3 Check source waveform measured with NPL's primary standard laser interferometer

To provide an independent verification of the main acoustic parameters for the check source it was decided to carry out a measurement of the check source waveform using NPL's primary standard laser interferometer. The operation of the interferometer is described by Bacon (1988), where an account is given of the manner in which the interferometer is used to provide a means of measuring acoustic particle displacement, allowing absolute values of acoustic pressure to be calculated. A primary standard calibration of a hydrophone can be obtained by placing the hydrophone at the same point at which displacement is measured and recording its output voltage.

For the purposes of this report, it is sufficient to state that an acoustically transparent but optically reflecting membrane (known as a pellicle) made of 3.5 μm thick Mylar coated with 25 nm of gold is aligned at the required measurement distance from a transducer. It is assumed that the pellicle moves with the acoustic particle, so that a beam from a 623.8 nm wavelength helium-neon laser can be used to detect displacement of the particle. The beam is 0.1 mm in diameter, so that in the case of the check source beam, spatial-averaging effects can be ignored.

Particle displacement waveforms were obtained from the check source at a transducer-to-hydrophone separation distance of 52 mm, as required for the work reported here. If plane wave propagation is assumed in the focal region of the check source, so that acoustic pressure is proportional to acoustic velocity, then the absolute acoustic pressure waveform can be derived from the differentiated displacement waveform. The pressure waveform can be corrected for the known frequency response of the interferometer and for transmission losses in the pellicle (the interferometer beam senses the displacement at the side of the pellicle further from the acoustic beam). In this way a pressure waveform may be obtained which is independent of any hydrophone measurement and is not subject to hydrophone bandwidth limitations, spatial-averaging effects and calibration uncertainties.

Figure 8 shows a typical acoustic pressure waveform derived from the interferometer measurement. The waveform gives values of 2.49 MPa for the peak-positive acoustic pressure, 1.16 MPa for the peak-negative acoustic pressure and 721,000 $\text{Pa}^2 \text{ s}$ for the pulse-pressure-squared integral. Typical combined uncertainties for the interferometer at the 95% confidence level where four repeat measurements are made to assess type A uncertainties are 4.2% at 5 MHz and 6.7% at 20 MHz.

It would also have been of interest to perform an interferometer measurement on the Dynamic Imaging scanner for comparison with results to be presented later in this report. However, such a measurement proved not to be possible owing to the very high pressure and consequently very high displacements generated by the scanner. The displacements exceeded the equivalent of a fringe on the NPL interferometer and are therefore not capable of being measured accurately with the current experimental apparatus. However, NPL is establishing a laser interferometer which relies on the Doppler effect to detect acoustic particle velocity. This interferometer can be operated in much higher pressure fields than the displacement interferometer. In future, it may

be possible, by means of the new interferometer, to obtain particle velocity waveforms relating to the high-pressure fields radiated by the Dynamic Imaging scanner which are independent of hydrophone measurements.

Check source: interferometer waveform

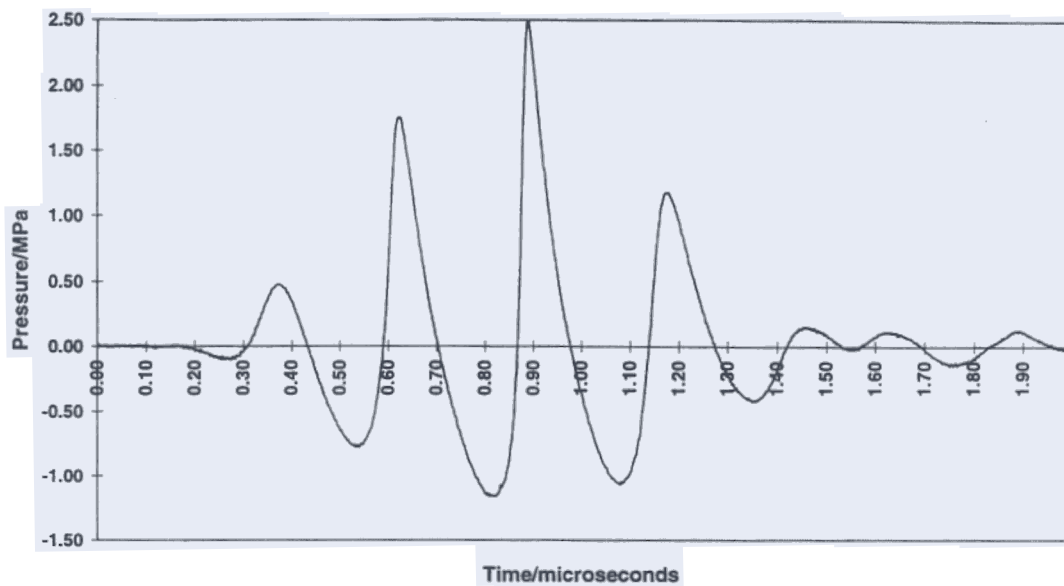


Figure 8: Typical check source pressure waveform obtained with NPL primary standard laser interferometer: peak-positive acoustic pressure, 2.49 MPa; peak-negative acoustic pressure, 1.16 MPa; pulse-pressure squared integral, 721,000 Pa² s

8. DYNAMIC IMAGING SCANNER: PART ONE RESULTS - DETERMINATION OF SCANNER SETTINGS FOR MAXIMUM OUTPUT

8.1 Identifying the scanner controls which affect acoustic output

The first stage of each laboratory's investigation of the acoustic output of the Dynamic Imaging scanner required them to identify those settings which gave the maximum acoustic output in accordance with IEC 61157. However, in order to simplify the task and to allow measurements to be completed in the allotted time, it was only necessary to investigate B and M mode separately, and not to investigate combined modes. In this section of the report a brief account of those scanner controls which appear to affect acoustic output is given.

The scanner operates in B and M mode (at high and low speed) and in combined B+M mode, and B+A mode. For the purposes of this project measurements are made in B mode and M mode only. The controls which affect the acoustic output of the scanner were investigated and it appears that the acoustic output can be varied by the following controls:

Magnification: For the 5 MHz linear probe, four magnification levels are available 1, 1.5, 2 and 3 times magnification.

Focal zone: the scanner has three focal zones. For identification purposes the zone nearest the transducer (or closest to the skin surface of the patient) is referred to as zone one and the furthest zone (deepest into the patient's body) is called zone three.

Skin line: The point in the body of the patient which is displayed at the top of the screen can be moved by changing this setting. On power-up the default setting is referred to as skin line one. Successively pressing the "up" arrow on the scanner controls moves deeper parts of the body towards the top of the screen. In addition to the default setting, three other skin line settings may be chosen each of which moves deeper parts of the image upwards. These other settings are referred to as skin lines two, three and four, where the increasing values indicate increasing movement towards the top of the screen. It should be noted that varying the skin line does not always affect the scanner's acoustic output. In magnification three, for example, at least three skin line settings appear to produce the same acoustic output. In magnification two, skin lines two, three and four seem to produce the same output, but this is higher than the skin line one output at the same measurement position.

Angle: It is possible to change the width of the image for linear array probes by pressing the angle key. There are two reductions in image width available from the "wide screen", 160 scan lines setting. Smaller widths result in a higher frame rate and a reduced number of scan lines. The 160 scan line setting has a frame rate of 24 Hz, the 120 scan line setting's frame rate is 33 Hz, and that of the 80 scan line setting, 49 Hz.

B mode: The 5 MHz linear array transducer contains 79 piezoelectric elements and these can be pulsed in various combinations to produce a maximum of 160 scan lines, at a scan repetition rate of 24.4 Hz. Where fewer scan lines are used, the image width is reduced and the scan repetition rate is increased, as explained above.

M mode: The M mode setting has two rates, high and low speed. The pulse repetition rate for high speed M mode is 244 Hz and for low speed, 122 Hz.

In order to operate the scanner correctly it is important to note some key aspects of its behaviour. On power-up, its default settings are magnification one, focal zone two, and skin depth one. However, the angle (or image width setting) remains at the setting which was in operation when the machine was last switched off. When changing magnification, the scanner defaults to focal zone two, skin line one. In addition, when operating in M mode it is necessary to change magnification in B mode before selecting M mode. To provide guidance for the participating laboratories, the scanner's instruction manual was circulated together with the scanner itself. In some cases, it was necessary for NPL to provide guidance on operating the scanner, usually at the point where part one results had been made available. Where such advice was given this is noted later in this report.

8.2 Identifying the maximum output conditions

To characterise a diagnostic scanner in accordance with IEC 61157 it is necessary to identify, in each mode of operation, the scanner settings and measurement positions which generate the largest values for temporal-average power, the pulse-pressure-squared integral and the spatial-peak temporal-average intensity. At least two laboratories made use of published protocols (Henderson et al., 1993). In the case of the pulse-pressure-squared integral, this is measured at the central scan line. For the spatial-peak temporal-average intensity in B mode, the contribution from all scan lines at the central scan line position is required.

NPL made an initial attempt to identify these maximum settings using our NPL Beam Calibrator. However, it was found that the peak-positive acoustic pressures which could be generated by the scanner at some settings exceeded the maximum value which our Beam Calibrator can measure (10 MPa). It was decided, therefore, at these high output settings, to rely on single-element hydrophone measurements in the NPL beam plotting facility.

8.3 Maximum output conditions reported by participating laboratories at the end of part one measurements

At the end of the first stage of their measurements on the check source and scanner each laboratory was asked to report those scanner settings which in its view gave maximum acoustic output for pulse-pressure-squared integral and spatial-peak temporal average intensity. These results are summarised separately for B and M mode in the following four tables 2, 3, 4 and 5. Where laboratories submitted amended part one reports this has been identified by the number 1 and 2 in the tables. If a laboratory submitted a range of settings apparently identical in acoustic output at stage one, these have been accommodated on one line of the table where possible. If this has not been possible additional lines have been used but these are not identified with numbers as they all relate to the same part one report. In any case where the part one results report has been ambiguous (especially for settings reported under the heading "Other"), the reports have been interpreted in the light of known information about the operation of the scanner and of the detailed results reported in participants' measurement reports.

Laboratory	SETTINGS: B MODE maximum pulse-pressure-squared integral				
	Magnification	Focal zone	Skin line	Other	Distance/mm
A	1	2	1	-	51.52
B	1	1	1 & 2	160 lines	23.4
C	3	1	1	-	27 & 41.5
D	3	1	1	-	23.3
E	3	1	1	80	26.2
F	3	2	2 to 4	160 lines	37 to 38.5
G	2	2	2	120 lines	38.4
H	2	2	1	-	37
J	2	1	1 & 2	80 lines	25.8
	3	1	1 to 4	80 lines	25.8
K (1)	3	2	4	scan line 42	38.7
K (2)	3	2	1 to 4	80 lines	38.8
	2	2	1 & 2	80 lines	38.8

Table 2: Dynamic Imaging scanner settings for B-mode maximum pulse-pressure-squared integral as reported by participating laboratories

Laboratory	SETTINGS: B MODE maximum spatial-peak temporal-average intensity				
	Magnification	Focal zone	Skin line	Other	Distance/mm
A	1	2	1	-	51.52
B	1	1	1 & 2	160 lines	23.4
C	3	1	1	-	27 & 41.5
D	3	1	1	80 lines	23.3
E	3	1	1	80 lines	26.2
F	1	3	1	80 lines	28-32
	1.5	3	4	80 lines	30
	1.5	2	4	80 lines	26
G	1	3	1	120 lines	30
H (1)	1.5	2	1	80 lines	33
H (2)	1.5	3	1	80 lines	33
J	1 & 1.5	3	1 to 4	80 lines	31
K (1)	1	3	4	-	32
K (2)	1	3	3 & 4	80 lines	32
	2 & 3	3	4	80 lines	32

Table 3: Dynamic Imaging scanner settings for B-mode spatial-peak temporal-average intensity as reported by participating laboratories

Laboratory	SETTINGS: M mode maximum pulse-pressure-squared integral				
	Magnification	Focal zone	Skin line	Other	Distance/mm
A	1	2	1	-	54.95
B	1	1	1	High speed	20.7
C	3	1 & 2	1	High speed	27 & 41.5
D	3	1	1	-	25.7
E	3	2	1	High speed	37.5
F	3	2	2 to 4	High speed	37.5 to 38
G	2	2	2	High speed	38.4
H (1 & 2)	2	2	1	High speed	37
J	2	2	1 & 2	High speed	36.5
	3	2	1 to 4	High speed	36.5
K (1)	no effect	1	1	-	25.5
K (2)	3	2	1 to 4	High speed	38.8
	2	2	1 & 2	High speed	38.8

Table 4: Dynamic Imaging scanner settings for M-mode maximum pulse-pressure-squared integral as reported by participating laboratories

Laboratory	SETTINGS: M mode maximum spatial-peak temporal average intensity				
	Magnification	Focal zone	Skin line	Other	Distance/mm
A	1	2	1	-	54.95
B	1	1	1	High speed	20.7
C	3	1 & 2	1	High speed	27 & 41.5
D	3	1	1	High speed	25.7
E	3	2	1	High speed	37.5
F	3	2	2 to 4	High speed	37.5 to 38
G	2	2	2	High speed	38.4
H (1 & 2)	2	2	1	High speed	37
J	2	2	1 & 2	High speed	36.5
	3	2	1 to 4	High speed	36.5
K (1)	no effect	1	1	High speed	25.5
K (2)	3	2	4	High speed	38.8

Table 5: Dynamic Imaging scanner settings for M-mode spatial-peak temporal-average intensity as reported by participating laboratories

As noted earlier, the scanner produces apparently identical acoustic outputs at a number of settings, and the fact that laboratories report different settings for the various maximum output requirements does not mean that they have not located the maximum output conditions in a particular case. Random factors such as the order in which settings were investigated, slight variations in set-up conditions from day to day and the length of time between switching on the scanner and beginning measurements will all contribute to measured differences between settings which have very similar or identical acoustic outputs.

It seems that in practice magnifications 1 and 1.5 behave in a similar way, as do magnifications 2 and 3. This has been confirmed by the manufacturers, Dynamic Imaging. In M mode maximum pulse-pressure-squared integral and spatial-peak temporal-average intensity can be found in magnifications 2 and 3, as is also the case for B-mode maximum pulse-pressure-squared integral. Spatial-peak temporal-average intensity and maximum power in B mode occur in magnifications 1 and 1.5.

Some laboratories reported difficulties in operating the scanner or difficulties became apparent when the part one results were reported. For example, laboratory H reported problems in varying the focal zone independently of magnification at the time they submitted their part one results. Once this difficulty had been resolved, they repeated some measurements and submitted a revised part one report. As a result, tables 2 to 5 show two sets of results for laboratory H, where the results before resolving the focal zone issue are labelled 1 and those after successful resolution of the problem are labelled 2. In fact, for laboratory H in tables 2, 4 and 5 there is no difference between sets

1 and 2, the only difference being in table 3, B-mode maximum spatial-peak temporal-average intensity. A similar problem arose with laboratory K, who initially reported that it was not possible to vary the magnification in M mode. Following advice from NPL, they also repeated measurements and submitted a revised part one report. These are again labelled 1 and 2 in tables 2 to 5. In our experience, it seems to be the case that the only way in which magnification in M mode can be altered is to carry out the change in B mode and then enter M mode. In this way, the B mode magnification is retained in M mode. Laboratory B also reported at stage one that they were unable to vary magnifications in M mode. After the problem had been clarified, they proceeded directly to the part two measurements without submitting revised part one results.

In the case of laboratory A, no data were provided in the part one results for spatial-peak temporal-average intensity in either B or M mode. Laboratory A advised NPL that they operated on the assumption that maximum pulse-pressure-squared integral and spatial-peak temporal-average intensity would be found at the same scanner settings, and, in addition, that in both B and M mode the maximum pulse-pressure-squared integral had been found at the scanner's power-up settings. Their part one results as reported in tables 2 to 5 have been modified to take account of this information, so that these tables include settings for maximum spatial-peak temporal-average intensity in both B and M mode.

8.4 Instructions for part two measurements

For the second stage of the project all participating laboratories were asked to report the results of their measurements at the maximum acoustic output settings as identified at the end of their stage one work. In addition, they were asked to perform measurements at settings nominated by NPL. As has been pointed out, a number of scanner settings appear to generate identical acoustic outputs and a request to make measurements at NPL-nominated settings does not imply that any participating laboratory had failed to find maximum output settings. In addition, NPL was trying to establish whether B-mode measured spatial-peak temporal-average intensities were directly proportional to the number of scan lines used for imaging, so that most laboratories were asked to investigate a particular combination of magnification, focal zone and skin depth at both 80 and 120 scan lines settings for this acoustic parameter. Laboratories which reported one of NPL's candidate settings for spatial-peak temporal-average intensity in B mode were asked to measure at an alternative maximum output setting.

The next two sections of this report set out the results of the measurements at the maximum acoustic output settings of the Dynamic Imaging scanner. Section nine summarises each laboratory's results at the settings reported in part one of the project (tables 2 to 5 above). Section ten sets out results for each laboratory at NPL's nominated settings.

9. MEASUREMENTS AT PART ONE SETTINGS

This section presents the results of measurements by each laboratory for the maximum pulse-pressure-squared integral and maximum spatial-peak temporal-average intensity settings notified in the part one reports (tables 2 to 5) for both B and M mode. NPL's measurements are included in this section of the report. The main results are tabulated here and also presented graphically in the same manner as was employed for the check source results in section seven.

9.1 B-mode measurements at part one settings

Tables 6a and 6b give B mode results at the part one settings for all laboratories. Laboratory H submitted two sets of results, one (set 1) relating to measurements made before they had discovered how to vary the focal zone independently and the other (set 2) after. Laboratory C also provided two sets of results. Set 1 is for scan line 39 on the 160 scan line setting and set 2 is for scan line 19 on the 80 scan line setting. Owing to limitations in digitiser performance, data from laboratory C for spatial-peak temporal-average intensity relate to a single scan line only. In the tables a single asterisk (*) indicates an item which was not measured or reported by a particular laboratory. Two asterisks (**) indicate a case in which random uncertainties only were reported. (See section 9.1.2 below.). Three asterisks (***) indicate a value determined from a single scan line only.

9.1.1. Measurement apparatus employed for measurements on scanner

In general, laboratories employed the same hydrophones and amplifiers, and radiation force balances, for the measurements on the scanner as they had used for the check source and full details are given in section 7.1 of this report. Listed below are those cases in which a laboratory used a different method or different equipment from the check source apparatus. In the cases where no information is provided, both reference devices were measured using the same apparatus.

Laboratory C

For the power measurements on the Dynamic Imaging scanner a Mettler AT250 semi-micro balance was employed with a 110 mm diameter absorbing target.

Laboratory D

Same hydrophone used as for check source, but a locally manufactured 1 mm diameter pvdf needle probe hydrophone was employed for measurement of the scanner's output beam dimensions.

Laboratory F

A 0.2 mm diameter active element, 9 μm thickness bilaminar hydrophone was employed for the scanner measurements with the same wideband amplifier as was employed with the check source. The scanner's power output was measured using a radiation force balance (absorbing target for B mode and reflecting target for M mode).

Laboratory H

An NPL beam calibrator was used for measurements on both check source and scanner; a locally manufactured pvdf needle probe hydrophone was employed for measurement of the scanner's output beam dimensions.

Laboratory J

Same hydrophone as for check source (0.5 mm active element, 25 μm thickness bilaminar membrane), but changed amplifier to NPL type 55641, 0 dB gain.

Laboratory K

Check source power measurement was performed by planar scanning, but scanner power measurement was carried out using a radiation force balance with an absorbing target. This was a Sartorius analytical balance 1702 with 0.1 mg resolution, and an absorbing rubber-based target of diameter 60 mm and thickness 20 mm. Transducer-target separation was approximately 5mm.

9.1.2 Measurement uncertainties

The uncertainties quoted for the data in the tables are the 95% confidence interval uncertainties as determined or suggested by the laboratory in their report. In some cases, laboratories reported that for systematic uncertainties (and occasionally for typical random uncertainties), they had followed the guidance set out in Preston, Bacon and Smith (1988). Where this was the case, the uncertainty values from this paper have been incorporated into the results.

Two laboratories employed an NPL beam calibrator and reported uncertainties derived from repeat measurements and the beam calibrator's built-in software. The operation of the beam calibrator is described in Preston (1988) and discussion of systematic uncertainties associated with beam calibrator measurements can be found in that paper.

If no uncertainties are quoted for a particular result given in tables 6a and 6b, this means that no uncertainty was quoted by the laboratory, or that no

guidance was provided in the laboratory's report as to how typical measurement uncertainties might be derived.

TABLE 6a: B MODE OWN SETTINGS		A	B	C(1)	C(2)	D	E
	Units						
Temporal-average power	mW	*	*	70.4 ($\pm 5\%$)	70.4 ($\pm 5\%$)	31.7	24.5 ($\pm 41.26\%$)
Peak-negative acoustic pressure (max)	MPa						
Peak-negative acoustic pressure (at max p.p.s.i)	MPa	2.7 ($\pm 17\%$)	3.75 ($\pm 17\%$)	4.083 ($\pm 11\%$)	3.9 ($\pm 11\%$)	3.73 ($\pm 2\%$)**	4.2 ($\pm 11.15\%$)
Output beam intensity	mW cm ⁻²	*	*	*	*	21.4	40.0 ($\pm 42.03\%$)
Spatial-peak temporal-average intensity	mW cm ⁻²	22 ($\pm 35\%$)	15.1 ($\pm 34\%$)	7.02 ($\pm 24\%$)***	12.83 ($\pm 24\%$)***		
Scanner settings for above values							
Power: magnification				1	1		
focal zone				3	3		
skin line				1	1		
no. of scan lines				160	160		
Max p.p.s.i: magnification		1	1	3	3	3	3
focal zone		2	1	1	1	1	1
skin line		1	1 & 2	1	1	1	1
Max I _{spta} : magnification		1	1	3	3	3	3
focal zone		2	1	1	1	1	1
skin line		1	1 & 2	1	1	1	1
no. of scan lines		120	160	160	80	80	80
Location of max. pulse-pressure-squared integral:	mm	52	23.4 ($\pm 1.3\%$)	26.7 ($\pm 1\%$)	26.7 ($\pm 1\%$)	23.3	26.2
- 6 dB beam width: parallel	mm	1.9 ($\pm 5\%$)	0.94 ($\pm 21\%$)	1.1 ($\pm 4\%$)	1 ($\pm 4\%$)	1.1	0.99 ($\pm 1\%$)
perpendicular	mm	4.9 ($\pm 5\%$)	2.63 ($\pm 8\%$)	2.7 ($\pm 4\%$)	2.3 ($\pm 4\%$)	3.2	2.16 ($\pm 1\%$)
Scan repetition rate: 80/120/160 lines	Hz	32.6(120)	24.41 (160)	24.4	48.8	49 (80)	48.8 (80)
Output beam dimensions: parallel	mm	85 ($\pm 5\%$)	*	18 ($\pm 4\%$)	18.5 ($\pm 4\%$)	18.5	8.03 ($\pm 4\%$)
perpendicular	mm	12.5 ($\pm 5\%$)	*	9 ($\pm 4\%$)	9 ($\pm 4\%$)	8	7.71 ($\pm 4\%$)
Acoustic working frequency	MHz	3	3.14	3.1 ($\pm 0.3\%$)	3.09 ($\pm 0.3\%$)	3.06	3.1 ($\pm 1\%$)
Bandwidth of acoustic waveform	MHz	1.1	12	0.93	0.85	1	1 ($\pm 1\%$)
Number of scan lines in a repetition period			160 at 24 Hz	160			
		120 at 33 Hz					
					80	80 at 49 Hz	80 at 49 Hz
Scan line separation	mm	0.5	*	*	*	0.5	0.4 ($\pm 1\%$)
Transducer-hydrophone separation: max p.p.s.i	mm	52	23.4	26.7 ($\pm 1\%$)	26.7 ($\pm 1\%$)	23.3	26.2
max p.	mm						
max I _{spta}	mm	52	23.4	26.7 ($\pm 1\%$)	26.7 ($\pm 1\%$)	23.3	26.2
Water temperature during measurements	°C		22.67 ($\pm 0.2\%$)	21 ($\pm 1\%$)	21.8 ($\pm 0.9\%$)	20.4 ($\pm 2.5\%$)	20 ($\pm 1\%$)

Table 6a: B-mode measurements at maximum output settings reported by laboratories A to E at end of part one of project (* data not provided; ** random uncertainties only; * value determined for a single scan line only).**

TABLE 6b: B MODE OWN SETTINGS		F	G	H(1)	H(2)	J	K
	Units						
Temporal-average power	mW	60.4 ($\pm 8\%$)	65 ($\pm 12.1\%$)	50.1 ($\pm 9\%$)	56.6 ($\pm 9\%$)	62.4 ($\pm 11\%$)	59 ($\pm 19\%$)
Peak-negative acoustic pressure (max)	MPa	4.45 ($\pm 9\%$)	4.7 ($\pm 11.2\%$)	-			
Peak-negative acoustic pressure (at max p.p.s.i)	MPa	4.2 ($\pm 9\%$)	4.3 ($\pm 11.2\%$)	4.22 ($\pm 12\%$)	4.3 ($\pm 12\%$)	4.73 ($\pm 7\%$)	4.047 ($\pm 24\%$)
Output beam intensity	mW cm ⁻²	33.1 ($\pm 25\%$)	23 ($\pm 23.1\%$)	22 ($\pm 11\%$)	24 ($\pm 11\%$)	43.1 ($\pm 11\%$)	24 ($\pm 25\%$)
Spatial-peak temporal-average intensity	mW cm ⁻²	123 ($\pm 25\%$)	121 ($\pm 23.1\%$)	89.8 ($\pm 27\%$)	100.7 ($\pm 27\%$)	106 ($\pm 17\%$)	93 ($\pm 47\%$)
Scanner settings for above values							
Power: magnification		1	1	-		1	1
focal zone		3	2	-		3	3
skin line		1	3	-		1	4
no. of scan lines		120	120			160	120
Max p.p.s.i: magnification		3	2	2		3	3
focal zone		2	2	2		1	2
skin line		2 to 4	2	1		1	4
Max I _{spk} : magnification		1	1	1.5	1.5	1	1
focal zone		3	3	2	3	3	3
skin line		1	1	1	4	1	4
no. of scan lines		80	120	80	80	80	80
Location of max. pulse-pressure-squared integral:	mm	38	38.4	37	37	26.71 ($\pm 1\%$)	39 ($\pm 15\%$)
- 6 dB beam width: parallel	mm	0.88 ($\pm 5\%$)	0.9 ($\pm 4.7\%$)	1.39 ($\pm 19\%$)		0.95 ($\pm 1.8\%$)	1 ($\pm 10\%$)
perpendicular	mm	1.81 ($\pm 5\%$)	1.9 ($\pm 4.7\%$)	2.20 ($\pm 19\%$)		2.288 ($\pm 1.3\%$)	2 ($\pm 5\%$)
Scan repetition rate: 80/120/160 lines	Hz	24.4/32.6/48.8	32.6 [120]	48.8	48.8	48.8/32.6/24.4	48.8 (80)
Output beam dimensions: parallel	mm	24 ($\pm 5\%$)	26.0 ($\pm 4.7\%$)	26.9 ($\pm 19\%$)		19.01 ($\pm 0.4\%$)	27.0 ($\pm 10\%$)
perpendicular	mm	7.3 ($\pm 5\%$)	8.9 ($\pm 4.7\%$)	8.6 ($\pm 19\%$)		7.61 ($\pm 1.6\%$)	9.0 ($\pm 10\%$)
Acoustic working frequency	MHz	3.1 ($\pm 1\%$)	3.01 ($\pm 1\%$)	3.17	3.19	3.064 ($\pm 1\%$)	3.0 ($\pm 7\%$)
Bandwidth of acoustic waveform	MHz	0.98 ($\pm 1\%$)	0.82 ($\pm 2\%$)	0.8	0.8	1.062 ($\pm 3\%$)	0.9 ($\pm 17\%$)
Number of scan lines in a repetition period		160 at 24 Hz					160 at 24 Hz
		120 at 33 Hz	120				120 at 33 Hz
		80 at 49 Hz		80		80	80 at 49 Hz
Scan line separation	mm	0.5	0.5	0.49	0.49	0.492 ($\pm 2.4\%$)	0.5 ($\pm 20\%$)
Transducer-hydrophone separation: max p.p.s.i	mm	38	38.4	37	37	26.71	38.8
max p.	mm	34	34.8				
max I _{spk}	mm	30	30.0	33	30	31.47	32
Water temperature during measurements	°C	20 $\pm$ 1	20 $\pm$ 1	20.5	20.5	22.94 $\pm$ 0.13	21.5 ($\pm 9\%$)

Table 6b: B-mode measurements at maximum output settings reported by laboratories F to K at end of part one of project (* data not provided; ** random uncertainties only).

9.2 Detailed analysis of B-mode part one results

In this section, some of the key results set out in tables 6a and 6b will be considered in more detail. We shall concentrate on numerical results for the main acoustic parameters required by the IEC 61157 standard. In the case of the check source results, means and standard deviations of each parameter as determined from the complete set of 10 reported values were given. For the Dynamic Imaging scanner, it appears that such an approach is not appropriate. It will be seen that there are a range of candidate scanner settings for maximum acoustic output and that for some acoustic parameters the spread of reported values is so great that a mean may be misleading. In the view of the author it would not be helpful to interpretation of the results to omit outlying values from determination of the mean. Furthermore, the aim of the project is not to come to an agreed view as to the “true” value of the maximum acoustic output values but to allow evaluation of laboratories’ interpretation of IEC 61157 and to provide useful experience for the participating laboratories in applying this standard.

9.2.1. Temporal-average power

IEC 61157 requires that the maximum temporal-average power shall be declared (section 4.2.2 (a)) and that for scanning modes this shall be the total power output of all the acoustic pulses. To meet this requirement, the most direct measurement technique is one based on radiation force. Guidance on ultrasonic power measurements in liquids in the frequency range from 0.5 MHz to 25 MHz is given in IEC 61161, *Ultrasonic power measurements in liquids in the frequency range 0.5 MHz to 25 MHz*, and this standard is required to be read and implemented in conjunction with IEC 61157.

IEC 61157 also recognises that the maximum temporal-average power (and consequently the output beam intensity) may occur at different system settings than those for peak-negative acoustic pressure and spatial-peak temporal-average intensity. In such a case, the corresponding system settings for maximum power and output beam intensity may be given in a separate footnote. In the light of this, the measurement protocol for this project did not require participating laboratories specifically to declare the system settings for maximum power. However, some laboratories did decide to include such information in their report and where this has been done the settings are reported in tables 6a and 6b. In other cases, it is reasonable to assume that laboratories found that the maximum power values occurred at the same settings as they reported for spatial-peak temporal-average intensity. However, tables 6a and 6b only report separate settings for maximum power when these data have actually been included as an independent item in that laboratory’s report.

Figure 9 summarises the values of maximum temporal-average power determined by each laboratory, with the associated 95% confidence intervals displayed as error bars. Laboratory A did not report power values for the

scanner. Laboratory B reported a value of 0.0779 mW ($\pm 34\%$) and this is too small to be displayed clearly on the same scale as the other results. It is understood that this difference arises because the data from this laboratory relate only to a single scan line rather than the total number of scan lines as required by IEC 61157. Note that two data sets are given for laboratories C and H as explained in section 9.1 above.

It can be seen from the scanner settings reported in tables 6a and 6b, both for maximum power and spatial-peak temporal-average intensity (where these data can be used to deduce power settings), that maximum power can be found at either magnification 1 or 1.5, but that settings for focal zone, skin lines and frame rate (or number of scan lines) vary from laboratory to laboratory. This is consistent with the findings of NPL that there seem to be a range of candidate settings for maximum power and maximum spatial-peak temporal-average intensity, and that within experimental uncertainties it can be difficult to separate out a specific setting as being substantially higher in output than others.

9.2.2 Peak-negative acoustic pressure

IEC 61157 (section 4.2.2 (b)) requires the declaration of the peak-negative acoustic pressure in the plane perpendicular to the beam axis which contains the maximum pulse-pressure-squared integral. However, the value of the maximum pulse-pressure-squared integral is not itself declared. It should also be noted that this value of peak-negative acoustic pressure may not, in fact, be the maximum for the whole field, given the requirement to measure in the plane of the maximum pulse-pressure-squared integral. Where laboratories have reported, for the sake of completeness, the maximum peak-negative acoustic pressure in the whole field this information is included in tables 6a and 6b but these results are not analysed in this section of the report.

Where the system settings which deliver maximum pulse-pressure-squared integral (and therefore peak-negative acoustic pressure) differ from those which produce maximum spatial-peak temporal-average intensity, IEC 61157 specifies that peak-negative acoustic pressure should also be specified for the settings which produce the highest spatial-peak temporal-average intensity. To limit the amount of work requested from participating laboratories, the measurement protocol did not ask for a separate measurement of peak-negative acoustic pressure at the maximum spatial-peak temporal-average intensity settings.

Figure 10 sets out the B-mode peak-negative acoustic pressure results for the participating laboratories own settings, as determined in part one of the project. Most laboratories produced peak-negative acoustic pressure values in the range from 3.7 to 4.7 MPa, and the quoted uncertainties show substantial overlap. It is likely that the differences between laboratories reflect differences in hydrophone calibration accuracy and in the determination of the position and settings for maximum pulse-pressure-squared integral. These differences can be seen in the results given in tables 6a and 6b. As explained earlier in

this report a number of settings (combinations of magnification, focal zone and skin line) appear to produce virtually identical acoustic outputs in magnifications 2 and 3. NPL's investigations suggest the maximum peak-negative acoustic pressure in the whole field does not occur in the plane of the maximum pulse-pressure-squared integral ; in addition maximum pulse-pressure-squared integral at some settings (particularly in focal zone 2 and magnifications 2 and 3) varies quite slowly with axial position so that clear identification of the plane in which the maximum lies can be problematic. In any series of measurements which take place over a long period of time, random variations arising from re-positioning transducers and hydrophones, warm-up times, electrical noise and pick-up can contribute to apparent measured differences between settings which are in fact very similar in acoustic output. However, it does appear that in the case of laboratory A the results for peak-negative acoustic pressure lie substantially outside the range of those reported by other laboratories.

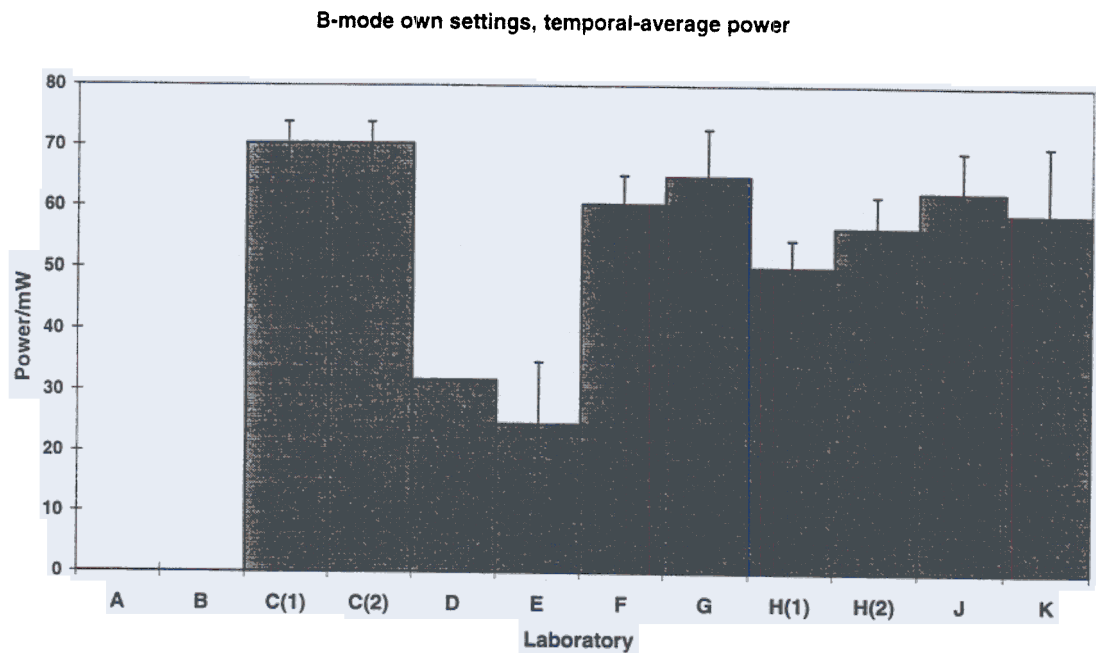


Figure 9: B-mode maximum temporal-average power, participating laboratories' own settings, 95% confidence interval uncertainties where reported by laboratory

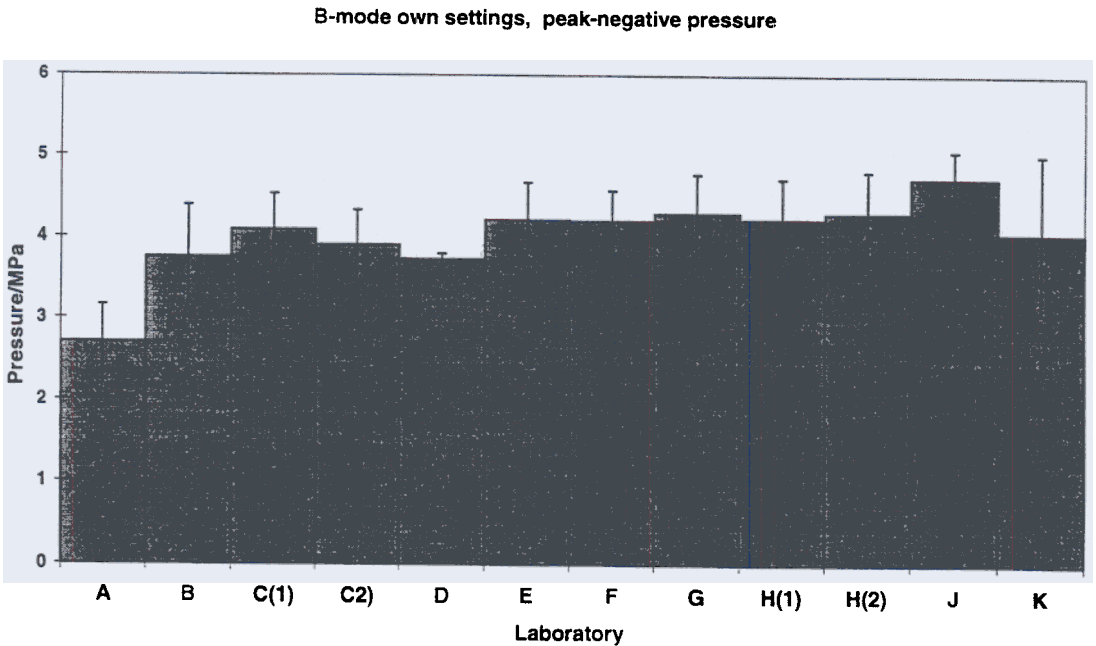


Figure 10: B-mode maximum peak-negative acoustic pressure, participating laboratories' own settings, 95% confidence interval uncertainties (except D random uncertainties only)

9.2.3 Spatial-peak temporal-average intensity

The spatial-peak temporal-average intensity, as the name implies, is the peak value of the time-averaged intensity for the whole ultrasound field. For scanning modes, IEC 61157 requires that this shall be determined for the central scan line and include contributions from overlapping scan lines in accordance with the IEC 1102 standard, *Measurement and characterization of ultrasonic fields using hydrophones in the frequency range 0.5 MHz to 15 MHz*. This can be a challenging experimental task, especially where there are a large number of overlapping scan lines and many modes of operation to be investigated. The situation is made more complicated for the Dynamic Imaging scanner by the fact that there are three separate scan frame rates: 24 Hz, 33 Hz and 49 Hz, comprising 160, 120 and 80 scan lines respectively. Even recognising this fact can pose problems. The scanner's keyboard does not identify specifically how one changes the frame rate for a linear array probe of the kind used in this study. It requires careful perusal of the accompanying manual in order to discover that the 90°/60° control, apparently only appropriate to sector scanners, can change the frame rate for linear arrays. In addition, there is no default frame rate setting, so that the scanner powers up at whichever frame rate it was set when it was last used. It is, in fact, possible that the scanner's control software and hardware may contain a fault. When the scanner was tested by NPL during the early stages of the project, it appeared that we could only obtain the 160 scan line and 120 scan line settings, and our initial measurements of spatial-peak temporal-average intensity concentrated on the 120 scan line setting. We later found that we could achieve 80 scan lines and, as far as we are aware, the problem did not arise for any of the other participating laboratories. When we identified this difficulty we contacted Dynamic Imaging for their advice and they suggested that the scanner be serviced. However, to do so would have severely prejudiced the time scale for completion of the project and invalidated measurements already made on the scanner. Now that the project has been completed, servicing of the scanner is recommended before it is used again.

Figure 11 summarises the results. Laboratories F to J show good agreement, with the peak values being found at similar magnifications (1 and 1.5) and similar distances from the transducer, 28 mm to 33 mm, even though for one laboratory the results are for 120 scan lines, rather than 80. Once again, this parameter is one where NPL found a range of candidate settings and transducer-to-hydrophone distances within the range quoted above which all gave very similar results, and it is not possible to make an unequivocal choice of maximum output setting. In the case of the other laboratories, especially where quoted values are much lower, it is possible that the contribution from overlapping scan lines has not been evaluated or has been evaluated incorrectly. One measurement problem which arises for determination of spatial-peak temporal-average intensity in B mode is exactly how many scan lines to measure. If a large number of lines overlap at the measurement point it may prove impracticable to measure each one separately and interpolated values may be used for those scan lines which have not been measured. This process can itself contribute to measurement uncertainties. Owing to lack of

experience, laboratory D did not include contributions from overlapping scan lines when it was attempting to locate the settings for spatial-peak temporal-average intensity during the part one stage of their work.

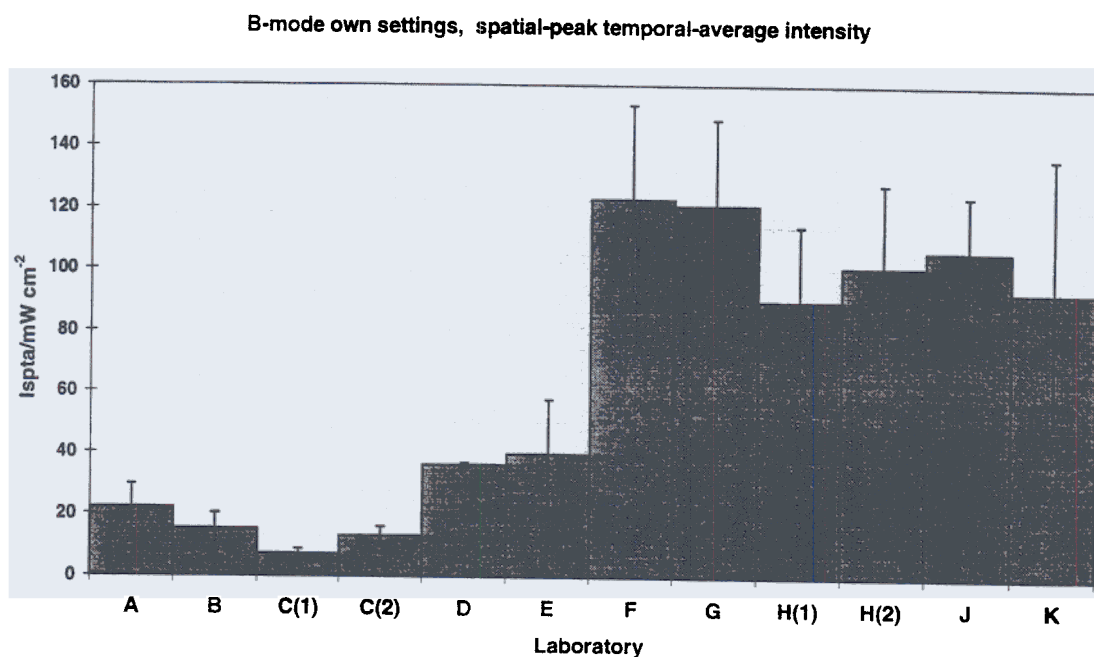


Figure 11: B-mode spatial-peak temporal-average intensity, participating laboratories' own settings, 95% confidence interval uncertainties (except D, random uncertainties only)

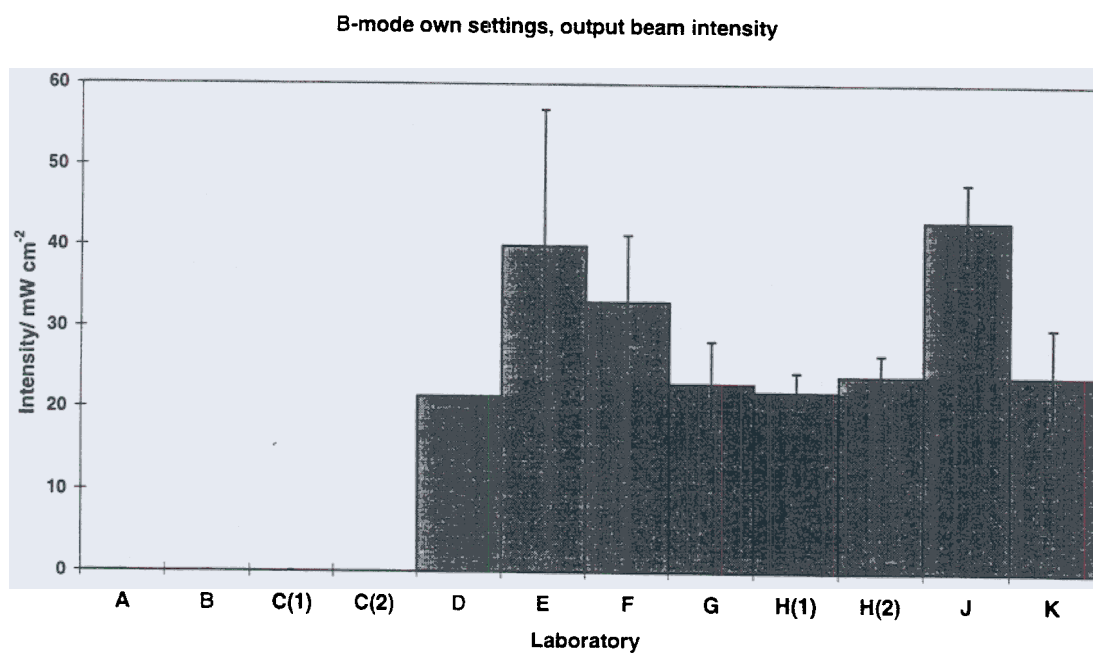


Figure 12: B-mode output beam intensity, participating laboratories' own settings, 95% confidence interval uncertainties where reported by laboratory

9.2.4 Output beam intensity

The output beam intensity is a parameter which has to be calculated from two separate measurements. IEC 61157 in section 3.15 defines the output beam intensity as the temporal-average power divided by the output beam area, where the output beam area is the area of the ultrasonic beam derived from the output beam dimensions. The output beam dimensions are themselves obtained from measurements of the -6 dB beam-width at the transducer output face, where the beam-width in question is derived from plots of pulse-pressure-squared integral values normal to the beam alignment axis. In addition, IEC 61157, in section 4.2.2 (i), points out that in scanning modes the output beam dimensions shall refer to the central scan line only, but that in many cases, especially contact systems (as applies to the Dynamic Imaging scanner), these dimensions may be taken as the geometrical dimensions of the ultrasonic transducer or ultrasonic transducer element group. Laboratory B employed the -6 dB beam-width in the plane of maximum pulse-pressure-squared integral for its calculation of output beam intensity and its results for output beam dimensions and output beam intensity have been excluded from the results, being marked as not measured in order not to mislead readers of this report.

Measurements close to the face of a linear array probe of the kind employed in this study can be difficult with membrane hydrophones of the single-element and multi-element types. It is easier to measure output beam dimensions with a probe hydrophone. In at least one case (laboratory A) it appears that the output beam dimensions were obtained from the transducer geometry, as allowed by IEC 61157. As a result, variations in output beam intensity values between participating laboratories will arise not only from differences in total power measured but in the manner and accuracy of the determination of output beam dimensions. In this part of the report, separate plots of results for output beam dimensions will not be presented and the interested reader is referred to tables 6a and 6b. Figure 12 sets out the results of the measurements of output beam intensity, where these have been reported by the laboratory in question and the figure should be interpreted in the light of the comments made above, especially those relating to the difficulty of measuring output beam dimensions.

9.2.5 -6 dB beam-width

The IEC 61157 standard requires the -6 dB pulse beam-width to be declared at the point of maximum pulse-pressure-squared integral. If the beam-widths in different directions differ by more than 10% of the maximum beam-width, the beam-width in two orthogonal directions must be specified, these being parallel and perpendicular to the reference direction (section 4.2.2.(g)). For scanning modes the beam-widths are reported for the central scan line only. The reference direction is itself defined in section 3.19 for scanning modes as the direction normal to the beam-alignment axis for an ultrasonic scan line and in the scan plane. In this section two figures are presented, one for the -6 dB beam-width parallel to the reference direction and the other perpendicular.

Figure 13 presents the -6 dB beam-width parallel direction results, and figure 14 gives the perpendicular direction results. It appears that there is close correlation between the two figures. If a laboratory obtains a high figure for its parallel beam-width then its perpendicular beam-width result is also high. In the case of laboratory A the broader reported beam-width may reflect the lower peak-negative acoustic pressure reported by this laboratory.

9.2.6 Acoustic working frequency

The final set of results from tables 6a and 6b to be presented graphically in this section of the report is that for the acoustic working frequency of the scanner. This is required information in IEC 61157 and is defined in section 4.2.2.(j) as the arithmetic-mean acoustic-working frequency measured by a hydrophone placed at the point of maximum pulse-pressure-squared integral. Section 3.30 of the standard defines this frequency as the arithmetic mean of the two frequencies at which the amplitude of the spectrum of the acoustic signal at the measurement position first becomes 3 dB lower than the peak amplitude. The bandwidth is not a required parameter in IEC 61157 but may be requested as background information. For this project, we decided to ask participants to declare the bandwidth in addition to the acoustic working frequency as in our view this represented very little additional work.

Figure 15 shows the acoustic working frequency results for each laboratory, with 95% confidence uncertainties where these were reported. It should be noted that nominally the transducer in question is a 5 MHz linear array but that its working frequency is close to 3 MHz.

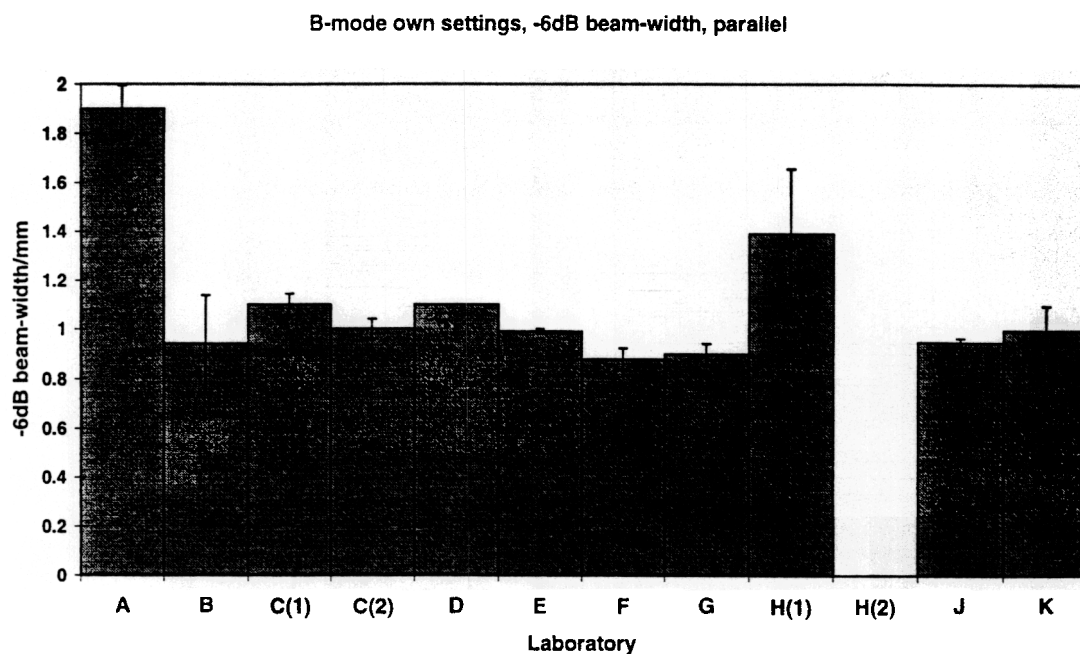


Figure 13: B-mode -6 dB beam-width parallel to reference direction, participating laboratories' own settings, 95% confidence interval uncertainties where reported by laboratory

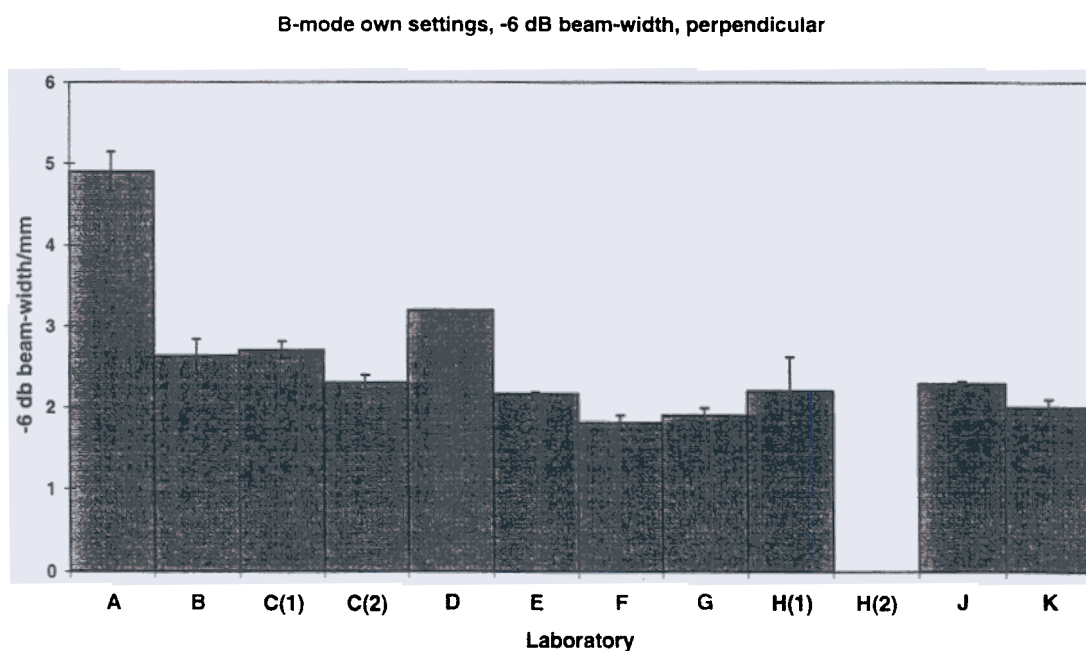


Figure 14: B-mode -6 dB beam-width perpendicular to reference direction, participating laboratories' own settings, 95% confidence interval uncertainties where reported by laboratory

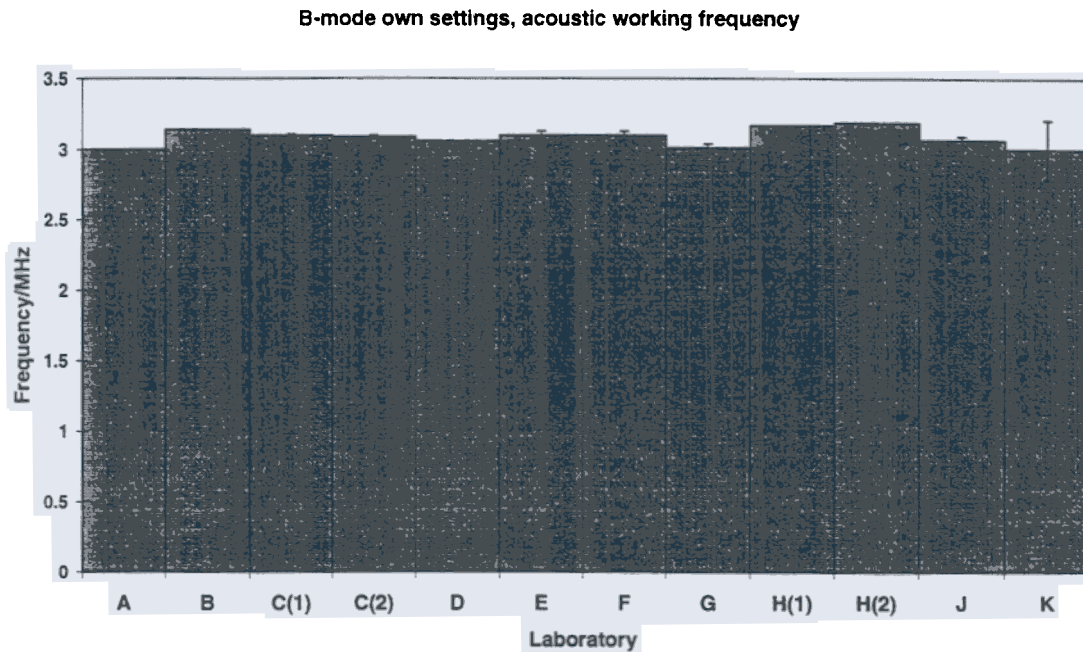


Figure 15: B-mode acoustic working frequency, participating laboratories' own settings, 95% confidence interval uncertainties where reported by laboratory

9.2.7 Other results

Other points to note from the results set out in table 6a and 6b are that those laboratories which found the maximum pulse-pressure-squared integral to be in focal zone 2 of magnifications 2 and 3 reported transducer-to-hydrophone separation in the range from 36 mm to 39 mm, whereas those who found it in focal zone 1 at the same magnifications reported distances of approximately 27 mm. The distance from the transducer face to the point of maximum pulse-pressure-squared integral is a parameter which is required to be declared by section 4.3.3.(f) of IEC 61157, as is the distance to the point of maximum spatial-peak temporal-average intensity if this is different from the maximum pulse-pressure-squared integral distance. All except one laboratory reported positions for spatial-peak temporal-average intensity in the range from 23 to 33 mm from the transducer face.

For scanning modes the ultrasonic scan line separation at the point of maximum pulse-pressure-squared integral is information which may be provided on request in accordance with IEC 61157 section 4.2.3.2.(b). This separation is defined as the distance between the points of intersection of two specified consecutive ultrasonic scan lines of the same type in the plane of measurement. Those laboratories which reported this parameter all produced values of 0.5 mm within measurement uncertainties.

10. M-MODE RESULTS AT LABORATORIES' OWN SETTINGS

This section of the report sets out the results of each laboratory's M-mode measurements at the settings they identified in the part one reports. The structure of this section follows that of section nine of the report, where results are presented in tabular form, followed by graphs relating to key acoustic parameters. Definitions of IEC 61157 requirements which are common to both M and B modes will not be repeated here. In addition, it should be noted that in order to keep the amount of work required from participating laboratories within reasonable limits, the measurement protocol did not ask for measurements in combined B and M mode.

M-mode measurements present a simpler measurement task than characterising a scanning mode such as B mode. In M mode one has what is essentially a one-dimensional imaging system in which each pulse of ultrasound is emitted in the same direction. Depth is displayed on one axis and reflected amplitude is used to modulate image brightness. Images from successive acoustic pulses are stacked to give a display of position against time. Thus the clinician can study the motion of a particular feature as a function of time. Making M-mode measurements is thus analogous to making measurements on a single-element transducer.

Tables 7a and 7b set out each participating laboratory's results, with 95% confidence intervals for uncertainties, where these have been provided. In the case of M-mode, there are only single sets of results from each laboratory, unlike B-mode where two laboratories each appear twice in the results table. Laboratory D reported that their M-mode maximum settings found during part one were not located during the part two measurements. They are unsure whether this arose from instabilities in the scanner output or from a malfunctioning measurement program. The reported values are those found during the second set of measurements.

10.1 Graphical presentation of results for laboratories' M-mode measurements at their own part one settings

This section summarises the M-mode results for laboratories' own part one settings in graphical form. It presents plots for the same key acoustic parameters as were displayed in section nine of this report for B mode.

Figure 16 displays the M-mode maximum temporal-average power results. Measurement of powers as low as a few milliwatts from diagnostic equipment can present a challenging experimental task. However, all laboratories reported M-mode results with relatively low uncertainties. Where the participating laboratories specifically reported the settings which gave maximum M-mode power these have been included in tables 7a and 7b. These settings are very similar to those which produced maximum power in B-mode for this scanner.

The M-mode peak-negative acoustic pressures at the maximum pulse-pressure-squared integral are set out in figure 17. In general, the values follow

closely those determined in B-mode by each laboratory, in terms of absolute values, system settings and measurement positions

Figures 18 and 19 present the results for spatial-peak temporal-average intensity and output beam intensity respectively. In all cases, participating laboratories reported that the spatial-peak temporal-average intensity was found at the same settings and position as produced maximum pulse-pressure-squared integral in M-mode. Two laboratories did not report results for output beam intensity and laboratory B's results for output beam intensity have been excluded (as was the case for their B-mode results) because they employed the - 6 dB beam-width in the plane of maximum pulse-pressure-squared integral to derive the output beam intensity, rather than measurements close to the transducer face.

The -6dB beam-widths at the position of maximum pulse-pressure-squared integral are summarised in figure 20 (parallel) and figure 21 (perpendicular) and as expected, these results tend to follow the pattern observed in B-mode.

The final graphical result displayed in this section (figure 22) is for the arithmetic-mean acoustic working frequency in M-mode. In all cases the results follow very closely those reported by each laboratory for B-mode.

TABLE 7a: M MODE OWN SETTINGS		A	B	C	D	E
	Units					
Temporal-average power	mW	2 ($\pm$ 34%)	*	6.63 ($\pm$ 6.6%)	2.22	1.34 ($\pm$ 41.25%)
Peak-negative acoustic pressure (max)	MPa					-
Peak-negative acoustic pressure (at max p.p.s.i)	MPa	2.7 ($\pm$ 17%)	4.18 ($\pm$ 17%)	3.95 ($\pm$ 11%)	3.89 ($\pm$ 2%)**	4.22 ($\pm$ 11.15%)
Output beam intensity	mW cm ⁻²	0.2 ($\pm$ 35%)	*	*	1.46	1.4 ($\pm$ 42.02%)
Spatial-peak temporal-average intensity	mW cm ⁻²	38 ($\pm$ 35%)	59.5 ($\pm$ 33%)	67.78 ($\pm$ 24%)	55.6 ($\pm$ 2%)**	108.7 ($\pm$ 40.71%)
Scanner settings for above values						
Max power: magnification				1		-
focal zone				3		-
skin line				1		-
Max p.p.s.i: magnification		1	1	3	3	3
focal zone		2	1	1	1	2
skin line		1	1	1	1	1
Max I _{spta} : magnification		1	1	3	3	3
focal zone		2	1	1	1	2
skin line		1	1	1	1	1
other		High speed	High speed	High speed	High speed	High speed
Location of max. pulse-pressure-squared integral	mm	55	20.7 ($\pm$ 1.5%)	27 ($\pm$ 1%)	23.3	37.5
- 6 dB beam width: parallel	mm	1.9 ($\pm$ 5%)	1.17 ($\pm$ 17%)	1.5 ($\pm$ 4%)	1.0	0.98 ($\pm$ 3%)
perpendicular	mm	5.2 ($\pm$ 5%)	3.49 ($\pm$ 6%)	2.4 ($\pm$ 4%)	3.2	1.95 ($\pm$ 2%)
Pulse repetition rate: high speed	Hz	244	243.96	244	244	244.5 ($\pm$ 0.01%)
Output beam dimensions: parallel	mm	85 ($\pm$ 5%)	*	19 ($\pm$ 4%)	19	12.5 ($\pm$ 4%)
perpendicular	mm	12.5 ($\pm$ 5%)	*	8.5 ($\pm$ 4%)	8	7.9 ($\pm$ 4%)
Acoustic working frequency	MHz	2.8	3.18	2.97 ($\pm$ 0.3%)	3.08	3.1 ($\pm$ 1%)
Bandwidth of acoustic waveform	MHz	0.9	20	0.85	1.05	1 ($\pm$ 1%)
Transducer-hydrophone separation: max p.p.s.i	mm	55	20.7 ($\pm$ 1.5%)	27 ($\pm$ 1%)	23.3	37.5
max p.	mm					-
max I _{spta}	mm	55	20.7 ($\pm$ 1.5%)	27 ($\pm$ 1%)	23.3	37.5
Water temperature during measurements	°C	20.8	23.1 ($\pm$ 0.05%)	21 ($\pm$ 1%)	*	20 ($\pm$ 1%)

Table 7a: M-mode maximum acoustic output measurements at settings notified in part one results for laboratories A to E (* data not reported; ** random uncertainties only)

TABLE 7b: M MODE OWN SETTINGS		F	G	H	J	K
	Units					
Temporal-average power	mW	5.53 ($\pm 16\%$)	6.0 ($\pm 12.1\%$)	4.66 ($\pm 9\%$)	4.76 ($\pm 11\%$)	3.6 ($\pm 14\%$)
Peak-negative acoustic pressure (max)	MPa	4.45 ($\pm 9\%$)	4.7 ($\pm 11.2\%$)			
Peak-negative acoustic pressure (at max p.p.s.i)	MPa	4.3 ($\pm 11\%$)	4.5 ($\pm 11.2\%$)	4.22 ($\pm 12\%$)	4.55 ($\pm 7\%$)	4.047 ($\pm 24\%$)
Output beam intensity	mW cm ⁻²	3.2 ($\pm 26\%$)	1.8 ($\pm 23.1\%$)	1.91 ($\pm 27\%$)	2.77 ($\pm 11\%$)	1.5 ($\pm 20\%$)
Spatial-peak temporal-average intensity	mW cm ⁻²	111 ($\pm 23\%$)	153 ($\pm 23.1\%$)	90.6 ($\pm 27\%$)	94 ($\pm 17\%$)	88 ($\pm 47\%$)
Scanner settings for above values						
Max power: magnification		1	1.5		1	1
focal zone		3	3		3	3
skin line		1	1		1	4
Max p.p.s.i: magnification		3	2	2	3	3
focal zone		2	2	2	2	2
skin line		2 to 4	2	1	1	4
Max I _{spta} : magnification		3	2		3	3
focal zone		2	2		2	2
skin line		2 to 4	2		1	4
other		High speed	High speed		High speed	High speed
Location of max. pulse-pressure-squared integral	mm	38	38.4	37	36.98 ($\pm 1\%$)	39 ($\pm 15\%$)
- 6 dB beam width: parallel	mm	0.94 ($\pm 5\%$)	0.9 ($\pm 4.7\%$)	1.34 ($\pm 19\%$)	0.9813 ($\pm 1\%$)	1.0 ($\pm 10\%$)
perpendicular	mm	2.08 ($\pm 5\%$)	1.95 ($\pm 4.7\%$)	2.24 ($\pm 19\%$)	2.203 ($\pm 4\%$)	2.0 ($\pm 5\%$)
Pulse repetition rate: high speed	Hz	244	245	244	244.1	244.1 ($\pm 0.04\%$)
Output beam dimensions: parallel	mm	24 ($\pm 5\%$)	26.0 ($\pm 4.7\%$)	26.9 ($\pm 19\%$)	24.17 ($\pm 0.4\%$)	27.0 ($\pm 10\%$)
perpendicular	mm	7.3 ($\pm 5\%$)	8.9 ($\pm 4.7\%$)	8.6 ($\pm 19\%$)	7.113 ($\pm 1\%$)	9.0 ($\pm 10\%$)
Acoustic working frequency	MHz	3.1 ($\pm 1\%$)	3.01 ($\pm 1\%$)	3.15	3.033 ($\pm 1.5\%$)	3.0 ($\pm 7\%$)
Bandwidth of acoustic waveform	MHz	0.98 ($\pm 1\%$)	0.82 ($\pm 2\%$)	0.865	0.920 ($\pm 3\%$)	0.93 ($\pm 16\%$)
Transducer-hydrophone separation: max p.p.s.i	mm	38	38.4	37	36.98 ($\pm 1\%$)	39 ($\pm 15\%$)
max p.	mm	34	33.6			
max I _{spta}	mm	38	38.4	37	36.98 ($\pm 1\%$)	39 ($\pm 15\%$)
Water temperature during measurements	°C	20 $\pm$ 1	20 $\pm$ 1	20.5	23.8 $\pm$ 0.29	21.5 ($\pm 9\%$)

Table 7b: M-mode maximum acoustic output measurements at settings notified in part one results for laboratories F to K (* data not reported; random uncertainties only)**

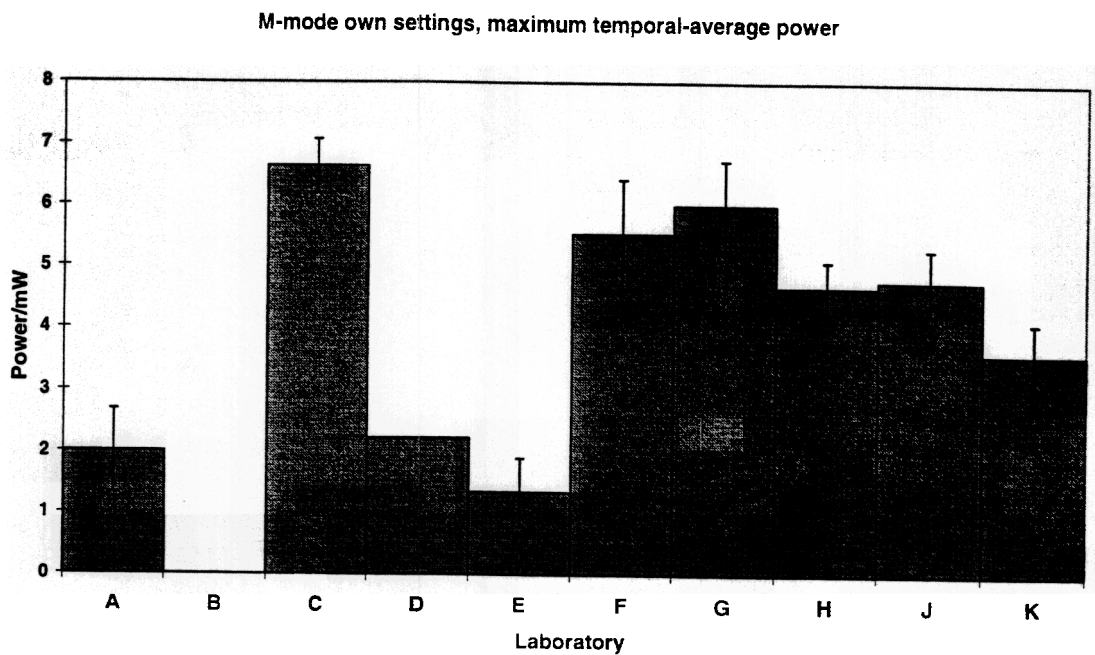


Figure 16: M-mode maximum temporal-average power, participating laboratories' own settings, 95% confidence interval uncertainties where reported by laboratory.

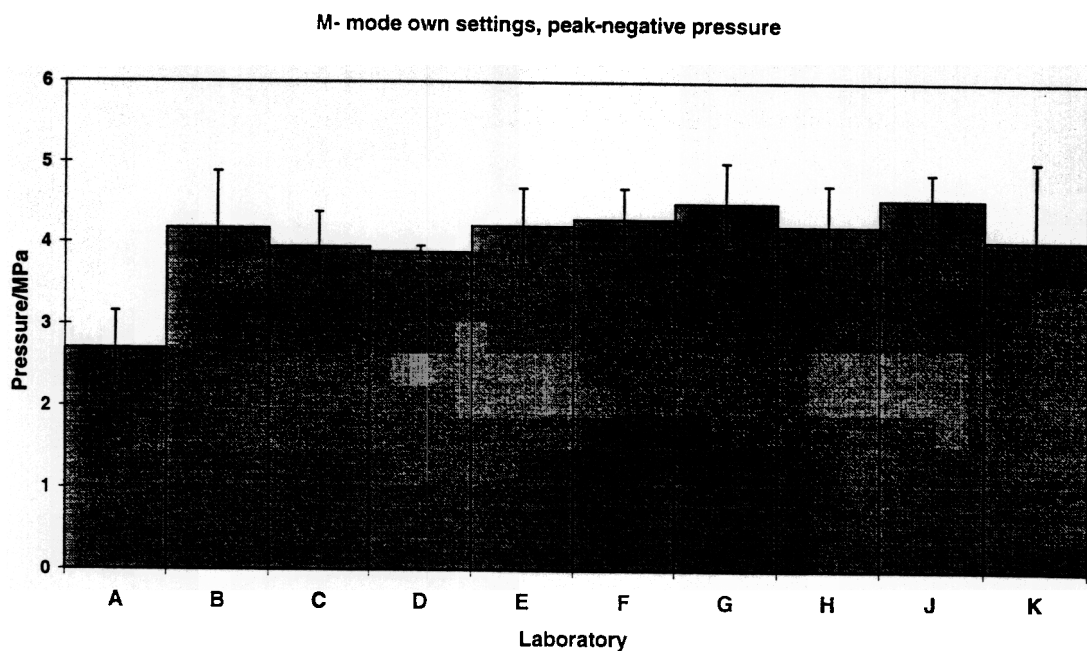


Figure 17: M-mode maximum peak-negative acoustic pressure, participating laboratories' own settings, 95% confidence interval uncertainties (except D random uncertainties only)

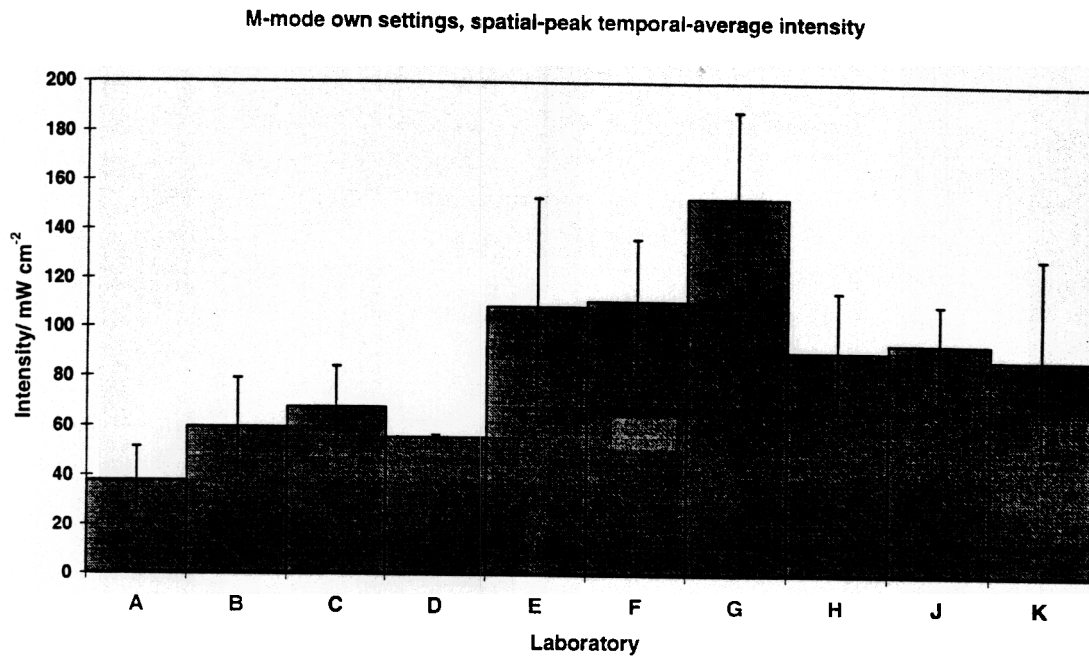


Figure 18: M-mode spatial-peak temporal-average intensity, participating laboratories' own settings, 95% confidence interval uncertainties (except D, random uncertainties only)

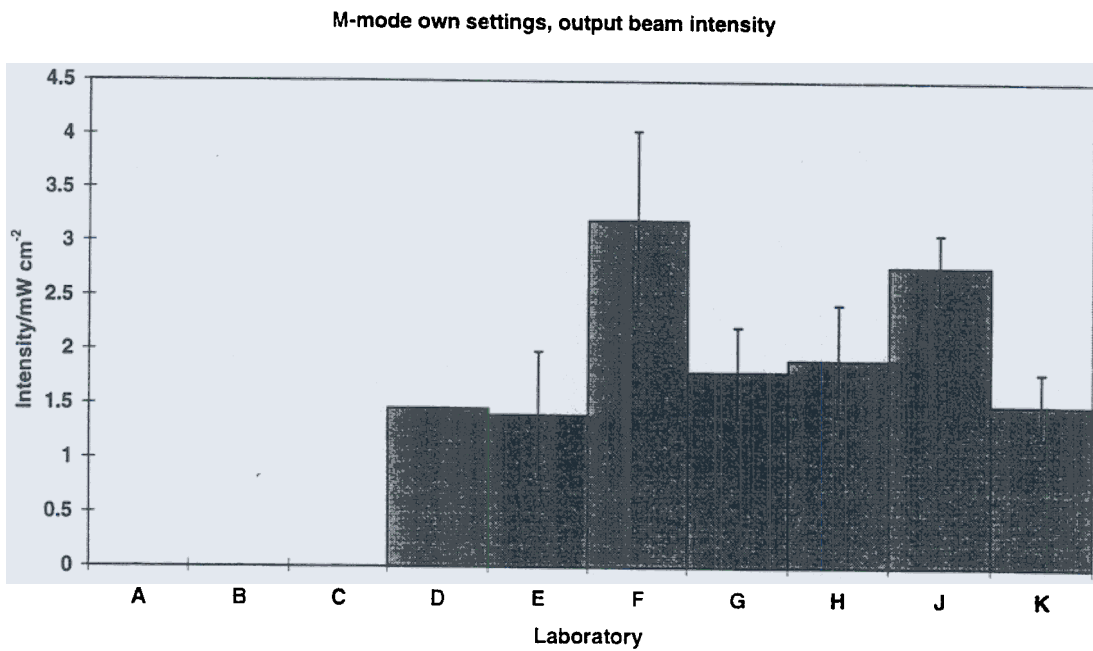


Figure 19: M-mode output beam intensity, participating laboratories' own settings, 95% confidence interval uncertainties where reported by laboratory

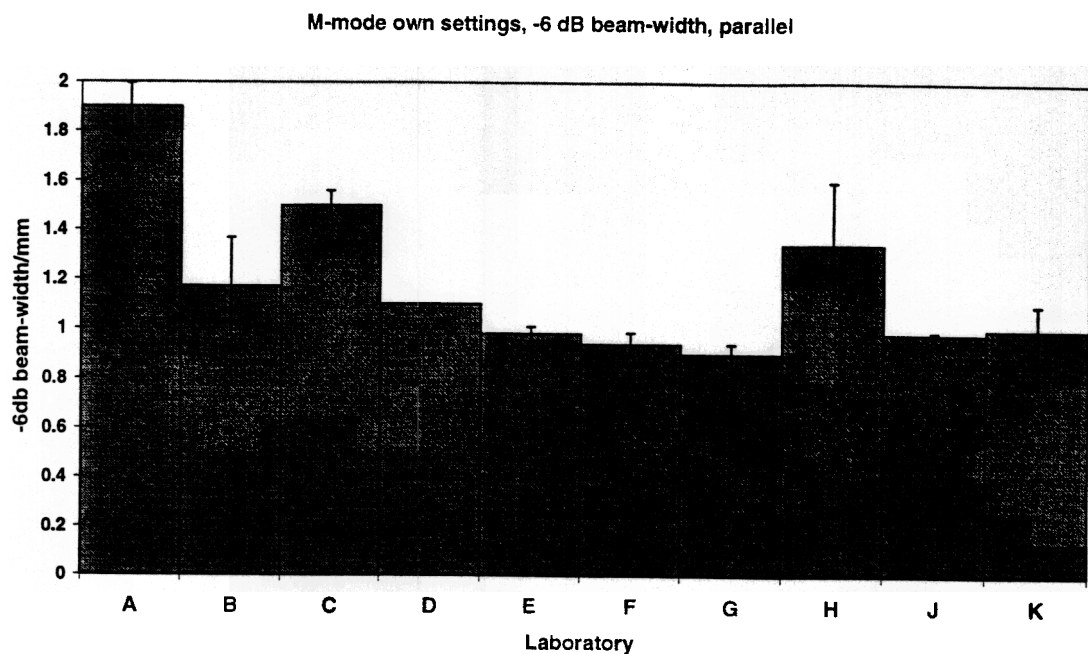


Figure 20: M-mode -6 dB beam-width parallel to reference direction, participating laboratories' own settings, 95 % confidence interval uncertainties where reported by laboratory

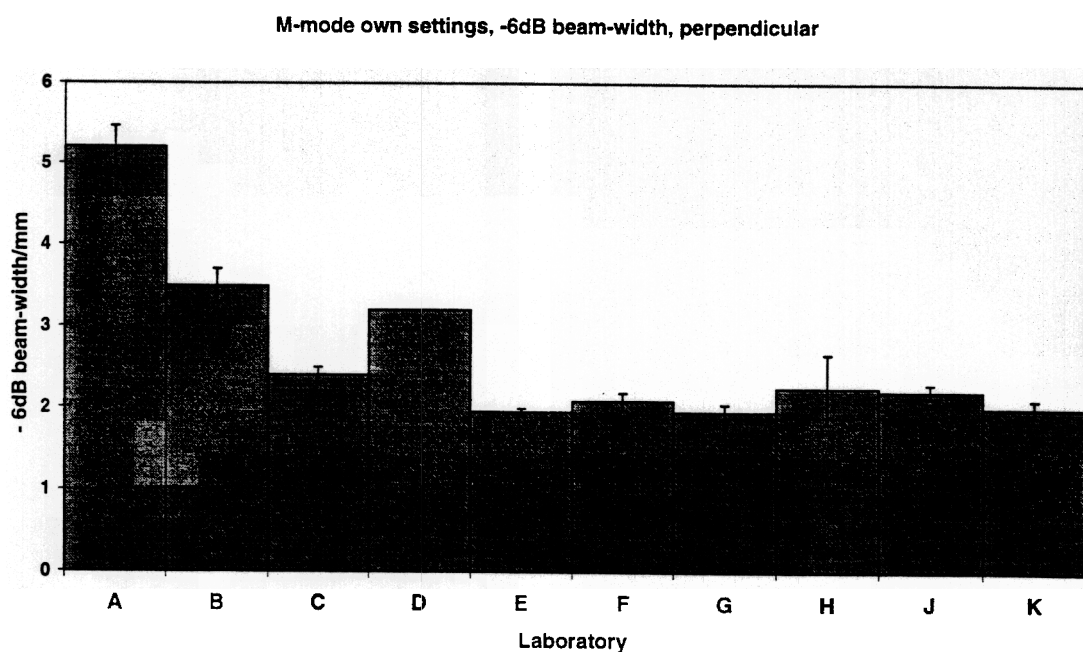


Figure 21: M-mode -6 dB beam-width perpendicular to reference direction, participating laboratories' own settings, 95 % confidence interval uncertainties where reported by laboratory

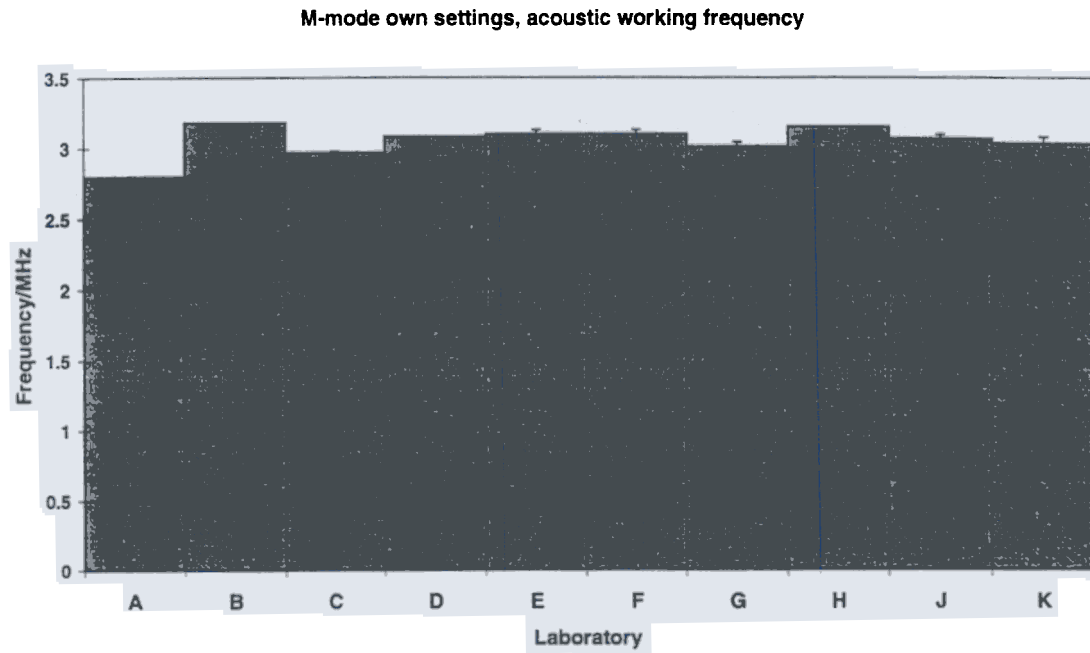


Figure 22: M-mode acoustic working frequency, participating laboratories' own settings, 95% confidence interval uncertainties where reported by laboratory

11. MEASUREMENTS AT NPL-NOMINATED SETTINGS

In addition to measurements at the maximum output settings which they had identified during the part one stage of the project, laboratories were required to make measurements at any additional settings notified to them by NPL. It is important to understand that the request to measure at NPL-nominated settings does not imply that the laboratory in question has not found the maximum output conditions at their own settings. During its own investigations of the scanner's maximum output settings NPL had found a number of settings which appeared to produce identical or very similar acoustic outputs. If a laboratory reported one or several of these settings at part one, it was commonly asked to measure at another of NPL's candidate settings at part two. This applied both for maximum pulse-pressure-squared integral and spatial-peak temporal-average intensity. In this latter case, it appeared to NPL that spatial-peak temporal-average intensity occurred at low magnifications and in a broad area of the beam where there were many overlapping scan lines. In addition, within experimental uncertainties, the exact position in space could not be easily defined. Thus, in this case, some laboratories were asked to measure at the extremes of the spatial range identified by NPL.

A second question which was investigated during part two, by requesting laboratories to make additional measurements, was whether there was a linear relationship between spatial-peak temporal-average intensity and the number of scan lines used to generate the image. To test this, a number of laboratories were asked to measure spatial-peak temporal-average intensity at both the 120 and 80 scan line settings. If a laboratory was not asked to make an additional measurement either for a particular mode or particular parameter then there is no entry under that mode and parameter for the laboratory in question.

Tables 8a and 8b identifies the settings which were nominated by NPL for each laboratory at the second stage of the project. Table 8a gives the nominated B-mode settings and table 8b gives those nominated for M-mode. Where laboratories were asked to measure at two settings for a particular parameter, then two separate entries appear under that laboratory's name for the parameter in question. In the tables the abbreviation p.p.s.i. refers to pulse-pressure-squared integral and Ispta to spatial-peak temporal-average intensity. Entries only appear in tables 8a and 8b if a particular laboratory was asked to make additional stage two measurements at NPL-nominated settings for the mode in question. The findings reported by each laboratory are set out in tabular form in this section of the report, with separate tables for B and M mode. Only if a laboratory actually reported measurements for a particular mode is it included in the table in question. In addition, the amount of information provided by participating laboratories for the NPL-nominated settings varied greatly, often depending on the amount of time available to the laboratory to complete the whole measurement programme. Laboratory C did not have time to complete hydrophone measurements at NPL-nominated settings, but was able to report power values at these settings. The results relating to the maximum power values found in this case are included in tables 9 and 10. Owing to this variability and the fact that not all laboratories appear

in each table, it was decided that graphical presentation of the results is probably not of direct assistance in understanding the information summarised in the tables.

LABORATORY		TABLE 8a:B-MODE SETTINGS NOMINATED BY NPL				
		Magnification	Focal zone	Skin line	Scan lines	Distance/mm
A	max p.p.s.i.	3	2	2		38
	max lspta	1	3	1	80	28
	max lspta	1	3	1	120	28
B	max p.p.s.i.	3	2	2	80	38
	max lspta	1	3	1	80	28
	max lspta	1	3	1	120	28
C	max p.p.s.i.	3	2	2		38
	max lspta	1	3	1	80	28
	max lspta	1	3	1	120	28
D	max p.p.s.i.	3	2	2		38
	max lspta	1	3	1	80	28
	max lspta	1	3	1	120	28
E	max p.p.s.i.	3	2	2		38
	max lspta	1	3	1	80	28
	max lspta	1	3	1	120	28
G	max p.p.s.i.	3	2	2	120	38.4
H	max p.p.s.i.	3	2	4		37
	max lspta	1	3	1	120	30
J	max p.p.s.i.	2	2	2	160	36.5
	max p.p.s.i.	3	2	2	160	36.5
K	max lspta	1	3	1	120	32
	max lspta	1	3	1	80	32

Table 8a: B-mode settings for pulse-pressure-squared integral and spatial-peak temporal-average intensity nominated by NPL for participating laboratories' part two measurements.

LABORATORY		TABLE 8b: M-MODE SETTINGS NOMINATED BY NPL				
		Magnification	Focal zone	Skin line	Other	Distance/mm
A	max p.p.s.i.	3	2	2	High speed	38
	max Ispta	3	2	2	High speed	38
B	max p.p.s.i.	3	2	2	High speed	38
	max Ispta	3	2	2	High speed	38
C	max p.p.s.i.	3	2	2	High speed	38
	max Ispta	3	2	2	High speed	38
D	max p.p.s.i.	3	2	2	High speed	38
	max Ispta	3	2	2	High speed	38
E	max p.p.s.i.	3	2	2	High speed	38
	max Ispta	3	2	2	High speed	38
G	max p.p.s.i.	3	2	2	High speed	38.4
	max Ispta	3	2	2	High speed	38.4
H	max p.p.s.i.	3	2	4	High speed	37
	max Ispta	3	2	4	High speed	37

Table 8b: M-mode settings for pulse-pressure-squared integral and spatial-peak temporal-average intensity nominated by NPL for participating laboratories' part two measurements.

TABLE 9a: B MODE NPL-REQUESTED SETTINGS		A	B(1)	B(2)	B(3)	B(4)	C	D
	Units							
Temporal-average power	mW	*	*	*	*	*	69.8 ($\pm 5\%$)	28.9
Peak-negative acoustic pressure (at max p.p.s.i)	MPa	2.6 ($\pm 17\%$)	3.01 ($\pm 17\%$)	3.98 ($\pm 17\%$)	2.58 ($\pm 15\%$)	2.55 ($\pm 16\%$)	*	4.26 ($\pm 2\%$)**
Output beam intensity	mW cm ⁻²	*	*	*	*	*	*	15.0
Spatial-peak temporal-average intensity: 80 lines	mW cm ⁻²	111 ($\pm 35\%$)	39.8 ($\pm 34\%$)		50.6 ($\pm 30\%$)		*	102.8
120 lines	mW cm ⁻²					38.2 ($\pm 31\%$)	*	72.6
Scanner settings for above values								
Max power: magnification							1	
focal zone							3	
skin line							1	
Max p.p.s.i: magnification		3	3	3			*	3
focal zone		2	2	2			*	2
skin line		2	2	2			*	2
Max I _{spta} : magnification		1			1	1	*	1
focal zone		3			3	3	*	3
skin line		2			1	1	*	1
no. of scan lines		80	80	160	80	120	*	80/120
Location of max. pulse-pressure-squared integral	mm	38	37.33 ($\pm 1.6\%$)	38.5 ($\pm 1.3\%$)	30.38 ($\pm 1.6\%$)	30.85 ($\pm 4.6\%$)	*	38
- 6 dB beam width: parallel	mm	2.6 ($\pm 5\%$)	-	2.28 ($\pm 9\%$)	11.4 ($\pm 2\%$)	11.4 ($\pm 9\%$)	*	1.2
perpendicular	mm	3.4 ($\pm 5\%$)	-	0.947 ($\pm 21\%$)	1.67 ($\pm 11\%$)	1.66 ($\pm 12\%$)	*	2.4
Scan repetition rate: 80/120/160 lines	Hz	48.8 (80)	48.82	24.41	48.82	32.55	32.6	49/33
Output beam dimensions: parallel	mm	85 ($\pm 5\%$)	*	*	*	*	*	23.3
perpendicular	mm	12.5 ($\pm 5\%$)	*	*	*	*	*	8.25
Acoustic working frequency	MHz	3	3.16 ($\pm 5\%$)	3.17 ($\pm 5\%$)	3.28 ($\pm 5\%$)	3.24 ($\pm 5\%$)	*	3.13
Bandwidth of acoustic waveform	MHz	1.1	10	12	30	30	*	0.93
Scan line separation	mm	0.5	*	*	*	*	*	0.5
Transducer-hydrophone separation: max p.p.s.i	mm	38	38 ($\pm 0.8\%$)	38 ($\pm 0.8\%$)			*	38
max p.	mm						*	
max I _{spta}	mm	28			28.0 ($\pm 1.1\%$)	28.5 ($\pm 1.1\%$)	*	28
Water temperature during measurements	°C	20.8	22.03 ($\pm 0.3\%$)	22.03 ($\pm 0.3\%$)	22.66 ($\pm 0.13\%$)	22.66 ($\pm 0.13\%$)	20.6-22.9	20.4 ($\pm 2.5\%$)

Table 9a: B-mode, NPL-nominated settings, results of measurements for laboratories A to D (*data not reported by this laboratory; ** random uncertainties only)

TABLE 9b: B MODE NPL-REQUESTED SETTINGS		E	G	H	J	K
	Units					
Temporal-average power	mW	*	54 ($\pm 12.1\%$)	55.5 ($\pm 9\%$)	62.4 ($\pm 11\%$)	
Peak-negative acoustic pressure (at max p.p.s.i)	MPa	*	4.3 ($\pm 11.2\%$)	4.45 ($\pm 12\%$)	4.52 ($\pm 7\%$)	
Output beam intensity	mW cm ⁻²	*	23 ($\pm 23.1\%$)	24 ($\pm 27\%$)	35.5 ($\pm 11\%$)	
Spatial-peak temporal-average intensity: 80 lines	mW cm ⁻²	48.5 ($\pm 64.5\%$)	-	-	106 ($\pm 17\%$)	17 ($\pm 47\%$)
120 lines	mW cm ⁻²	34.7 ($\pm 57.1\%$)	80 ($\pm 28.9\%$)	75.9 ($\pm 27\%$)		17 ($\pm 47\%$)
Scanner settings for above values						
Max power: magnification			3		1 (160)	
focal zone			2		3	
skin line			2		1	
Max p.p.s.i: magnification		3	3		2	
focal zone		2	2		2	
skin line		2	-		2	
Max I _{spta} : magnification		1	3	1	1	1
focal zone		3	2	3	3	3
skin line		1	2	1	1	1
no. of scan lines		80/120	120	120	80	80, 120
Location of max. pulse-pressure-squared integral	mm	37.5	38.4	37	37.62 ($\pm 1\%$)	
- 6 dB beam width: parallel	mm	*	0.9 ($\pm 4.7\%$)	1.39 ($\pm 19\%$)	1.0063 ($\pm 1\%$)	
perpendicular	mm	*	1.95 ($\pm 4.7\%$)	2.20 ($\pm 19\%$)	2.247 ($\pm 2.5\%$)	
Scan repetition rate: 80/120/160 lines	Hz	33[120], 49[80]	32.6 [120]	32.6 [120]	48.8 (80)	
Output beam dimensions: parallel	mm	*	26.0 ($\pm 4.7\%$)	26.9 ($\pm 19\%$)	23.69 ($\pm 0.5\%$)	
perpendicular	mm	*	8.9 ($\pm 4.7\%$)	8.6 ($\pm 19\%$)	7.425 ($\pm 1\%$)	
Acoustic working frequency	MHz	3.1 ($\pm 1\%$)	3.01 ($\pm 1\%$)	3.18	3.074 ($\pm 0.4\%$)	
Bandwidth of acoustic waveform	MHz	1 ($\pm 1\%$)	0.82 ($\pm 2\%$)	0.8	0.954 ($\pm 1.9\%$)	
Scan line separation	mm		0.5	0.49	0.5016 ($\pm 1.1\%$)	
Transducer-hydrophone separation: max p.p.s.i	mm	37.5	38.4		37.62 ($\pm 1\%$)	
max p.	mm		35.2			
max I _{spta}	mm	26.2	30.0	30	31.47	32
Water temperature during measurements	°C	20 ($\pm 1\%$)	20 $\pm$ 1	21	23.96 $\pm$ 0.15	

Table 9b: B-mode, NPL-nominated settings, results of measurements for laboratories E to K (*data not reported by this laboratory; ** random uncertainties only)

TABLE 10: M MODE NPL-REQUESTED SETTINGS		A	B(1)	B(2)	C	D	E	G	H
	Units								
Temporal-average power	mW	2 ($\pm$ 34%)	3.88 ($\pm$ 34%)	1.31 ($\pm$ 34%)	4.52 ($\pm$ 8.4%)	2.03	*	4.0 ($\pm$ 12.1%)	4.66 ($\pm$ 9%)
Peak-negative acoustic pressure (max)	MPa							4.5 ($\pm$ 11.2%)	
Peak-negative acoustic pressure (at max p.p.s.i)	MPa	2.7 ($\pm$ 17%)	3.91 ($\pm$ 17%)	3.98 ($\pm$ 17%)	*	4.10 ($\pm$ 2%)**	*	4.3 ($\pm$ 11.2%)	4.45 ($\pm$ 12%)
Output beam intensity	mW cm ⁻²	0.2 ($\pm$ 35%)	225.91	76.27	*	1.07	*	1.7 ($\pm$ 23.1%)	1.91 ($\pm$ 27%)
Spatial-peak temporal-average intensity	mW cm ⁻²	44 ($\pm$ 35%)	84.9 ($\pm$ 34%)	84.9 ($\pm$ 34%)	*	58.1 ($\pm$ 2%)**	109.0 ($\pm$ 40.71%)	148 ($\pm$ 23.1%)	89.1 ($\pm$ 27%)
Scanner settings for above values									
Max power: magnification					3			3	3
focal zone					2			2	2
skin line					2			2	1
Peak-negative pressure:magnification		3	3	3	*	3	3	3	
focal zone		2	2	2	*	2	2	2	
skin line		2	2	2	*	2	2	2	
Max I _{spta} : magnification		3	3	3	*	3	3	3	
focal zone		2	2	2	*	2	2	2	
skin line		2	2	2	*	2	2	2	
other		High speed	High speed	High speed	High speed	High speed	High speed	High speed	
Location of max. pulse-pressure-squared integral	mm	38	36.75 ($\pm$ 1%)	38.1 ($\pm$ 1%)	*	38	37.5	38.4	37
- 6 dB beam width: parallel	mm	2.1 ($\pm$ 5%)		1.00 ($\pm$ 20%)	*	1.2	*	0.8 ($\pm$ 4.7%)	1.34 ($\pm$ 19%)
perpendicular	mm	3.4 ($\pm$ 5%)	2.11 ($\pm$ 9%)		*	2.6	*	1.95 ($\pm$ 4.7%)	2.24 ($\pm$ 19%)
Pulse repetition rate: high speed	Hz	244	243.96	243.96	*	244	244.5	245	244
Output beam dimensions: parallel	mm	85 ($\pm$ 5%)	2.20 ($\pm$ 9%)	2.20 ($\pm$ 9%)	*	23	*	26.0 ($\pm$ 4.7%)	26.9 ($\pm$ 19%)
perpendicular	mm	12.5 ($\pm$ 5%)	0.994 ($\pm$ 9%)	0.994 ($\pm$ 9%)	*	8.25	*	8.9 ($\pm$ 4.7%)	8.6 ($\pm$ 19%)
Acoustic working frequency	MHz	2.9	3.12 ($\pm$ 5%)	3.12 ($\pm$ 5%)	*	3.06	3.1 ($\pm$ 1%)	3.01 ($\pm$ 1%)	3.17
Bandwidth of acoustic waveform	MHz	1.2	12	12	*	*	1 ($\pm$ 1%)	0.82 ($\pm$ 2%)	0.865
Transducer-hydrophone separation: max p.p.s.i	mm	38	37.85 ($\pm$ 1.3%)	37.85 ($\pm$ 1.3%)	*	38	37.5	38.4	37
max p.	mm							35.2	
max I _{spta}	mm	38				38	37.5	38.4	
Water temperature during measurements	°C	20.8	22.36 ($\pm$ 0.1%)	22.36 ($\pm$ 0.1%)	20.6 to 22.9	*	20 ($\pm$ 1%)	20 $\pm$ 1	20.5

Table 10: M-mode, NPL-nominated settings, results of measurements for laboratories A to H (*data not reported by this laboratory; ** random uncertainties only)

In tables 9a and 9b the asterisks have the following meaning: * results for this parameter were not reported by the laboratory in question; **random uncertainties only. One laboratory reported four separate sets of results, sets 1 and 2 are for maximum pulse-pressure-squared integral at 80 and 160 scan lines respectively, and sets 3 and 4 are for spatial-peak temporal-average intensity at 80 and 120 scan lines. Thus there are four sets of data for this laboratory.

In table 10 the meaning of the asterisks is as follows: * results for this parameter were not reported for the laboratory in question; ** random uncertainties only. As in table 9 one laboratory reported separate results for measurements perpendicular (set 1) and parallel (set 2) to the reference direction and these are also listed separately.

The key finding from the work at NPL-nominated settings is the range of results obtained for what should have been identical measurement conditions. This is apparent for both peak-negative acoustic pressure (which ranges from 3.01 MPa to 4.26 MPa in M mode, for example) and spatial-peak temporal-average intensity (ranging from 44 mW cm^{-2} to $714.09 \text{ mW cm}^{-2}$, also in M mode) and may reflect both differences in hydrophone and amplifier bandwidth and in the measurement techniques and the methods of calculating results which were adopted by participating laboratories.

12. INTERPRETING IEC 61157

Some laboratories, either in their reports or during communications with NPL, commented on difficulties in interpreting the IEC 61157 standard. Laboratory J included lengthy comments on this topic in their report (these appear in Appendix 3 of this report), and it is useful and interesting to summarise some of their key points here.

They comment that the requirements for some parameters are unclear, sometimes contradictory and that the document is difficult to follow as it is necessary to continually refer back and forth to different places in the standard. There is no guidance on transient behaviour of scanners or on settling times to reach steady state values. The laboratory also comments on perceived inadequacies in definitions of output beam intensity and its measurement, and points out internal inconsistencies within the standard. Their final point is that the whole standard is based around measurement of pulse-pressure-squared integral but the rationale for this is not given in the standard and there is no requirement to declare this parameter.

Laboratory C commented that IEC 61157 does not state at what distance power measurements should be made and concluded that this could only be at “zero distance” for three reasons: the standard asks for the “maximum” power value; the output beam intensity is obtained by dividing the power by the output beam area, which refers to zero distance; and, at finite distances streaming and possibly nonlinear distortions would have to be estimated, which is difficult and is not addressed by IEC 61157.

It should also be noted that laboratory E has expressed the view that IEC 61157 is relatively straightforward to interpret and that they did not regard the standard itself as a source of difficulty.

During the final meeting of project participants, a round-table discussion on the challenges of working with IEC 61157 were discussed. Key points made during that discussion were:

- the standard performs a useful and important function and its continued existence must be supported;
- the standard is written for manufacturers who are required to declare acoustic output parameters and is not primarily a safety standard although it requires measurement of acoustic parameters which are safety-related;
- standards are not always totally prescriptive and in some cases there is scope of a laboratory to choose an alternative method of making a required measurement, provided that the chosen method has been validated;
- it may be of assistance to working physicists who are required to make measurements to produce additional guidance notes which are less formal than the standard itself.

13. DISCUSSION

13.1 Check source measurements

The check source measurements act as a means of evaluating the performance of participants' measuring systems and before beginning more detailed consideration of the results for the Dynamic Imaging scanner it is instructive to review some of the issues raised by the check source work. In the view of the author, the main differences between laboratories are due to differences in their measurement systems. However, study of the waveforms included in the report from laboratory A suggest amplifier overloading or saturation as a cause of the substantial departures from the values obtained by other participants for the check source's main acoustic parameters.

As pointed out earlier in this report, participants used a range of types of hydrophone. Although all hydrophones employed pvdf as the active element, both needle and membrane hydrophones were used with different bandwidths and different active element sizes. It is instructive to consider the effect such a range may have on measurements of the check source waveform. Table 11 summarises the hydrophone type, active element size and bandwidth of the combined hydrophone-amplifier system for the participating laboratories.

Table 11: HYDROPHONES USED FOR CHECK SOURCE MEASUREMENTS			
Laboratory	Bandwidth MHz	Element size/mm	Type
A	20	0.5	NP-1000 pvdf needle probe
B	23	0.4	Multi-element 25 micron pvdf bilaminar membrane
C	20	0.5	Force Institute pvdf needle probe
D	23	0.5	25 micron pvdf bilaminar membrane
E	25	0.5	25 micron pvdf bilaminar membrane
F	60	0.5	9 micron pvdf coplanar membrane
G	60	0.4	Force Institute pvdf needle probe
H	23	0.5	Multi-element 25 micron pvdf bilaminar membrane
J	23	0.5	25 micron pvdf bilaminar membrane
K	60	0.4	Force Institute pvdf needle probe

Table 11: Hydrophones used by participating laboratories for check source measurements (note that all membrane hydrophones in this table are manufactured by GEC-Marconi).

The check source waveform possesses some frequency components higher than 25 MHz. However, these have peak amplitudes less than 5% of the fundamental in magnitude and the major part of the acoustic signal lies below 20 MHz, the fifth harmonic being less than 10% of the fundamental in magnitude. This is within the bandwidth of all the hydrophone-amplifier combinations used in the work analysed here. However, there remains the

question of the extent to which the response of the hydrophone is flat across the frequency range of interest. It is generally accepted that pvdf needle probe hydrophones show fluctuations in sensitivity at low MHz frequencies (Robinson, 1988, Harris and Gammell, 1998). In addition, membrane hydrophones demonstrate a resonance at their thickness mode natural frequency. Differences in bandwidth limitations and in the flatness of frequency response between hydrophones used by participating laboratories may account for the variation of results, especially for peak-positive acoustic pressure.

For the check source, spatial-averaging effects are likely to be a much smaller source of variation. All participants used hydrophones of 0.4 mm or 0.5 mm active element diameter and the -6dB beam-width in the focal region of the check source is 2.49 mm. The theory developed by Du and Breazeale (1986) can be used to estimate the beam-width of the check source's higher harmonics. Employing the relationship that the beam-width of the n th harmonic is proportional to the square root of n , it can be estimated that the -6 dB beam-width of the fifth harmonic is 1.1 mm. In the experience of the author this approach tends to under-estimate the beam-widths of higher harmonics as determined experimentally. It can therefore be seen that all hydrophones used by participating laboratories have active element sizes less than half the -6 dB beam-width of the fifth harmonic of the check source acoustic field at its focus. Further guidance on spatial-averaging effects in nonlinear fields can be found in Zeqiri and Bond (1992).

An attempt was made to estimate the effect of hydrophone bandwidth on measurements of the check source waveform. The interferometer waveform presented in figure 8 was regarded as representing a "true" measurement of the waveform in the absence of hydrophone effects. The theoretical frequency responses, including electrical cable effects, of a range of hydrophones of different thicknesses of pvdf and different active element sizes were derived using the method outlined in Bacon (1982). The theoretically-derived responses were then convolved with the interferometer waveform to obtain prediction of the effect of the hydrophone on the "true" waveform. Figure 23 shows the interferometer waveform and the convolution of that waveform with the theoretically-derived frequency response of a 25 μ m thickness pvdf, 0.5 mm diameter active element bilaminar membrane hydrophone. For clarity, the predicted hydrophone waveform has been offset towards the right hand side of figure 23. The prediction can be regarded as representing the response of the hydrophone when employed with an unmatched ideal wide bandwidth unity gain amplifier. Note the overshoot at the location of peak-positive acoustic pressure and the distorted shape caused by "ringing" in the falling pressure part of the wavefront, just after the main shock. These effects are typical of limited bandwidth membrane hydrophones when used to measure fields with substantial high frequency content. The peak-positive acoustic pressure obtained from the hydrophone prediction (3.23 MPa) is commensurate with the values of peak-positive acoustic pressure obtained by those participating laboratories who used membrane hydrophones of this type (see figure 2 for check source peak-positive acoustic pressure results).

Figure 24 shows a similar prediction for a 9 μm thickness 0.5 mm diameter active element coplanar membrane, whose theoretical frequency response is convolved with the interferometer waveform. Once again, the predicted hydrophone waveform is offset to the right. This hydrophone has a much wider bandwidth than a 25 μm bilaminar membrane and this is reflected in the much closer agreement between the measured waveform from the interferometer and the predicted waveform. Peak-positive acoustic pressure for the predicted hydrophone waveform is 2.52 MPa.

Check source: interferometer and 25 micron 0.5 mm bilaminar membrane compared

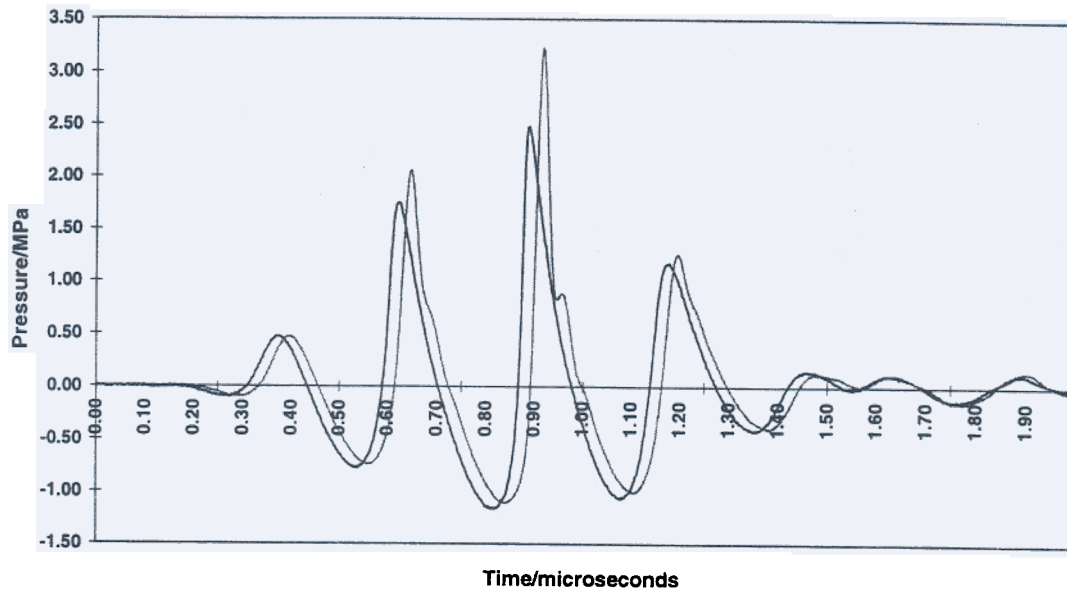


Figure 23: Check source: interferometer waveform (see figure 8) and convolution of that waveform with theoretical frequency response of 25 micron thickness pvdf, 0.5 mm diameter active element bilaminar membrane hydrophone (hydrophone waveform offset to the right)

Check source: interferometer and 9 micron 0.5 mm coplanar membrane compared

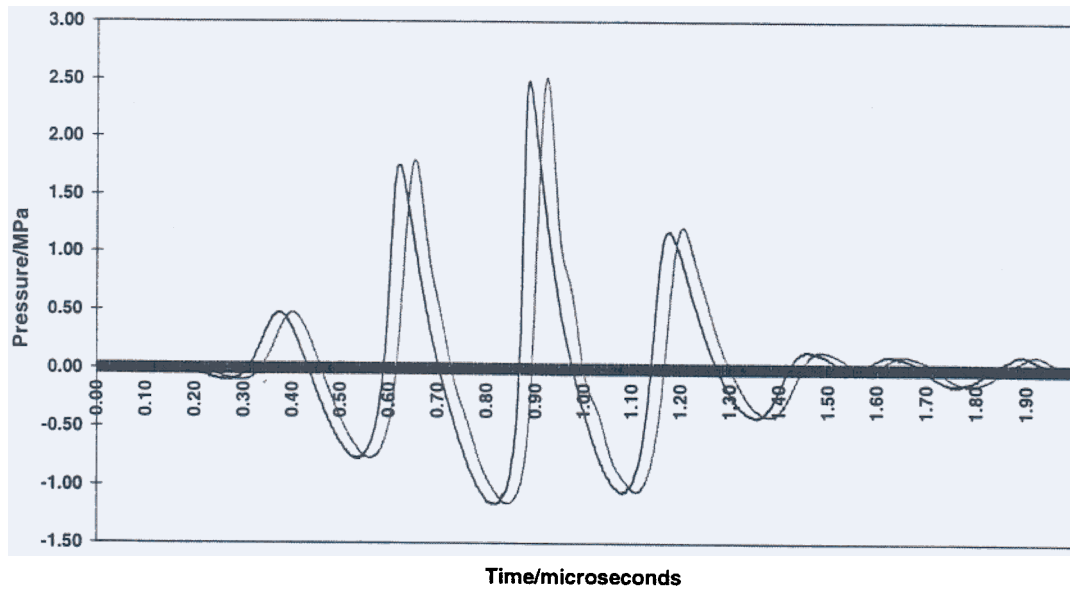


Figure 24: Check source: interferometer waveform (see figure 8) and convolution of that waveform with theoretical frequency response of 9 micron thickness pvdf, 0.5 mm diameter active element coplanar membrane hydrophone (hydrophone waveform offset to the right)

13.2 Dynamic Imaging scanner measurements

In this section of the report the main findings of the measurements on the Dynamic Imaging scanner are discussed. This discussion will concentrate on the results reported by participating laboratories for some key acoustic parameters measurements at the part one settings (the settings which each laboratory had identified for maximum acoustic output).

As explained earlier in this report, although the Dynamic Imaging scanner appears to be a relatively simple device, it presents a substantial challenge to many measurement systems owing to the highly-shocked, tightly-focused field it radiates at certain settings. Figure 25 shows a typical uncorrected waveform from one of the scanner's high magnification settings. The waveform is for the central scan line in magnification 3, focal zone 2 and skin line 4 of B-mode, 160 scan lines per frame, and it was obtained on the beam axis 35 mm from the transducer with a 9 μm pvdf thickness bilaminar membrane hydrophone of 0.2 mm diameter active element. This waveform represents one of the settings which produce the highest peak-positive acoustic pressures (this is not a parameter required by IEC 61157). However, NPL has measured higher pressures from this scanner (occasionally exceeding 16 MPa) in both B and M-mode, and one of the participating laboratories (G) has reported a peak-positive acoustic pressure exceeding 17 MPa. There are two main consequences of such high pressures and such shocked waveforms. It is necessary to ensure that hydrophone-amplifier systems have sufficient dynamic range to be able to cope with the high peak-positive acoustic pressures. NPL first investigated the performance of the scanner using its multi-element hydrophone Beam Calibrator system but soon realised that, as our Beam Calibrator can cope only with maximum pressures of 10 MPa, it was unsuitable for investigating the full range of acoustic outputs obtainable from the scanner. As a result, all our scanner measurements were made with a single-element hydrophone in a beam-plotting tank. The second consequence is that such shocked waveforms have substantial high-frequency content and that hydrophone-amplifier bandwidth limitations may lead to measurement errors, especially where there is signal at frequencies beyond the hydrophone-amplifier system's bandwidth limit.

Figure 26 shows the normalised frequency spectrum of the typical high-pressure scanner waveform presented in figure 25. The spectrum indicates that there are frequency components in the signal up to and beyond 50 MHz and that these are of the order of 10% of the amplitude of the fundamental. Measurement systems with bandwidth limits in the range from 20 to 25 MHz will be unable to capture the full range of frequencies present in the signal.

Dynamic Imaging scanner: typical time domain waveform

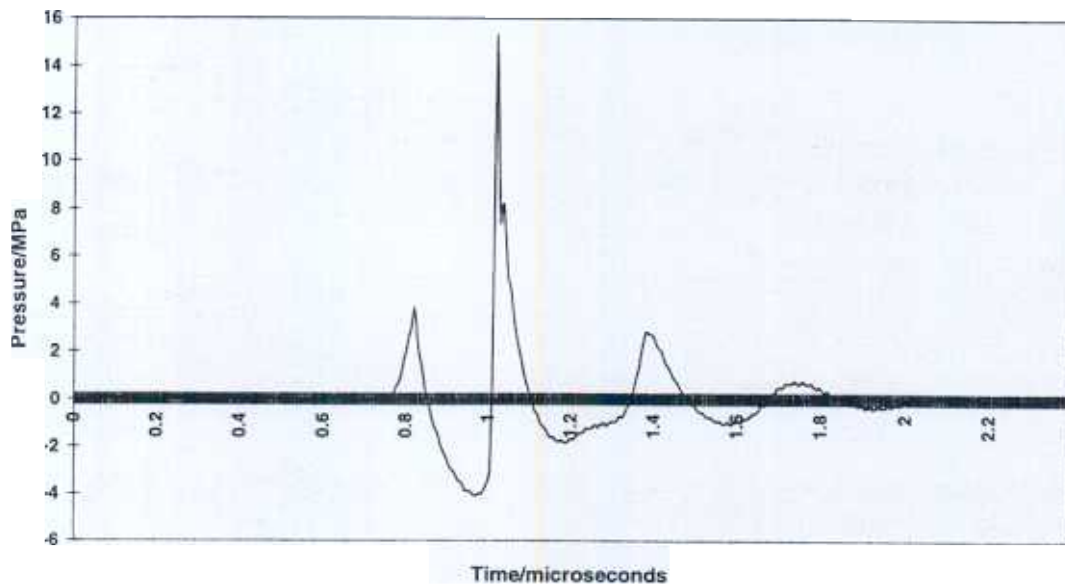


Figure 25: Dynamic Imaging scanner: typical time domain waveform, B-mode, 160-scan line setting, central scan line, 3x magnification, focal zone 2, skin line 4, 35 mm transducer-to-hydrophone separation; waveform acquired with 9 μm thickness pvdf bilaminar membrane hydrophone with 0.2 mm diameter active element

Normalised spectrum of typical scanner waveform

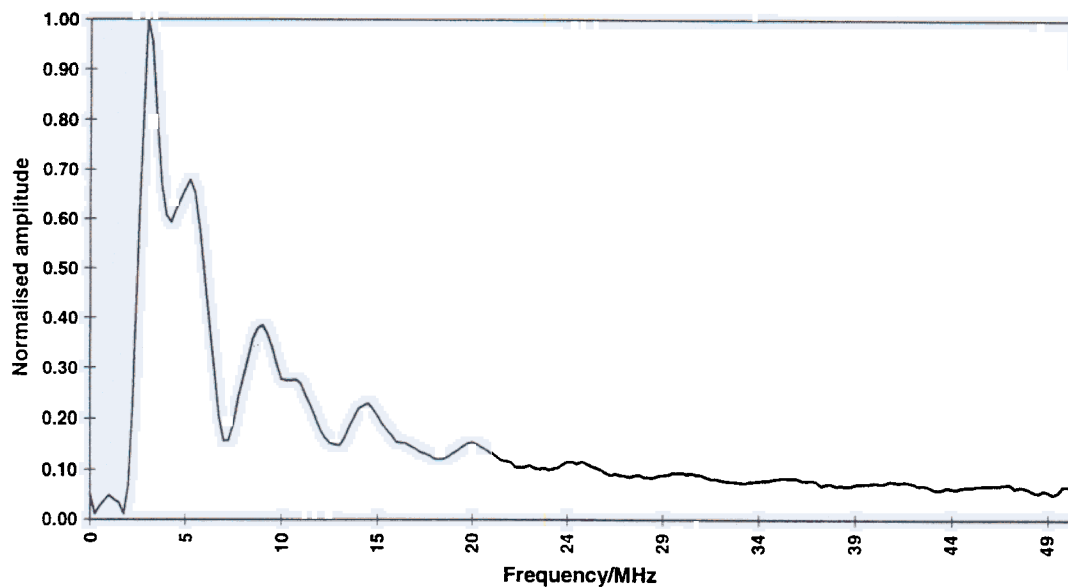


Figure 26: Normalised frequency spectrum of typical Dynamic Imaging scanner waveform shown in figure 25

13.2.1 Power measurements

Measurements of total power output from an imaging transducer such as that used in this project present a number of experimental challenges. The transducer is a large linear array with a tightly-focused beam. For those laboratories which used radiation force balances for their measurements, the questions to be addressed prior to making measurements are what size of target to use and whether that target should be reflecting or absorbing. Measurements using reflecting targets are very sensitive to small variations in alignment of the transducer. During its investigations, NPL noticed that uncertainties obtained with a reflecting target were more than twice those obtained with an absorbing target. In addition, as laboratory J emphasised in its measurement report, the IEC standard which governs power balance measurements (IEC 61161 *Ultrasonic power measurements in liquids in the frequency range 0.5 MHz to 25 MHz*) assumes that the target inside a radiation force balance is circular in shape and requires that the target's diameter should be at least 1.5 times larger than the appropriate dimension of the ultrasonic transducer. The physical dimensions of the output face of the transducer are 85 mm by 13 mm, requiring a target 128 mm in diameter.

Intercomparisons of power measurements can produce excellent results when well-behaved reference transducers are employed. For example, three of the laboratories involved in the present project (PTB, TNO and NPL) performed an intercomparison of power measurements using air-backed quartz circular piston transducers in the frequency range from 1 to 10 MHz (Beissner et al., 1996). The intercomparison produced excellent agreement between the three laboratories. However, the Dynamic Imaging scanner is much more difficult to characterise, and close agreement between the laboratories participating in this project should not be expected (see figure 9). This is even more the case when comparing radiation force techniques with measurements based on hydrophones. Laboratory E carried out its power measurements by means of hydrophone-based raster scans, laboratory B used an NPL Beam Calibrator with a multi-element hydrophone, and laboratory D also employed a hydrophone. Other laboratories used various kinds of radiation force balance, except laboratory A which did not report power measurements.

Choice of measurement distance for power measurements can also pose problems. If the acoustic beam is radiated into a water-filled vessel there will be some attenuation of the signal on the way to the target, and losses due to attenuation will be a function of distance. In addition, cavitation and streaming are possible, although this is unlikely for the case of this Dynamic Imaging scanner.

Owing to time constraints, laboratory E used a relatively small number of points in its scan, and it is possible that this leads to an underestimate of total power radiated. In addition, laboratory B may have reported results which relate to only one scan line rather than to all scan lines. Identifying the settings for maximum power output can also be problematic. Laboratory C also reported several B-mode settings in which the power output was within 10%

of their maximum measured power output. During NPL's investigations of B mode we found 18 combinations which produced power outputs within 10% of our maximum power output. These were all in magnifications 1 and 1.5 and focal zones 2 and 3, with various skin depth settings from 1 to 4, and either 120 or 80 scan lines per frame. It is likely to be the case where experiments take place over a period of time, and where there are varying environmental and other random factors, a laboratory may determine a maximum power output setting during one experimental session and then select an alternative candidate for maximum power output during another session of measurements. It is probably the case that the single most important factor for identifying maximum power is the need to allow time for the scanner to stabilise when starting from cold, and when switching between modes.

In M mode where power outputs are much lower, NPL also found a large number of low magnification settings which produced similar power outputs. 14 settings produced total power within 10% of the maximum power output. Owing to the low power levels radiated in M-mode NPL carried out its M-mode measurements with a reflecting target and consequently observed uncertainties twice those seen in B mode with an absorbing target. Comparison of the relative sizes of error bars in figure 9 (B-mode power measurements) and figure 16 (M mode) seem to suggest that other laboratories obtained higher uncertainties in their M-mode power values.

Uncertainties in power measurements also have consequences for the measurement of output beam intensity, as this is derived from the total power divided by the output beam dimensions. The wide range of values reported for output beam intensity, especially in B mode, appears to reflect variations in power measurements as well as variations in measurement of output beam dimensions.

13.2.2 Peak-negative acoustic pressure and spatial-peak temporal-average intensity

The two most important acoustic parameters to be determined by hydrophone measurements are the peak-negative acoustic pressure and the spatial-peak temporal-average intensity. In the case of peak-negative acoustic pressure participating laboratories reported values for B mode in the range from 3.8 to 4.7 MPa. M-mode values varied from 3.9 to 4.6 MPa. These figures exclude the results from laboratory A, whose scanner waveforms suggest that the amplifier overloading or saturation problem indicated by the check source results is still present in the scanner measurements. The range of the peak-negative acoustic pressure values (0.9 MPa for B mode and 0.7 MPa for M mode) is about 20% of the mean value of this parameter. This is in line with the check source results, which showed a variation of about 0.2 MPa on a mean peak-negative acoustic pressure of 1.2 MPa (excluding laboratory A). Once again, it appears that differences in hydrophone-amplifier systems may account for the differences between laboratories both in terms of absolute

values of pressure measured and in the location of the transducer-to-hydrophone separation which produced maximum pulse-pressure squared integral. Eight of the participating laboratories employed the same hydrophone-amplifier combination for the check source and scanner measurements. Laboratory F used a 0.2 mm active element diameter, 9 μm thickness pvdf bilaminar membrane hydrophone for the scanner measurements, in place of the 0.5 mm coplanar membrane they had employed for the check source measurements. Laboratory J measured both devices with a 25 μm thickness pvdf 0.5 mm diameter active element bilaminar membrane hydrophone, but changed from an unmatched amplifier to a matched amplifier for the scanner measurements.

As pointed out earlier in the discussion of results at laboratories' part one settings, measurement of spatial-peak temporal-average intensity in scanning modes requires the contribution from overlapping scan lines to be taken into account. The wide range of values reported for this parameter may reflect the difficulty in assessing this contribution, especially as most laboratories reported similar scanner settings and locations for this parameter. Alternatively, it may be the case that some laboratories have reported spatial-peak temporal-average intensity for one scan line only. It is difficult to assess whether this is the case. It might be expected that M-mode measurements of spatial-peak temporal-average intensity would show closer agreement, because this is a non-scanning mode. However, M-mode results also show substantial variations from one laboratory to another, with reported values ranging from 38 mW cm^{-2} to 153 mW cm^{-2} .

In the light of the above it may have been helpful to request an additional measurement in the project protocol, that of the spatial-peak temporal-average intensity for the central scan line only at the laboratory's chosen setting. Although this is clearly not a parameter required by IEC 61157, it would have been of assistance in interpreting the reported results.

13.3 Measurements at NPL-nominated settings

Discussion of measurements at NPL-nominated settings is problematic, as not all laboratories were asked to make measurements at all settings and in addition, some laboratories had insufficient time to complete all measurements. In any case, it appeared to NPL that both for maximum pulse-pressure-squared integral and spatial-peak temporal-average intensity in B and M mode there were several candidate settings for maximum values and if a laboratory had reported one of these candidate settings at part one it was usually asked to test one of the other candidate settings at part two.

For peak-negative acoustic pressure in B mode at the plane of maximum pulse-pressure-squared integral six laboratories reported values at NPL-nominated control settings. For three laboratories (B set 2, D,H), measurements at the NPL-nominated produced higher values than were reported for the laboratory's own part one settings, and three (A,G, J) reported lower values at the NPL settings. A similar pattern appears for peak-negative

acoustic pressure in M mode, where five laboratories reported values at NPL-nominated settings, two being higher than that laboratory's own setting (D, H), two being lower (B, G) and one being identical (A).

In the case of NPL-nominated settings for spatial-peak temporal-average intensity in B mode, seven laboratories reported measurements. In three cases (A, B, D) the NPL settings produced substantially higher values than those laboratories' part one settings and in two cases (J, K) there appeared to be no difference. An attempt by NPL to compare results for 80 and 120 scan lines at the same settings suggested that there is an approximate scaling factor of 1.4 to 1.5 which can be applied to the 120 scan line results to obtain a prediction of the 80 scan line value. However, no other firm conclusions can be drawn from the B-mode spatial-peak temporal-average intensity results.

For M-mode spatial-peak temporal-average intensity, six laboratories reported results at NPL-nominated settings. Within experimental uncertainties, five laboratories (A, D, E, G, H) produce values which were virtually identical to those they had measured at their own part one settings. Only one laboratory (B) shows a substantial increase in intensity at the NPL-nominated settings. These results reinforce the earlier observation that there appear to be a number of settings all of which produce similar values of this parameter.

13.4 Corrections for bandwidth limitations and spatial averaging

In general, it is preferable to avoid the need for corrections to the measurements for bandwidth limitations for spatial averaging, by using small receivers of wide bandwidth. It is clear from table 11 that some participating laboratories did not employ systems of sufficient bandwidth to detect all the frequency components present in the fields radiated by the Dynamic Imaging scanner. At the final meeting of project participants, the question of correction methods was discussed. For example, laboratory D commented that although they were able in some cases to correct their measurement for spatial averaging, correction for limited bandwidth using the methods outlined in IEC 61220: 1993, *Guidance for the measurement and characterization of ultrasonic fields generated by medical ultrasonic equipment using hydrophone in the frequency range 0.5 MHz to 15 MHz* was problematic even for the check source waveform. This guidance note assumes that the falling slope of a distorted waveform can be approximated by an ellipse or an exponential function which can be fitted through three points on the actual measured waveform. Laboratory G described results of work that they had carried out using these correction techniques and also of their own method, based on fitting a polynomial to the falling slope. They argued that following the IEC 61220 procedure may result in considerable differences in peak-positive acoustic pressures in the corrected waveforms, depending on where the points chosen for the fit are located. Further information about correction methods can be found in Hekkenberg et al (1990,1994).

14. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE ACTION

14.1 General conclusions

This project has involved a wide range of laboratories: for example, national measurement institutions, academic organisations, medical physicists concerned with quality assurance, and specialists in acoustic output measurements, all with varying levels of experience in working with IEC 61157. Although the main project task consists of an intercomparison of ultrasonic field measurements on a Dynamic Imaging diagnostic scanner, its aim has not been to define a set of acoustic parameters and scanner settings which can be regarded as identifying the maximum acoustic output of the scanner. The main purpose and main benefit of the project was intended to be the provision of experience in working to the IEC 61157 standard, in order to allow participating laboratories to gain confidence in their ability to implement the standard and to obtain an appreciation of some of the sources of systematic error in the acoustic output measurements required by the standard. A secondary aim was to indicate any lack of clarity or any apparent inconsistencies in the standard, which might cause difficulties. In this way, problems in applying the standard throughout Europe should be minimised by the experience gained by the participating laboratories during the intercomparison. Subsidiary aims of the project included provision of information to the IEC for assessing output levels and for possible future revision of the standard, and contributions to regulatory requirements, industrial competitiveness and the continued safety of diagnostic medical ultrasound in Europe.

As far as the main aims of the project are concerned, the intercomparison has undoubtedly been a success. Ten laboratories from seven E.C. countries have carried out measurements on a modern, portable diagnostic scanner whose radiated fields pose a substantial challenge even to the most up-to-date measurement technologies. The Dynamic Imaging transducer produces tightly-focused highly-shocked fields which require wide bandwidth hydrophones and amplifiers with small diameter active elements for accurate measurement. The tightly-focused fields also pose a challenge for power measurements made using radiation force balances or hydrophones. These lead to the possibility of large random and systematic measurement errors. Another problem presented by the scanner was that at several settings in both B and M mode it produced acoustic outputs which were very similar, or even identical in nature. It seems likely that an important factor which contributes to the ability of a laboratory to make successful measurements to IEC 61157 is the extent of its previous experience of making measurements in accordance with that standard.

There were clear differences in the prior experience of the laboratories, as evidenced by some of the problems identified in finding maximum output control settings, but it appears that the single most important factor which

contributes to differences between the results reported by participating laboratories is the range of different hydrophone and amplifier systems used, specifically the differences in hydrophone types (both membranes and needle probes were employed), active element size (these ranged from 0.2 mm to 0.5 mm in diameter) and in system bandwidth (varying from about 20 MHz to greater than 60 MHz). The measurements which were required on the NPL check source were extremely helpful in identifying effects arising from the different measurement systems. In almost all cases, differences between laboratories' check source results can be attributed to measurement system differences. The measurements on the Dynamic Imaging scanner highlight the need for laboratories to employ hydrophones with small diameter active elements of sufficient bandwidth in order to limit the need for corrections to measured values of acoustic parameters. There is also a need to consider carefully the consequences of any instability in the acoustic output of scanners to ensure that measurements are performed in a consistent manner, with sufficient time being allowed after power-up and after switching between modes to allow the scanner to settle to a steady state. If this was not allowed for, the systematic variation of output with time could mask differences due to machine settings. Finally, in relation to the power-up mode of the Dynamic Imaging scanner, it is of interest to note that the scanner does not have a unique power-up setting as the number of scan lines and therefore scan frame rate depend on the setting at which the scanner was last used.

14.2 Future work

It is possible to make a number of specific recommendations which could be the subject of future work.

- Benefit would be gained by further investigation into some of the large discrepancies in the results of certain participants, either individually or in collaboration with others.
- Both the check source and scanner should be made available to laboratories who might wish to repeat measurements or make further studies of sources of uncertainty in their measurements.
- The results of this study should be made available to the IEC and those participating laboratories who have representatives on the relevant IEC technical committees and working groups should be encouraged to make proposals which may be taken into account in possible future standards. (Section 12 of this report and appendix 3 are relevant here.)
- Systematic study of the influence of different measurement systems on the fields radiated by the Dynamic Imaging scanner could be carried out both experimentally and by theoretical modelling, perhaps by means of collaborations between the co-ordinating laboratory, NPL (which possesses a large collection of different sizes and types of hydrophone), and other participating laboratories.

14.3 Exploitation of results

Owing to the nature of the project, there are no new products or designs arising from the work reported here which may be the subject of future commercial exploitation. Nevertheless, it is planned to disseminate the results of the project in several ways.

- At least one scientific paper will be produced by the co-ordinator for submission to a European journal, following acceptance of this report by the European Commission. This will help publicise the results to a wider scientific community.
- A project summary will be provided to the European Commission by the co-ordinator to allow the Commission to publicise the results of the project more widely throughout the Community.
- The findings of the project may be publicised by means of a poster at the 25th BCR Anniversary Conference, which takes place in Brussels in November 1998.
- As mentioned in the previous section, the reference devices will be made available to participating laboratories who wish to check the quality of the measurements or re-test aspects of their own measurement protocols.

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APPENDIX 1: TABULATION OF CHECK SOURCE RESULTS

TABLE A1: CHECK SOURCE - LABORATORY A	
Transducer-hydrophone separation 52 mm - indicate how measured	Time delay
Total power (indicate how measured)	8 mW ($\pm 34\%$)
Peak-negative acoustic pressure	1.9 MPa ($\pm 17\%$)
Peak-positive acoustic pressure	2.2 MPa ($\pm 17\%$)
Spatial-peak temporal-average intensity	160 mW cm ⁻² ($\pm 35\%$)
Pulse-pressure-squared integral	1400000 Pa ² s ($\pm 35\%$)
-6 dB beam-width	2.7 mm ($\pm 5\%$)
Acoustic working frequency	3.7 MHz ($\pm 7\%$)
Pulse repetition rate	1.75 kHz
Temperature of water during measurements	20.5° C
Hydrophone:	
type	NP-1000 pvdf needle
element size	0.5 mm diameter
bandwidth	1-20 MHz
sensitivity free-field end-of-cable	1.407 μ V Pa ⁻¹ -237 dB re 1V μ Pa ⁻¹
calibration (indicate method and date of last calibration)	16 th February 1990 planar scanning technique
Amplifier:	HP-2130
gain	30 dB
bandwidth	500 kHz-40 MHz
Method of data capture and digitisation	Waveform digitiser WD 4000 and Tektronix TDS 520A oscilloscope

TABLE A2: CHECK SOURCE - LABORATORY B	
Transducer-hydrophone separation 52 mm - indicate how measured	Mechanical - slide gauge
Total power (indicate how measured)	4.73 mW ($\pm 29\%$) Beam calibrator hydrophone
Peak-negative acoustic pressure	1.28 MPa ($\pm 15\%$)
Peak-positive acoustic pressure	2.82 MPa ($\pm 15\%$)
Spatial-peak temporal-average intensity	103 mW cm ⁻² ($\pm 29\%$)
Pulse-pressure-squared integral	878000 Pa ² s ($\pm 29\%$)
-6 dB beam-width	2.48 mm ($\pm 8\%$)
Acoustic working frequency	3.65 MHz ($\pm 5\%$)
Pulse repetition rate	1.73611 kHz
Temperature of water during measurements	21.7° C ($\pm 0.5\%$)
Hydrophone:	
type	GEC-Marconi pvdf 21-element membrane hydrophone, type Y-34-6522
element size	0.4 mm diameter 0.6 mm spacing between elements
bandwidth	0.5-20 MHz
sensitivity free-field end-of-cable	520 nV Pa ⁻¹
calibration (indicate method and date of last calibration)	Nonlinear intercomparison method, NPL 17 th August 1994
Amplifier:	UBC module SN0002E
gain	0-59dB in 1 dB steps
bandwidth	23 MHz (-3dB)
Method of data capture and digitisation	8-bit flash ADC, 7.5 to 60 MHz

TABLE A3: CHECK SOURCE - LABORATORY C	
Transducer-hydrophone separation 52 mm - indicate how measured	Time delay
Total power (indicate how measured)	4.37 mW ($\pm 6.4\%$)
	Power balance
Peak-negative acoustic pressure	1.18 MPa ($\pm 11\%$)
Peak-positive acoustic pressure	2.82 MPa ($\pm 11\%$)
Spatial-peak temporal-average intensity	91.46 mW cm ⁻² ($\pm 24\%$)
Pulse-pressure-squared integral	777000 Pa ² s ($\pm 22\%$)
-6 dB beam-width	2.5 mm ($\pm 4\%$)
Acoustic working frequency	3.6 MHz ($\pm 0.3\%$)
Pulse repetition rate	1.748 kHz ($\pm 1\%$)
Temperature of water during measurements	24° C ($\pm 0.2^{\circ}\text{C}$)
Hydrophone:	
type	Force Institute pvdf needle
element size	0.5 mm
bandwidth	0.5-20 MHz
sensitivity free-field end-of-cable	127.4 nV Pa ⁻¹ ($\pm 7\%$)
calibration (indicate method and date of last calibration)	April 1997, June 1997; time delay spectrometry
Amplifier:	details not provided
gain	
bandwidth	
Method of data capture and digitisation	8-bit resolution, 200 MHz bandwidth digital oscilloscope

TABLE A4: CHECK SOURCE - LABORATORY D	
Transducer-hydrophone separation 52 mm - indicate how measured	Time delay
Total power (indicate how measured)	3.76 mW ($\pm 24\%$)
Peak-negative acoustic pressure	Hydrophone 1.32 MPa ($\pm 12\%$)*
Peak-positive acoustic pressure	3.6 MPa ($\pm 12\%$)*
Spatial-peak temporal-average intensity	122 mW cm ⁻² ($\pm 22\%$)*
Pulse-pressure-squared integral	1080000 Pa ² s ($\pm 22\%$)*
-6 dB beam-width	2.5 mm ($\pm 7\%$)
Acoustic working frequency	3.61 MHz ($\pm 1\%$)
Pulse repetition rate	1.748 kHz
Temperature of water during measurements	19.5° C
Hydrophone:	
type	GEC-Marconi bilaminar shielded membrane type Y-34-3598
element size	0.5 mm
bandwidth	1-25 MHz
sensitivity free-field end-of-cable	41 μ V Pa ⁻¹ ($\pm \%$) for combined hydrophone and amplifier system
calibration (indicate method and date of last calibration)	August 1993: nonlinear intercomparison method at NPL
Amplifier:	GEC-Marconi Y-33-9724
gain	17 dB
bandwidth	0.2 - 23 MHz
Method of data capture and digitisation	Tektronix TDS360 digital oscilloscope, calibrated 1997

* values corrected for spatial averaging by hydrophone.

TABLE A5: CHECK SOURCE - LABORATORY E	
Transducer-hydrophone separation 52 mm - indicate how measured	Mechanically
Total power (indicate how measured)	3.6 mW ($\pm 41.25\%$) Hydrophone - planar scanning
Peak-negative acoustic pressure	1.18 MPa ($\pm 11.14\%$)
Peak-positive acoustic pressure	3.34 MPa ($\pm 20.30\%$)
Spatial-peak temporal-average intensity	101.7 mW cm ⁻² ($\pm 40.71\%$)
Pulse-pressure-squared integral	860800 Pa ² s ($\pm 40.61\%$)
-6 dB beam-width	2.47 mm ($\pm 1\%$) (parallel) 2.41 mm ($+ 1\%$) (perpendicular)
Acoustic working frequency	3.6 MHz ($\pm 1\%$)
Pulse repetition rate	1.748 kHz ($\pm 0.01\%$)
Temperature of water during measurements	20 $\pm$ 0.2° C
Hydrophone:	
type	GEC-Marconi 25 μ m thickness pvdf bilaminar shielded membrane type Y-34-6527
element size	0.5 mm
bandwidth	1-25 MHz
sensitivity free-field end-of-cable	53 nV Pa-1 ($\pm 6\%$) for combined hydrophone and amplifier system
calibration (indicate method and date of last calibration)	May 1992: nonlinear intercomparison method at NPL
Amplifier:	GEC-Marconi pre-amplifier
gain	-6.73 $\pm$ 0.05 dB
bandwidth	75 MHz
Method of data capture and digitisation	Tektronix TDS520 digital oscilloscope

TABLE A6: CHECK SOURCE - LABORATORY F	
Transducer-hydrophone separation 52 mm - indicate how measured	Time delay
Total power (indicate how measured)	3.63 mW ($\pm 19\%$) hydrophone
Peak-negative acoustic pressure	1.2 MPa ($\pm 8\%$)
Peak-positive acoustic pressure	2.57 MPa ($\pm 10\%$)
Spatial-peak temporal-average intensity	88.5 mW cm ⁻² ($\pm 16\%$)
Pulse-pressure-squared integral	735000 Pa ² s ($\pm 17\%$)
-6 dB beam-width	2.52 mm ($\pm 6\%$) parallel 2.37 ($\pm 6\%$) perpendicular
Acoustic working frequency	3.6 MHz
Pulse repetition rate	1.738 kHz
Temperature of water during measurements	20° $\pm$ 1° C
Hydrophone:	
type	GEC-Marconi coplanar membrane, 9 μ m thick pvd film
element size	0.5 mm diameter
bandwidth	> 60 MHz
sensitivity (value at acoustic working frequency): free-field open circuit	32.5 nV Pa ⁻¹
calibration (indicate method and date of last calibration)	NPL nonlinear intercomparison method February 1995
Amplifier:	
gain	-7.5 dB
bandwidth	> 60 MHz
Method of data capture and digitisation	Tektronix 2430A digital oscilloscope

TABLE A7: CHECK SOURCE - LABORATORY G	
Transducer-hydrophone separation 52 mm - indicate how measured	Mechanical positioning system of beam plotting tank controlled by Sony Magnescales with resolution of 2 μm
Total power (indicate how measured)	4.1 mW ($\pm 12.1\%$) radiation force balance 3.9 mW ($\pm 28.3\%$) planar scanning
Peak-negative acoustic pressure	1.1 MPa ($\pm 11.2\%$)
Peak-positive acoustic pressure	3.0 MPa ($\pm 11.2\%$)
Spatial-peak temporal-average intensity	85 mW cm ⁻² ($\pm 23.1\%$)
Pulse-pressure-squared integral	718000 Pa ² s ($\pm 22.3\%$)
-6 dB beam-width	2.40 mm ($\pm 3.9\%$) parallel 2.25 ($\pm 3.9\%$) perpendicular
Acoustic working frequency	3.58 MHz
Pulse repetition rate	1.751 kHz
Temperature of water during measurements	20° $\pm$ 1° C
Hydrophone:	
type	Force Institute pvdf needle probe type MHA9-4
element size	0.4 mm diameter
bandwidth	> 60 MHz
sensitivity (value at acoustic working frequency):	30.3 nV Pa ⁻¹ (free field end-of cable)
calibration (indicate method and date of last calibration)	Two transducer reciprocity: October 1995
Amplifier:	
gain	not specified
bandwidth	> 60 MHz
Method of data capture and digitisation	Tektronix 2440 digital oscilloscope

TABLE A8: CHECK SOURCE - LABORATORY H	
Transducer-hydrophone separation 52 mm - indicate how measured	NPL Beam Calibrator: mechanical positioning system
Total power (indicate how measured)	4.3 mW ($\pm 9\%$) Bath Mark 2 power balance 4.7 mW ($\pm 58\%$) NPL Beam Calibrator
Peak-negative acoustic pressure	1.24 MPa ($\pm 12\%$)
Peak-positive acoustic pressure	2.77 MPa ($\pm 20\%$)
Spatial-peak temporal-average intensity	100 mW cm ⁻² ($\pm 27\%$)
Pulse-pressure-squared integral	859000 Pa ² s ($\pm 27\%$)
-6 dB beam-width	2.48 mm ($\pm 19\%$) parallel 2.48 ($\pm 19\%$) perpendicular
Acoustic working frequency	3.65 MHz
Pulse repetition rate	1.736 kHz
Temperature of water during measurements	21.5° C
Hydrophone:	
type	GEC-Marconi 21-element array hydrophone for NPL beam calibrator
element size	0.5 mm diameter
bandwidth	
sensitivity (value at acoustic working frequency)	
calibration (indicate method and date of last calibration)	Nonlinear intercomparison method at NPL November 1992
Amplifier:	
gain	
bandwidth	
Method of data capture and digitisation	NPL Beam Calibrator, software version 5.0

TABLE A9: CHECK SOURCE - LABORATORY J	
Transducer-hydrophone separation 52 mm - indicate how measured	Time delay - corrected for temperature
Total power (indicate how measured)	4.67mW ($\pm 10\%$) radiation force balance
Peak-negative acoustic pressure	1.108 MPa ($\pm 8\%$)
Peak-positive acoustic pressure	3.17 MPa ($\pm 8\%$)
Spatial-peak temporal-average intensity	103 mW cm ⁻² ($\pm 18\%$)
Pulse-pressure-squared integral	820000 Pa ² s ($\pm 16\%$)
-6 dB beam-width	2.438 mm ($\pm 1.5\%$)
Acoustic working frequency	3.6047 MHz ($\pm 0.1\%$)
Pulse repetition rate	1.747878 kHz ($\pm 0.002\%$)
Temperature of water during measurements	22.86° C $\pm$ 0.12°C
Hydrophone:	
type	GEC-Marconi bilaminar shielded membrane type Y-34-3598
element size	0.5 mm diameter
bandwidth	> 20 MHz
sensitivity (value at acoustic working frequency): free-field open circuit free-field end-of-cable loaded	49 nV Pa ⁻¹ ($\pm 6\%$) 46 nV Pa ⁻¹ ($\pm 6\%$)
calibration (indicate method and date of last calibration)	Nonlinear intercomparison method, NPL: March 1995
Amplifier:	GEC-Marconi type Y-33-9724
gain	17.0 $\pm$ 0.3 dB
bandwidth	23 MHz
Method of data capture and digitisation	LeCroy 9350AM digital sampling oscilloscope

TABLE A10: CHECK SOURCE - LABORATORY K	
Transducer-hydrophone separation 52 mm - indicate how measured	Time delay
Total power (indicate how measured)	5.3 mW ($\pm 38\%$)
Peak-negative acoustic pressure	1.096 MPa ($\pm 17\%$)
Peak-positive acoustic pressure	2.655 MPa ($\pm 17\%$)
Spatial-peak temporal-average intensity	82 mW cm ⁻² ($\pm 37\%$)
Pulse-pressure-squared integral	700000 Pa ² s ($\pm 43\%$)
-6 dB beam-width	2.60 mm ($\pm 5\%$)
Acoustic working frequency	3.56 MHz ($\pm 6\%$)
Pulse repetition rate	1.748 kHz ($\pm 0.1\%$)
Temperature of water during measurements	22.5° C ($\pm 9\%$)
Hydrophone:	
type	pvdf needle with integral pre-amplifier
element size	0.4 mm diameter
bandwidth	approximately 60 MHz
sensitivity	average sensitivity 50 nV Pa ⁻¹ in 50 Ω load
calibration (indicate method and date of last calibration)	29 th November 1995 at Force Institute, Denmark; method assumed to be time delay spectrometry
Amplifier:	
gain	information not provided
bandwidth	60 MHz
Method of data capture and digitisation	analogue-to-digital converter, 8 bit, 200 megasamples per second

APPENDIX 2: ADDRESSES OF PARTICIPATING LABORATORIES AND EUROPEAN COMMISSION PROJECT OFFICER

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APPENDIX 3: COMMENTS ON WORKING WITH IEC 61157 BY LABORATORY J.

This appendix sets out the specific comments on working with IEC 61157 which were submitted by laboratory J and these should be regarded as representing the views of that laboratory only.

Summary

1. The requirements for the measurement of some parameters are unclear, sometimes contradictory and scattered in several obscure corners of the document.
2. The document is very difficult to follow and it is necessary to constantly refer back and forth.
3. The standard makes no allowance for transients, or settling times to reach steady state values.
4. The whole standard is based around the measurement of pulse pressure squared integral but the rationale for this is not given and there is no requirement to declare this parameter.

Specific comments

1. The maximum temporal average power is a very important safety related parameter in its own right and is crucial for calculating I_{ob} , yet it is not rigorously defined anywhere in the standard.
2. The method of measuring output beam intensity (I_{ob}) for scanning modes is unclear. According to paragraphs 3.15, 3.13, and 3.14 the definition of I_{ob} is the temporal average power divided by the output beam area derived from the -6 dB maximum beam dimensions at the transducer output face. Paragraph 4.2.2.a) states that for scanning modes temporal average power shall be the “total power output of all the acoustic pulses” - presumably meaning that it corresponds to the total temporal average power for the whole field. Paragraph 4.2.2.i) states that the output beam dimensions should be those of the central scan line. Is this correct?
3. The system settings under which the parameters (a) to (q) in Section 4.2.2 should be measured should be stated more clearly:

The second paragraph of Section 4.2.2 implies the settings for:

- a) temporal average power
- b) p - in the plane of maximum pressure squared integral (p_i)
- c) I_{ob}
- d) I_{SPTA}

should be those that maximise each of these (presumably respectively). Yet it also states that, unless otherwise specified, the system settings for the remaining parameters should be the same as for “these” parameters (presumably meaning parameters (a) to (d). So, for example, what control settings should be used when measuring W_{pb6} ? Those that maximise a), b), c) or d)?

The final paragraph of Section 4.2.2 infers that the system settings for power should be the same as for I_{ob} - parameters a) and c) are grouped together in this paragraph and power and I_{ob} share the same settings in the example of Table A1 (Annex A). This will not always be true since changing the aperture of an array, for example as a result of changing the focal length, may not change the output power in strict proportion to the change in output beam area.

4. Section 4.2.2, paragraph. 2. It would be helpful if “for a particular mode” were inserted after “for a particular transducer assembly and associated ultrasound instrument console”.

5. Paragraph 4.2.2.f). In scanning modes, the range at which the I_{SPTA} is found is frequently different to that of max. ppsi. The “NOTE:” suggests this occurs only when multiple foci or sector scanner are used.

6. Paragraph 4.2.3.1.a). The beam alignment axis is defined as passing through two points of spatial peak temporal peak pressure. Since p. need not occur at the point of maximum ppsi, this axis may not pass through the point of maximum ppsi, as required by the final sentence of paragraph. 4.2.3.1a).

7. Paragraph 4.2.2.g). “For scanning modes, the beam-width shall correspond to the central scan line only”. This will not always be the scan line that passes through the point of max ppsi, as required by the first sentence of paragraph. 4.2.2.g).

8. Paragraph. 4.2.2.j). It is stated here that arithmetic mean acoustic working frequency (f_{awf}) should be measured at the point of maximum ppsi. This contradicts paragraph. 3.30, which states that the definition of f_{awf} conforms to IEC 1102, paragraph 3.4.2. The latter specifies that the measurement should be made at the point of spatial-peak temporal-peak acoustic pressure.

9. Paragraph 3.42. The reference to IEC 61102, paragraph. 3.51 is presumably a typing error for paragraph 3.57.

10. There is inconsistency in these references to IEC 61102, in that some are identical to the definition in IEC 61157 (as in 10 above) and are therefore unnecessary, and some are in conflict (as in 9 above).

11. The output of scanners can vary considerably with time after power-up, and after switching between modes. Large percentage variations in all the acoustical parameters a) to d) can occur, depending on how soon after power up or the switching of modes any measurements are made. There is no mention in the standard of letting outputs settle to steady state before measurements.

12. The parameter “spatial peak temporal peak acoustic pressure” is mentioned in the definition of beam-alignment axis (and elsewhere) but is not itself defined anywhere in this document.
13. In paragraph. 3.14 it is stated that output beam dimensions should be made at the transducer output face. This may be impractical due to the physical size of the hydrophone and the presence of multiple reflections. Would it not be more realistic to say “as close as possible to the output face”, and to require that the distance from the face be reported?
14. The whole standard is based around the measurement of max. pulse pressure squared integral but it is nowhere required to declare its value. If it is so important, why not declare it? (The plot of ppsi is only required as background information.) There is no justifying argument given for the use of maximum ppsi as a determining factor for other measurement.
15. Section 4.2.2 (first paragraph) states it is necessary to declare values of parameters for combined operating modes only if the system can “operate only in combined-operating modes”. Annex C paragraph. 10 contradicts this and states the requirement is the declaration of acoustic output information “for combined-operating modes only if their levels exceed those of any of the discrete operating modes”. This paragraph is supported by the last two paragraphs of Annex B, section 4.2 and elsewhere.
16. See Table A1. The output beam dimensions for something that is presumably a rectangular probe (phased array) are quoted as a diameter. There is no mention of “equivalent diameters” anywhere in this standard.

APPENDIX 4: PROJECT PROTOCOL

PROCEDURE

**AN ASSESSMENT OF MEDICAL ULTRASONIC
FIELD
MEASUREMENTS**

Contract no. MAT1-CT940064

Author: Trevor Esward

October 1995

Introduction

This document describes the procedure to be employed for the European collaborative project entitled "An assessment of medical ultrasonic field measurements" (contract no. MAT1-CT940064). The aim of the project is to assess the ability of metrology laboratories and other relevant organisations to apply the measurement procedures set out in the International Electrotechnical Commission Standard IEC 61157: 1993, "Requirements for the declaration of the acoustic output of medical diagnostic ultrasonic equipment". This standard is already being used by European manufacturers as a means of demonstrating compliance with the Essential Requirements of the E.C. Medical Devices Directive which came into effect on 1 January 1995 (93/42/EEC). The project is being co-ordinated by the National Physical Laboratory (NPL), UK.

The remainder of this document describes briefly the two systems on which measurements are required, provides some practical guidance on the making of those measurements and indicates how the results are to be reported.

Any questions relating to the project should in the first instance be addressed to the Project Manager at the address below:

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Project summary

The project will be organised radially, with NPL making an initial set of reference measurements on the devices to be characterised and then forwarding the devices to the first participating laboratory. It is envisaged that each laboratory will require the devices for approximately three months. When a laboratory has completed its measurements the devices will be returned to NPL. NPL will then undertake further test measurements to confirm the stability of the acoustic output parameters, and send the devices to the next participating laboratory.

Measurements of acoustic output parameters are required for two systems: an NPL check source and a Dynamic Imaging Concept M/C scanner fitted with a 5 MHz linear array transducer. Both the check source and the scanner transducers are fully immersible in water.

The acoustic parameters to be measured in the course of the project are taken to be as defined in section 3, paragraphs 3.1 to 3.42 of IEC 61157. The attention of participating laboratories is also drawn to section 7 of IEC 61157 which specifies that test methods should be based on the use of hydrophones in accordance with IEC 1102¹, or the use of radiation force balances for power measurements in accordance with IEC 61161². If participants employ measurement techniques which are outside the scope of IEC 61157, this fact must be identified in the reports for the measurements.

Check source

The check source is a simple, self-contained system which provides a stable acoustic output via a 13 mm diameter single-element transducer connected to electronic

¹Measurement and characterization of ultrasonic fields in the frequency range 0.5 MHz to 15 MHz

²Ultrasonic power measurement in liquids in the frequency range 0.5 MHz to 25 MHz.

circuitry housed within its casing. The front panel control provides a power-on switch, a choice of low or high amplitude settings and a trigger output point. For the project only the high amplitude output should be used.

The purpose of requiring measurements to be made on the check source is to provide a simple test of the accuracy of the participants' measurement systems. The data from the check source measurements, including calculations of uncertainties in those measurements, will assist in the interpretation of the results obtained with the 5 MHz linear array.

In making the check source measurements, all participating laboratories are required to conform to the following procedure:

1. The check source transducer should be placed in position and left switched on for an hour before measurements are begun.
2. The transducer-to-hydrophone distance employed for the measurements shall be 52 mm. The laboratory may determine this distance either by a mechanical measurement of the transducer-hydrophone separation, or by calculating the time delay from the trigger signal to the receipt of the acoustic pulse. The method of determining the separation must be reported.
3. The acoustic data to be provided at the 52 mm position are:

- Total power;
- Peak-negative acoustic pressure;
- Peak-positive acoustic pressure³;
- Spatial-peak temporal-average intensity;
- Pulse-pressure-squared integral;
- 6 dB beam-width;
- Acoustic working frequency;

³Although International Standards do not require the declaration of this parameter, it is required here as it may provide valuable information concerning the measurement system used.

Pulse repetition rate;

Plot of the acoustic pulse waveform.

Report the temperature at which measurements are made.

4. Provide details of the type, geometrical size of the element and -3 dB bandwidth of the hydrophone used for the measurements, together with details of its free-field open circuit sensitivity at the acoustic working frequency (see IEC 1102), and the gain and bandwidth of amplifiers. If an integral hydrophone/amplifier is used, give the free-field loaded sensitivity of the hydrophone/amplifier combination (see IEC 1102). If power measurements are made by other methods, such as a radiation force balance, please give details of the method employed and cite relevant references from the scientific literature. Also, please specify if calibrations of hydrophones, amplifiers, force balances etc. are traceable to national or international standards.

5. Give values for the random and systematic uncertainties for each measured quantity, including brief details of how the uncertainties were estimated. For the random uncertainty, state the number of repeat measurements made. The attention of participants is drawn to the document "The expression of uncertainty in electrical measurements", NAMAS Executive Publication B3003, edition 7, 1986, National Measurement Accreditation Service, National Physical Laboratory, Teddington, Middlesex TW11 0LW, UK.

6. If corrections to the raw data are made for such effects as spatial-averaging, or the limited bandwidth of hydrophones and amplifiers, please provide both raw and corrected data together with details of the correction methods employed, citing any references to the scientific literature, where appropriate. If spatial-averaging and bandwidth corrections are made in accordance with IEC 61220, "Guidance for the measurement and characterisation of ultrasonic fields generated by medical ultrasonic equipment using hydrophones in the frequency range 0.5 to 15 MHz", it will be sufficient to cite that document and no further details need be provided.

Scanner

Details of the method of operation of the Dynamic Imaging scanner are contained in the manufacturer's manual which is enclosed with the scanner. It should be noted that the rear panel of the scanner has been modified to provide two trigger points: that marked "Reset" provides signals at the frame repetition rate, and that marked "P.R.F." at the individual pulse or scan line repetition rate. The trigger signals consist of positive going rectangular pulses of 0 to 20 Volts into a 50 Ohm load.

In the case of the scanner, all participating laboratories are required to carry out and report the results of a complete characterisation of the device in accordance with section 4 of IEC 61157 for modes B and M. The work on the scanner must be carried out in two stages.

Part 1 consists of participants investigating the operation of the scanner and identifying the system settings and transducer-hydrophone separations where the maximum pulse-pressure-squared integral and the maximum spatial-peak temporal-average intensity are to be found in both operating modes. These settings and distances must then be reported to NPL in a form given in Appendix 1. At the same time, if possible, the acoustic waveform for the check source must also be provided. These settings and distances will be compared to those determined at NPL and participants will be authorised to proceed to Part 2 of the measurements either at the settings they have determined during Part 1 or at settings specified by NPL. If it becomes necessary for NPL to specify the settings and they differ from those determined by the participant during Part 1, then following the completion of the Part 2 measurements the participating laboratory shall report measurements both for its own determined settings and those provided by NPL.

Participating laboratories shall follow the procedures laid down in IEC 61157, with the exception that if it is found that the settings which give the maximum pulse-pressure-squared integral and the maximum spatial-peak temporal-average intensity are different, then in the case of the maximum spatial-peak temporal-average intensity it shall only be necessary to report its value, the hydrophone-transducer separation, and the settings which gave that value.

During investigations of the scanner, participating laboratories will find it necessary to vary both the focal zone and skin line settings. Focal zone 1 should be taken to be the zone closest to the transducer, as shown on the scanner display. The skin line default setting on power up should be regarded as setting no. 1 and skin line setting values should be treated as increasing as deeper parts of the image are brought closer to the top of the display screen.

Reporting the results

Results should be reported in accordance with the guidance set out in the Appendices.

Appendix 1 provides a form for reporting the scanner settings which give maximum output, a completed copy of which may be faxed to NPL together with a copy of the check source acoustic waveform, following completion of Part 1 of the investigation.

Appendix 2 gives a list of information required for the check source. The table provided in this appendix may be used as the basis of the report to NPL. However, laboratories may also find it necessary to provide additional information about their measurement system and measurement methods, assessment of uncertainties etc. in accordance with the guidance set out earlier in this protocol.

Appendix 4 provides a check list of data required for the scanner measurements following Part 2 which may also be used as a pro-forma report form.

APPENDIX 1**Reporting of Part 1 results - scanner settings for maximum output**

TABLE 1 : SCANNER SETTINGS FOR MAXIMUM OUTPUT				
	B MODE		M MODE	
SETTINGS	Max psi	Max I_{SPTA}	Max psi	Max I_{SPTA}
Magnification				
Focal zone				
Skin line				
Other ⁴				
Transducer-hydrophone separation				

psi = pulse-pressure-squared integral

I_{SPTA} = spatial-peak temporal-average intensity

IN ADDITION, PLEASE PROVIDE A COPY OF CHECK SOURCE ACOUSTIC WAVEFORM.

⁴If necessary, indicate any other scanner control which appeared to affect the scanner output.

APPENDIX 2**Check source - acoustic data required to be reported**

TABLE 2: CHECK SOURCE - INFORMATION REQUIRED	
Transducer-hydrophone separation 52 mm - indicate how measured	
Total power (indicate how measured)	
Peak-negative acoustic pressure	
Peak-positive acoustic pressure	
Spatial-peak temporal-average intensity	
Pulse-pressure-squared integral	
-6 dB beam-width	
Acoustic working frequency	
Pulse repetition rate	
Temperature of water during measurements	
Hydrophone:	
type	
element size	
bandwidth	
sensitivity (value at acoustic working frequency): free-field open circuit free-field end-of-cable	
calibration (indicate method and date of last calibration)	
Amplifier:	
gain	
bandwidth	
Method of data capture and digitisation	

TABLE 2: CHECK SOURCE - INFORMATION REQUIRED	
Acoustic pulse waveform (provide plot of waveform)	

PLEASE PROVIDE VALUES PRIOR TO APPLYING ANY CORRECTIONS TOGETHER WITH RANDOM UNCERTAINTIES AND CORRECTED VALUES.

APPENDIX 4

Table 3 provides a check list of the main parameters required for the IEC 61157 characterisation of the Dynamic Imaging scanner. **Note that the list is provided for guidance only. It is not intended to provide an exhaustive account of the required acoustic parameters.** Participating laboratories should refer to IEC 61157 for full details of the necessary measurements.

If measurements are made at two settings, those originally identified by the participating laboratory following the completion of Part 1 and the preferred settings notified by NPL, a separate copy of the table should be completed for each set of measurements.

TABLE 3: DYNAMIC IMAGING SCANNER - CHECK LIST OF MAIN PARAMETERS REQUIRED FOR EACH MODE OF OPERATION		
	B MODE	M MODE
Maximum temporal-average power output		
Peak-negative acoustic pressure		
Output beam intensity		
Spatial-peak temporal-average intensity		
Instrument console settings for each of the above values		
Distance from transducer output face to point of maximum pulse-pressure squared integral		
-6dB beam-width (perpendicular and parallel)		
Pulse repetition rate		
Output beam dimensions parallel and perpendicular to reference direction.		
Acoustic working frequency		
Axial plot of peak-negative acoustic pressure and pulse-pressure-squared integral		
Acoustic pulse waveform at position of maximum pulse-pressure-squared integral		
Bandwidth of acoustic waveform		

TABLE 3: DYNAMIC IMAGING SCANNER - CHECK LIST OF MAIN PARAMETERS REQUIRED FOR EACH MODE OF OPERATION		
	B MODE	M MODE
Number of scan lines in a repetition period		
Scan line separation		
Hydrophones and amplifiers (only provide information if different from those used for check source measurements)		
Transducer-hydrophone separation (indicate method of determining distances)		
Temperature of water during measurements		

PLEASE PROVIDE UNCORRECTED VALUES TOGETHER WITH RANDOM UNCERTAINTIES AND CORRECTED VALUES AS REQUESTED FOR CHECK SOURCE MEASUREMENTS.