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THE PERFORMANCE OF THE NPL ULTRASOUND BEAM CALIBRATOR: PART 1 PHYSIOTHERAPY TRANSDUCERS

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SUMMARY

The performance of the NPL Ultrasound Beam Calibrator (BECA2) has been assessed for measurements of the acoustic output of physiotherapy transducers. Reflection from the polyvinylidene fluoride membrane hydrophone used to determine the sound field and lack of cylindrical symmetry of the beam emitted by physiotherapy transducers are considered, and guidelines given for minimising their effect on the measurements. Sources of systematic and random uncertainty are considered and typical values for these quantities are given.

CONTENTS

1. INTRODUCTION

The NPL Ultrasound Beam Calibrator, BECA2, has been developed to provide rapid quantitative measurements of the acoustic output of medical ultrasonic equipment. It consists of a multielement membrane hydrophone and a fast data acquisition and presentation system to provide a real-time display of the beam profile and the acoustic pressure temporal waveform. The membrane hydrophone is made of polyvinylidene fluoride and has a linear array of 21 active elements, each one of diameter 0.5 mm spaced at 1 mm intervals. It is mounted horizontally in a versatile test-tank filled with deionised/degassed water, as shown in Figure 1, and the transducer under test is held above the hydrophone by a clamp in a coordinate-positioning system which has adjustment in a horizontal plane and which can also be rotated about a vertical axis. The separation between the hydrophone and the transducer can also be varied. The system stores the acoustic pressure waveform data from each of the hydrophone elements and can be instructed to calculate a whole set of acoustic pressure, derived-intensity and total-power parameters.

This report deals with the application of the BECA2 system to measurements of the acoustic output of ultrasonic physiotherapy transducers - whilst a subsequent report will deal with the application to measurements of the acoustic output of ultrasonic diagnostic transducers.

2. PHYSIOTHERAPY TRANSDUCERS

Ultrasonic transducers used for physiotherapy usually have plane circular active elements with diameters between 10 mm and 30 mm, operate in the frequency range 0.5 to 3 MHz, and are electrically excited in continuous wave or long tone-burst mode. When the Beam Calibrator, BECA2, is used for the determination of the acoustic output of this type of transducer, problems can occur because the ultrasound reflected from the membrane affects the output of the transducer. In addition, standing waves can be produced if the transducer also reflects the ultrasound. For a bilaminar hydrophone, which is the type usually used in BECA2, the amplitude reflection coefficient varies between 9% and 45% over the frequency range 0.5 to 3 MHz and this is high enough to create significant problems. Whilst the usual method of minimising the effects of membrane reflections is to rotate the hydrophone so that the reflected wave misses the transducer, an additional problem for physiotherapy transducers is that the usual requirement is to measure acoustic output parameters in the near field of the transducer, often within a distance of one or two transducer diameters, so that a large angular rotation of the hydrophone is required. This could introduce errors due to the directional response function of the hydrophone active element; the effect of hydrophone rotation has therefore been investigated and procedures are given for determining appropriate correction factors.

Yet another problem in making measurements in the near field of ultrasonic transducers is the presence of fine structure in the spatial distribution of the ultrasonic field. With only 21 active elements, the linear-array membrane hydrophone used for BECA2 samples only a small portion of the ultrasonic field, i.e. only along the line defined by the array of active elements of the hydrophone. The determination of the spatial-maximum for acoustical parameters is achieved simply by moving the transducer in a horizontal plane until the maximum signal at a chosen hydrophone element is observed. However, parameters which require the whole field to be sampled, such as total power and spatial-average temporal-average derived intensity, are calculated by BECA2 on the assumption that the beam is cylindrically symmetrical and that the line sample is along a diameter or radius of the beam, i.e. it is assumed that the centre of the beam can be located. The significance of this assumption can be assessed using the facility provided on BECA2 which allows the transducer to be rotated so that a different line sample of the beam is taken and then comparing the results obtained; a number of measurements on typical physiotherapy transducers at different angular orientations are reported.

3. MEMBRANE HYDROPHONE PERFORMANCE

Figure 2 shows the amplitude and intensity reflection coefficients as a function of frequency for a bilaminar membrane hydrophone made from polyvinylidene fluoride of thickness 0.050 mm (1). As already mentioned, the interference between the ultrasound emitted by a physiotherapy transducer and the ultrasound reflected from the plane membrane introduces significant uncertainties in the measurements made using the hydrophone. It is possible to reduce these uncertainties by tilting the hydrophone, and this is accomplished in the usual BECA2 hardware configuration, shown in Figure 1, by rotating the membrane hydrophone about an axis passing through the plane of the membrane and colinear with the axis of the linear array.

3.1 Effects of membrane reflections on measurements

To investigate the effect of hydrophone rotation on the determination of relevant acoustic output parameters using BECA2, a series of measurements was undertaken on a 1.5 MHz physiotherapy transducer with an active element of diameter 20 mm and with the array axis of the membrane hydrophone 20 mm from the face of the transducer.

Figure 3 shows the total power, P, and the spatial-average temporal-average derived intensity, I_{SATA}, as a function of angular rotation of the hydrophone. As expected from interference effects, large oscillations occur at near-normal incidence but these decrease in amplitude with increasing hydrophone rotation. From a simple geometrical model, ultrasound emitted from the centre of the transducer and reflected from the membrane should miss the transducer for membrane angles greater than 14^{o} and this is approximately the angle at which the values derived for the two acoustical parameters do stabilise. Beyond this angle, the values for P and I_{SATA} begin to decrease due to the directional response of the hydrophone. Clearly, the directional response also influences the measurements at lower angles of rotation, but interference effects mask such observations. Hence, if the hydrophone rotation facility is to be used to overcome the problem of the interfering reflected ultrasound, it is necessary to correct the measurements of acoustical parameters for the directional response of the hydrophone. The following sections deal with measurement of directional response at discrete frequencies and the prediction of the directional response at other frequencies, leading to a general correction procedure for measurements made using BECA2.

3.2 Measurement of the hydrophone directional response

To evaluate the effect of the hydrophone directional response on the measured intensities, the amplitude directional response was determined at 2.25, 1.5 and 1.09 MHz. In all cases, the hydrophone was rotated about an axis in the plane of the membrane and colinear with the array axis. The separation between the transducer face and the array axis was equivalent to approximately the near field distance for each transducer used (a_1^2/λ where a_1 is the radius of the transducer active element and λ is the acoustic wavelength). Gated tone-burst excitation of the transducer with at least 20 cycles was used in all cases. Figure 4 shows the normalised results extending over the angular range of interest. Note that the intensity directional response, which is relevant to the determination of intensity or power parameters, is derived by squaring the amplitude response.

3.2.1 Predicting the directional response

The amplitude directional response function for a membrane hydrophone at a specified angular rotation, θ, depends on the frequency, f, according to the following relationship (2)

$$D_\theta(f) \propto \frac{J_1(x)}{x}$$

where J_1 is the first order Bessel function, $x = ka \sin \theta$, a being the radius of the active element of the hydrophone (0.25 mm in these measurements), and k ($=2\pi/\lambda$) the wavenumber. Thus, for a given angular rotation, θ, the ratio of the directional response at frequency f_1 to that at f_2 is given by

$$\frac{D_\theta(f_1)}{D_\theta(f_2)} = \frac{J_1(x_1)}{J_1(x_2)} \cdot \frac{x_2}{x_1} \qquad \ldots[1]$$

where x_1 and x_2 correspond to the frequencies f_1 and f_2 respectively.

Thus, by measuring the directional response at a particular frequency, it is possible to derive the directional response at other frequencies. The measured response at 2.25 MHz was used as a reference from which theoretically-derived responses were determined for other frequencies, and these were then compared with the corresponding experimentally-determined directional responses. Figure 5 shows the comparison between the experimentally-determined and theoretically-derived amplitude directional responses at 1.09 MHz; similar results were also obtained for 1.5 MHz. As the correction factor to be applied to measured acoustic pressure parameters is given by the inverse of the directional response factor, the accuracy of the correction may be estimated by examining the difference between the experimental and predicted correction factors. At frequencies of 1.5 and 1.09 MHz the root-mean-square difference is 12% and 20% respectively. In practice, the rotation of the hydrophone is less than 20^{o} so that the correction to be applied to the measured acoustic pressure parameters is usually less than +15%; consequently the uncertainty in the correction is less than $\pm$ 3%. For the derived intensity parameters and total power, corrections are less than +30% and the corresponding uncertainty less than $\pm$ 6% (assuming the usual plane progressive wave approximation for the relationship between acoustic pressure and intensity).

3.3 Procedure for choosing the angle of rotation

Once the distance between the transducer and the plane in which measurements are to be made has been decided, typically a distance equal to one or two times the transducer diameter, the hydrophone is gradually rotated about the array axis until the variation caused by interference decreases to an acceptable level. Peak-to-peak variation of less than 10% in acoustic pressure is a reasonable criterion to adopt. In practice, it is preferable to undertake measurements as a function of angular rotation and prepare a plot of the results similar to those shown in Figure 3 so that objective assessments of the residual oscillation can be made. Once the angle of rotation has been set, it is compared with the angle determined by geometrical considerations of the reflected ultrasound as mentioned in Section 3.1. If a_1 is the radius of the active element of the transducer and ℓ is the distance between the face of the transducer and the membrane array axis, then the angle given by geometrical considerations is $\tan^{-1}(a_1/2\ell)$. This angle has been found to be usually within $\pm$ 3^{o} of that found by rotating the hydrophone and observing when the oscillation decreases to less than 10%.

3.4 Determination of the directional response factor

In order to correct measurements for the effects of the hydrophone rotation, its directional response factor must be determined and there are three possible methods for doing this. The first is to derive a value from the experimental plots shown in Figure 4, the second is to use the data given in Figure 4 directly, whilst the third is to undertake separate measurements of the directional response. Whilst the latter is the most accurate and reliable method, and takes account of possible differences between hydrophones, it is not the most convenient. In practice, the most satisfactory method is to undertake a set of measurements of the directional response at a number of frequencies over the frequency range of interest and then to use the second method. The following procedures can be used in each case.

3.4.1 Derivation from experimental data

The amplitude directional response factor corresponding to the hydrophone rotation angle, θ_1, is read directly from the reference curve at 2.25 MHz shown in Figure 4. Equation [1] is now used to determine the directional response at frequency f from:

$$D_{\theta_1}(f) = D_{\theta_1}(2.25) \cdot \frac{J_1(x_1)}{J_1(x_2)} \cdot \frac{x_2}{x_1},$$

with $x_1 = 2\pi fa \sin\theta_1/c$,

and $x_2 = 2\pi 2.25\times10^6 a \sin\theta_1/c$

where $a = 2.5\times10^{-4}$ m.

3.4.2 Direct use of experimental data

If the frequency f is close to 1.09 or 1.5 MHz, the directional response factor may be read directly from the experimentally-determined values given in Figure 4. In practice, as most physiotherapy transducers operate at 1, 1.5 or 3 MHz, this procedure is adequate for many purposes.

3.4.3 Separate experimental determination

The third method is to determine experimentally the directional response factor in a manner similar to that described in Section 3.2.

3.5 Correcting for the directional response

Measurements made using BECA2 are corrected for the directional response factor in the following manner. For acoustical pressure parameters the results are divided by the directional response factor, D_θ, and for derived intensity parameters or total power the results are divided by the square of the directional response factor. A systematic uncertainty of $\pm$ 20(1-D_θ)% is applied to pressure parameters and $\pm$ 20(1-D_θ^2)% is applied to intensity and power parameters.

Figure 6 shows the result of correcting the measurements made on the 1.5 MHz physiotherapy transducer (given in Figure 3) using the experimental directional response data shown in Figure 4. Ideally, beyond the angle at which interference effects introduce variations, the corrected data should be independent of the rotation angle of the hydrophone. However, it would appear from Figure 6 that there is a gradual increase in the values for both acoustical parameters beyond an angle of 10°. This is probably due to the fact that the directional response data given in Figure 3 were determined in the far field of a transducer (where the field approximates to a plane wave) whilst the results have been applied to correct nearfield measurements. Nevertheless, providing the angular rotation of the hydrophone is chosen to be only just sufficient to overcome the interference effects in the manner outlined in Section 3.3, additional uncertainties from such over-correction are negligible.

4. CYLINDRICAL SYMMETRY OF THE TRANSDUCER

BECA2 is intended to be used for determining acoustical parameters which are related to the spatial distribution of the acoustical beam profile, such as beam-area, spatial-average temporal-average intensity and total power. It is assumed that the data recorded represent a diametrical sample of a cylindrically-symmetrical beam. The centre of the sample is assumed to be the 'centre' element of the hydrophone array; this can be any one of the 21 active elements although the default value is the central element (number 10). However, two assumptions are made. The first is that the orientation of the array axis represents a true diametrical or radial sample; whilst this is easy to achieve in situations where the beam profile has a single distinct peak, measurements undertaken in the near field of a transducer may be such that no single peak can be readily identified as being at the centre of the beam. The second assumption is that the beam is cylindrically symmetrical.

The following sections deal with measurements made on typical physiotherapy transducers, they detail procedures for reducing and estimating uncertainties.

4.1 Transducer rotation

To investigate the assumption of cylindrical symmetry, a number of measurements were made using BECA2 for different angular rotations of the transducer about an axis through the centre of the transducer parallel to the direction of propagation of the ultrasound. In these cases a unique peak in the beam distribution could be identified even though measurements were made at a transducer/hydrophone separation equal to approximately the diameter of the transducer. Thus, for each angular rotation, the horizontal position of the transducer was optimised for maximum signal at the designated centre element of the hydrophone. In practice, the central element was either element 2 or element 18 as the beam-width of the transducer exceeded that of the 21 element array (20 mm), so the data acquired by BECA2 represented a radial rather than a diametrical scan. The BECA2 software routines automatically treat such data as deriving from a radial rather than a diametrical scan as the control variable is the chosen centre element (denoted by + on the BECA2 display). Actually, for a transducer of the size used for physiotherapy applications, a multi-element hydrophone with 1 mm active elements spaced every 2 mm would be more appropriate.

The first set of measurements was undertaken on a 1.5 MHz transducer with the hydrophone tilted by approximately 12.5° and data were corrected using a factor of 0.94 for acoustic pressure parameters and 0.88 for intensity and power parameters, with residual uncertainties of $\pm$ 1.2% and $\pm$ 2.4% respectively. Figure 7 shows the derived spatial-average temporal-average intensity and the total power as a function of transducer rotation covering one complete rotation. Acoustical data may be derived either from the complete set of 18 measurements or from a sub-set of these diametrical (or radial) samples using the following method.

By treating the beam as being composed of sectors and letting f_n be the value of the particular acoustical parameter f derived from the n'th sector of angular width θ_n (in degrees), the average value $\bar{f}$ is given by:

$$\bar{f} = \frac{1}{360}\sum_{n=1}^{N} f_n\ \theta_n$$

where N is the total number of sectors. For equi-angular intervals this reduces to

$$\bar{f} = \frac{1}{N}\sum_{n=1}^{N} f_n.$$

This type of analysis was applied to the data shown in Figure 7 in two ways; the first was to treat it as a full set of 18 sectors and the second was to consider four sub-sets, each set composed of four measurements made with the transducer rotated by either 80° or 100° between successive measurements. The analysis was extended to include three other relevant acoustical parameters and the results are given in Table 1 together with three uncertainty values for each. The first uncertainty is the standard deviation derived from the variation within each set. The second is the random uncertainty, and the third is the overall uncertainty in the measurements (see Section 5.2), both expressed at 95% confidence level. Of course, these random uncertainties include contributions from cylindrical asymmetry.

It is interesting to note that the standard deviation for the full set is similar to the ones for the four smaller sets, showing that the measurements represent a mutually consistent set, a consequence of there being no major deviations from cylindrical symmetry in the ultrasonic beam. To examine the accuracy which can be achieved by taking only four measurements in a single sub-set, and consequently to provide guidance on the minimum number of rotational measurements which need be taken, the random uncertainties for the sets were compared. There is clearly agreement between all the sets of measurements well within the random uncertainties. In all cases, the total spread of results for the four sub-sets was less than 10%. Again, these confirm that the assumption of cylindrical symmetry was justified and that a limited number of diametrical samples is adequate for this transducer.

Results for independent measurements are also given in Table 1, based on measurements made using a single-element hydrophone and an extensive beam-plotting facility or, in the case of total power, a radiation-pressure technique. Uncertainties given for the independent measurements represent the total systematic uncertainty at 95% confidence level. As can be seen, there is agreement between the

Table 1 Values for five acoustical parameters determined from measurements on a 1.5 MHz physiotherapy transducer, where each set corresponds to a combination of measurements made at different transducer rotations. Three values of uncertainty are given: the first is the standard deviation; the second is the random uncertainty and the third is the overall uncertainty, both expressed at 95% confidence level. Comparison is also made with the results of independent measurements where the uncertainties correspond to the overall uncertainty (95% confidence level).

	p_+ (MPa)	I_{SPTA} (W cm^{-2})	I_{SATA} (W cm^{-2})	P (W)	Beam-area (cm^2)
Full set	0.290	2.37	0.561	2.73	4.61
	± 0.009	± 0.11	± 0.063	± 0.40	± 0.36
	± 0.005	± 0.06	± 0.032	± 0.20	± 0.18
	± 0.031	± 0.51	± 0.124	± 0.61	± 0.32
Sub-set 1	0.292	2.37	0.56	2.85	4.88
	± 0.011	± 0.06	± 0.071	± 0.36	± 0.06
	± 0.011	± 0.06	± 0.070	± 0.36	± 0.06
	± 0.033	± 0.51	± 0.138	± 0.71	± 0.29
Sub-set 2	0.288	2.33	0.570	2.74	4.59
	± 0.008	± 0.20	± 0.08	± 0.26	± 0.31
	± 0.008	± 0.20	± 0.08	± 0.26	± 0.30
	± 0.031	± 0.54	± 0.146	± 0.64	± 0.40
Sub-set 3	0.286	2.33	0.555	2.82	4.70
	± 0.012	± 0.05	± 0.067	± 0.58	± 0.51
	± 0.012	± 0.05	± 0.067	± 0.57	± 0.50
	± 0.032	± 0.50	± 0.136	± 0.83	± 0.57
Sub-set 4	0.290	2.42	0.567	2.63	4.40
	± 0.012	± 0.13	± 0.063	± 0.48	± 0.49
	± 0.012	± 0.12	± 0.062	± 0.47	± 0.48
	± 0.032	± 0.53	± 0.136	± 0.73	± 0.54
Independent measurements	0.254	2.20	0.500	2.80	4.80
	± 0.025	± 0.44	± 0.120	± 0.28	± 0.24

independent measurements and the various sets to well within the overall uncertainties.

For the four sub-sets, the average random uncertainty for the determination of the spatial-average temporal-average intensity and the total power parameters was ± 12% and ± 15% respectively.

Measurements were also made on a 1 MHz physiotherapy transducer with an active element of diameter 25 mm. Three sets of eight measurements were made, each set corresponding to a different transducer/hydrophone separation or transducer excitation voltage. Again the hydrophone was tilted so that the reflected ultrasound did not significantly interfere with the measurements, and the appropriate correction for directional response was applied as before. Results are given in Table 2 for two relevant acoustical parameters and, in the case of total power, comparison is made with independent measurements. Compared with the results for the 1.5 MHz transducer, the uncertainties for the sub-sets are generally larger because the beam is less symmetrical. Again, results agree with those obtained from independent measurements but overall the conclusion is that for this transducer a set of four measurements is probably insufficient to ensure 95% confidence uncertainties below ± 15%.

For the results given in Table 2, the average random uncertainty for the sub-sets was approximately ± 16% and ± 20% for I_{SATA} and total power respectively.

In comparing the results using BECA2 with the independent measurements, it is necessary to take account of additional sources of uncertainty when using BECA2 (see Section 5). The largest source of uncertainty is the absolute calibration of BECA2, which contributes ± 7.5% to acoustic pressure measurements and ± 15% to derived intensity measurements (95% confidence). Once these uncertainties are combined with those given in Tables 1 and 2, the uncertainties obtained using BECA2 are comparable with those using a single-element hydrophone but, as expected, exceed those associated with a radiation-pressure determination of total power.

Table 2 Values for I_{SATA} and total power determined from three different sets of measurements on a 1 MHz physiotherapy transducer. Each set corresponds to a combination of eight measurements made at different angular rotations of the transducer and is broken down into the full set of eight measurements or two sub-sets each of four measurements. Uncertainties correspond to the random uncertainties at 95% confidence level.

	I_{SATA} (W cm^{-2})	P (W)
Excitation 110 V, separation 117 mm:-		
Full set	2.20 ± 0.16	4.24 ± 0.53
Sub-set 1	2.09 ± 0.20	4.05 ± 0.82
Sub-set 2	2.31 ± 0.20	4.05 ± 0.82
Excitation 110 V, separation 25 mm:-		
Full set	4.74 ± 0.42	4.34 ± 0.57
Sub-set 1	4.62 ± 0.66	4.26 ± 0.68
Sub-set 2	4.86 ± 0.60	4.42 ± 1.03
Independent measurement	-	3.83 ± 0.38
Excitation 50 V, separation 25 mm:-		
Full set	0.78 ± 0.13	0.92 ± 0.14
Sub-set 1	0.80 ± 0.14	0.94 ± 0.27
Sub-set 2	0.76 ± 0.24	0.90 ± 0.13
Independent measurement	-	0.97 ± 0.10

4.2 Centralising the transducer

In the examples given in Section 4.1, a unique peak was identified in the beam profile which corresponded to the approximate geometrical centre of the beam. It was therefore possible to use this feature to maximise the signal at the chosen central element of BECA2. Such features can occur both in the near field of transducers as well as in the far field.

However, the prominence of the feature may depend on the vibration mode of the transducer, and a weak feature may not be readily located if the signal-to-noise ratio is poor. Under these circumstances, reliable measurements can be made using BECA2 only if the transducer can be positioned geometrically in the horizontal plane such that the array axis of the hydrophone represents a diametrical (or radial) sample. If this is not possible, then only parameters which have a spatial maximum can be determined reliably as it would not be possible to rotate the transducer about the centre element of the hydrophone array. However, if the transducer rotation is such that its acoustic axis passes through the hydrophone centre element, an alternative arrangement could be used to overcome this problem. It is possible to use the existing facilities of BECA2 to achieve such an arrangement because the rotation axis of the coordinate positioning rig is mechanically arranged so that it passes through the central element of the hydrophone array. However, it is essential to ensure that the transducer is set up in its mount so that its acoustic axis is colinear with this rotation axis. The following procedure is be used.

The transducer/hydrophone separation is increased until a distinct single peak is observed in the beam profile. The transducer is translated for maximum signal at the central element (element 10) on the hydrophone. After increasing the transducer/hydrophone separation further, the process is repeated and if the maximum now appears at a different element then the acoustic axis is not colinear with the mechanical axis. The tilt of the transducer in its mount can then be adjusted to correct this error and the process repeated until the maximum is found at the same element for both transducer/hydrophone separations. By reducing the transducer/hydrophone separation to the distance at which measurements are required, the array sample line should now represent a diameter of the beam. Hence, it should still be possible to rotate the transducer about the centre of the beam, thereby allowing the required measurements to be made with each measurement representing a diametrical sample.

5. ACCURACY OF MEASUREMENTS

5.1 Random uncertainties

Random uncertainties were determined from a number of repeat sets of measurements (typically five measurements in each set) made using a physiotherapy transducer at a distance of one transducer diameter. Table 3 gives the standard deviation and the random uncertainty for five relevant acoustical parameters. In each set, the transducer was re-positioned for maximum signal at the chosen central element. The random uncertainties given in Table 3 are intended only to provide guidance on typical values; in practice they must be assessed for each particular set of measurements.

Table 3 Typical values for the standard deviations and random uncertainties expressed at 95% confidence level for the determination of five acoustical parameters using BECA2.

Acoustic parameter	Standard deviation (%)	Random uncertainty (%)
Peak-positive acoustic pressure (p_+)	$\pm$ 4	$\pm$ 10
Spatial-peak temporal-peak derived intensity (I_{SPTP})	$\pm$ 7	$\pm$ 20
Spatial-peak temporal-average derived intensity (I_{SPTA})	$\pm$ 4	$\pm$ 11
Spatial-average temporal-average derived intensity (I_{SATA})	$\pm$ 3	$\pm$ 6.5
Total power (P)	$\pm$ 2	$\pm$ 3
Beam-area	$\pm$ 4	$\pm$ 10

As measurements would normally be made for a number of orientations of the transducer in order to take into account any lack of cylindrical symmetry of the beam profile, the random uncertainty would be included in such a set of measurements as shown in Section 4.

5.2 Systematic uncertainties

5.2.1 Corrections

Corrections may be applied to measurements made using BECA2 to take account of a number of sources of systematic uncertainty. Two corrections already mentioned are those for the directional response of the hydrophone (Section 3.5) and membrane reflections (Section 3.3) and there are three others which need to be considered. The first is associated with the assumption that instantaneous intensity is proportional to the square of the acoustic pressure. The second is to take into account the attenuation of the water when considering the determination of total power, and the third is for the effect of noise on the measurements. Assessment of these will be dealt with in the following sections.

Pressure squared

It can be shown (3) that, on the axis of a piston-like source, the ratio of the true intensity, I, to the intensity, I_p, derived from the square of the acoustic pressure is given by

$$I/I_p = 2/(1 + x/(1 + x^2)^{1/2})$$

with $x = \ell / a_1$,

where ℓ is the distance between the measurement plane and the face of the transducer and a_1 is the radius of the active element of the transducer. Typically, for x = 2 (corresponding to measurements made at a distance of one transducer diameter) the ratio I/I_p is 1.056 and for x = 4 it is 1.015. Hence, intensities derived from measurements made with BECA2 are in general slight overestimates. The above expression is valid only on the axis of a transducer, but it can be used as an estimate of the general correction with an uncertainty assigned to it which is equal to one half the correction.

Attenuation

Although most measurements made using BECA2 refer to the characteristics of the ultrasonic field, the total power parameter usually refers to the power at the transducer and so a correction for attenuation in the water has to be made. The total power, P_o, at the transducer is related to the measured total power, P, by

$$P_o = P \exp(-2 \alpha \ell)$$

where α is the amplitude attenuation coefficient and ℓ is the transducer/hydrophone separation. At 20 °C, α is approximately $2.5 \times 10^{-14} f^2 m^{-1}$ where f is the frequency.

Noise

Depending on the gain setting of the analogue amplifier, noise produces an output from BECA2 even with no acoustic signal present. This is particularly important for the determination total power as the noise is integrated over all the signals present. A correction for this source of uncertainty may be determined from measurements made after the ultrasonic generator has been turned off and processing the BECA2 data as if they resulted from a true acoustic signal. Of course, noise also contributes to the random uncertainty and this is taken into account during the normal assessment procedures for determining random uncertainty.

5.2.2 Assessment of systematic uncertainties

The major source of systematic uncertainty in the measurements made using BECA2 is the absolute calibration of the hydrophone and analogue amplifier. Whilst this source of uncertainty contributes directly to measurements of acoustical pressure, and is doubled for derived intensity and power measurements, it does not contribute to the uncertainty in the determination of beam-area as the latter depends only on relative measurements. For this reason, independent measurements of acoustical quantities have been given in earlier tables in order to provide separate assessments of the probable accuracy of BECA2.

A list of sources of systematic uncertainty is given in Table 4 for typical measurements such as those given in Table 1; they have been combined in accordance with the guidelines given by the British Calibration Service (4).

Table 4 Components of uncertainty in the determination of various acoustical parameters using BECA2 for a typical set of measurements made on a 1.5 MHz physiotherapy transducer.

	p_+, p_-	I_{SPTP}	I_{SPTA}	I_{SATA}	P	Beam-area
Primary calibration	± 7.5	± 15	± 15	± 15	± 15	-
ADC linearity	± 0.2	± 0.4	± 0.4	± 0.4	± 0.4	± 0.4
ADC resolution	± 2	± 4	± 4	± 4	± 4	± 4
Amplifier gain	± 5	± 10	± 10	± 10	± 10	-
$I \propto p^2$	-	± 2.8	± 2.8	± 2.8	± 2.8	-
Directional response	± 1.2	± 2.4	± 2.4	± 2.4	± 2.4	± 2.4
Temporal averaging	-	-	± 3	± 3	± 3	-
Interpolation	-	-	-	± 2	-	± 2
Reflections	± 5	± 10	± 10	± 10	± 10	-
Cylindrical symmetry combined with the random uncertainty (Table 1)	± 2.8	± 5.6	± 8.6	± 14	± 9.5	± 6.5
Overall (95% confidence)	± 12	± 25	± 26	± 28	± 26	± 9

6. CONCLUSION

The performance of the NPL Ultrasound Beam Calibrator, BECA2, for the determination of the acoustic output of typical physiotherapy transducers has been assessed. The system was originally developed at NPL to provide rapid and reliable measurements of the acoustic output of pulsed ultrasonic transducers. However, the results given here demonstrate that, even when used with continuous-output devices, the potential problems such as reflection from the membrane hydrophone and the need to undertake measurements in the near field of large transducers can be overcome. Problems due to the reflection are overcome by tilting the hydrophone and then correcting the measurements for the effects of the directional response of the hydrophone; procedures are given for determining the directional response and deriving the corrections. Problems due to lack of cylindrical symmetry in the beam profiles when measurements are made in the near field have been studied; improvements in the accuracy and reliability of measurements have been obtained by rotating the transducer and repeating the measurements.

Finally, sources of systematic uncertainty have been identified and overall estimates given of uncertainty at 95% confidence level. Comparison with alternative measurement methods shows excellent agreement, i.e. well within the combined uncertainties of the two methods. For acoustic pressure parameters, typical uncertainties are ± 12% and for derived intensity and power parameters they are between ± 25% and ± 28%.

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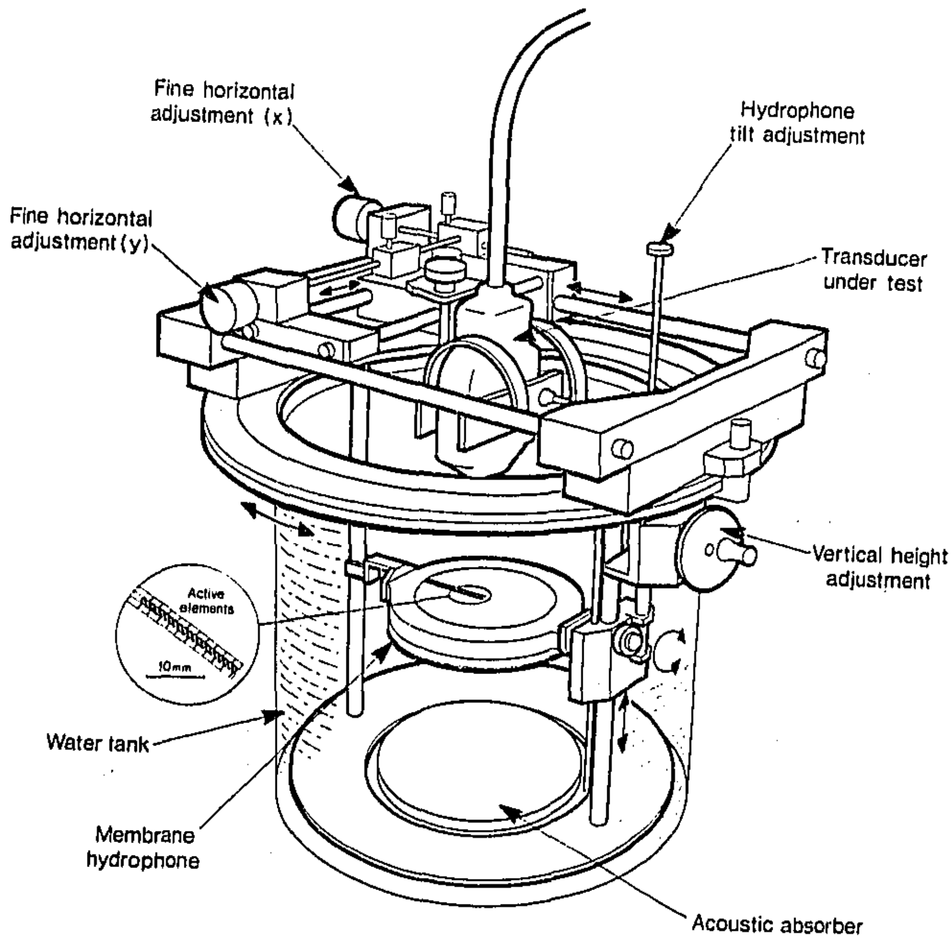

Figure 1 Schematic diagram of the test-tank used for the Ultrasound Beam Calibrator showing the various degrees of freedom available for adjusting the position of the transducer.

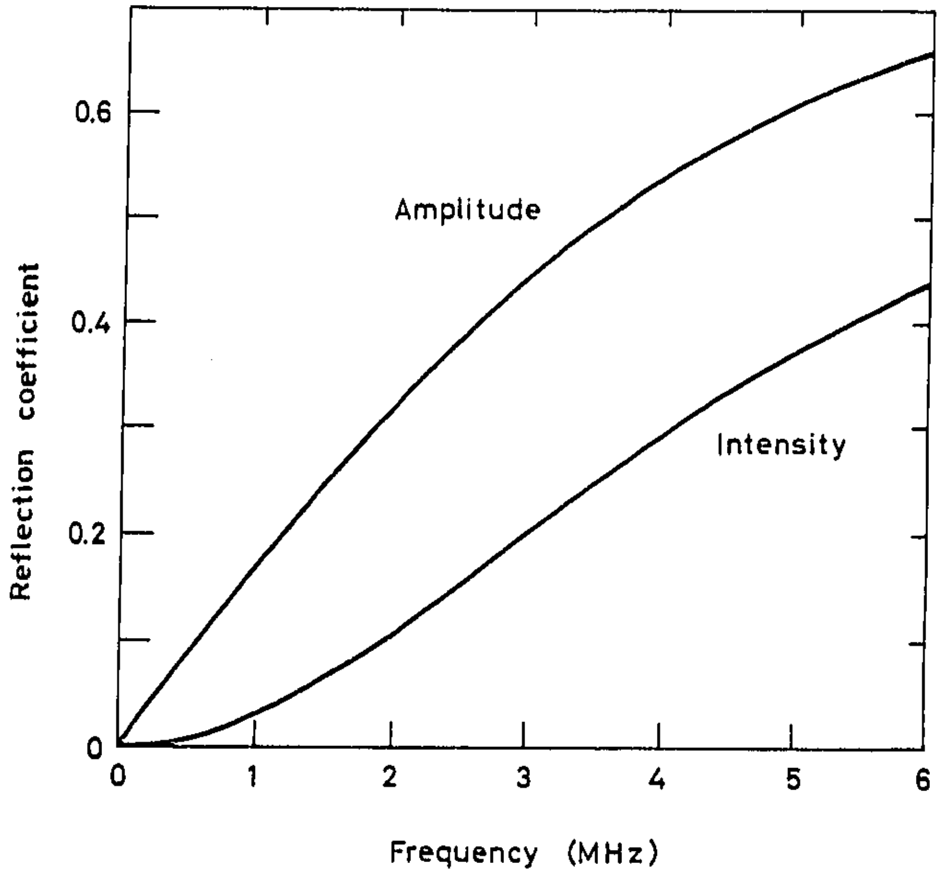

Figure 2 Amplitude and intensity reflection coefficients for a polyvinylidene fluoride membrane hydrophone of thickness 0.050 mm.

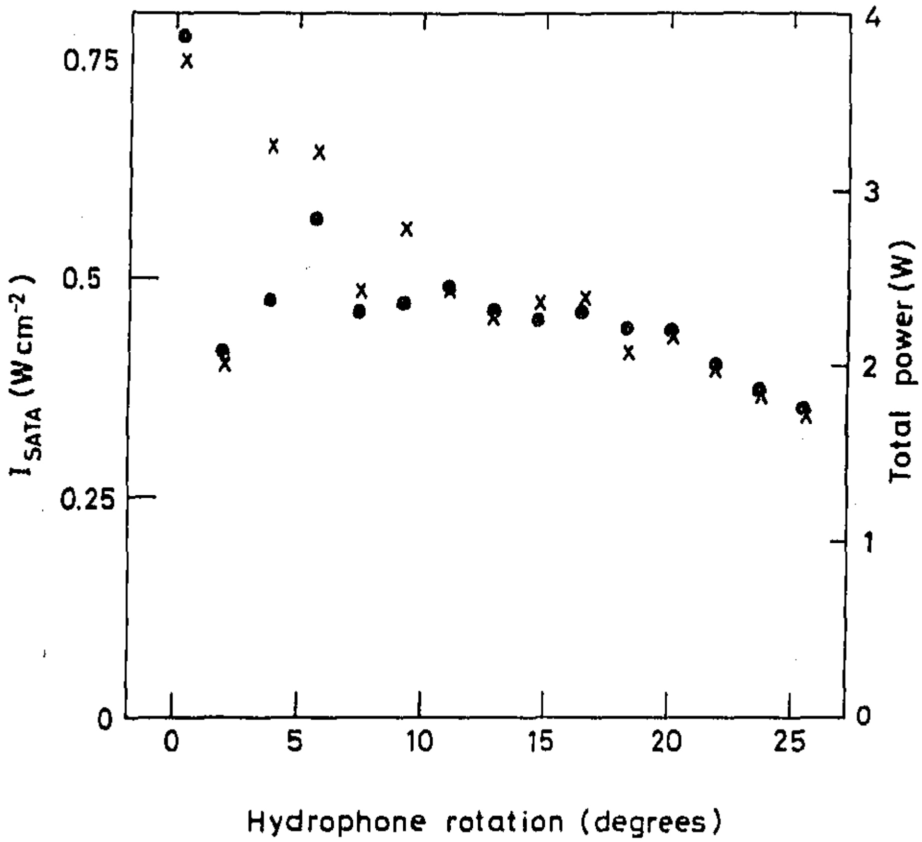

Figure 3 Variation of the results of measurements of two acoustical parameters with hydrophone rotation for a 1.5 MHz physiotherapy transducer.

● Total power,

x I_{SATA}.

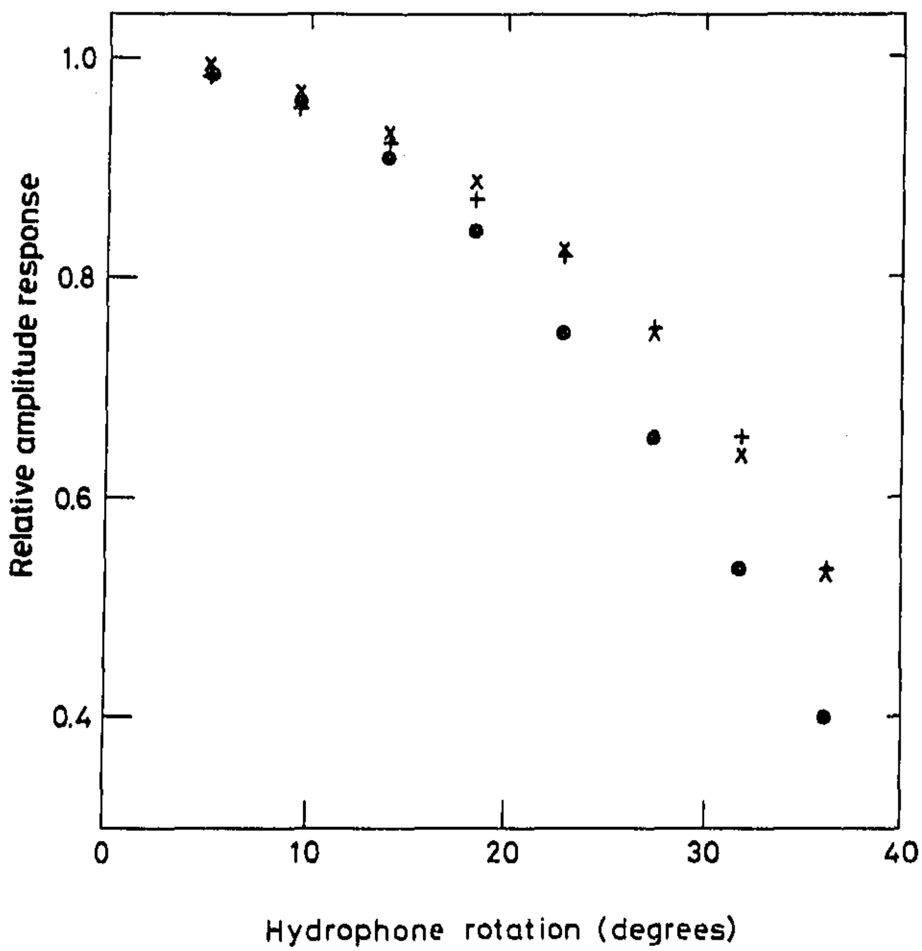

Figure 4 Experimental directional responses.
● 2.25 MHz,
× 1.50 MHz,
+ 1.09 MHz.

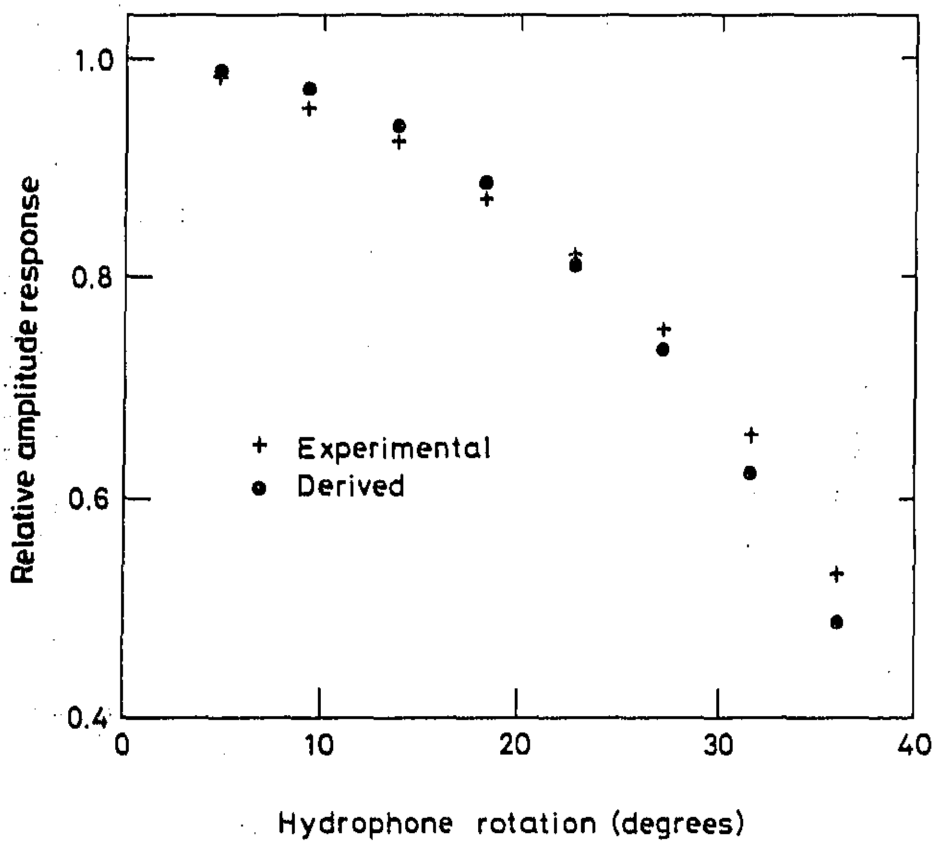

Figure 5 Comparison between the experimentally determined 1.09 MHz directional response and the 1.09 MHz response derived from the 2.25 MHz experimental data.

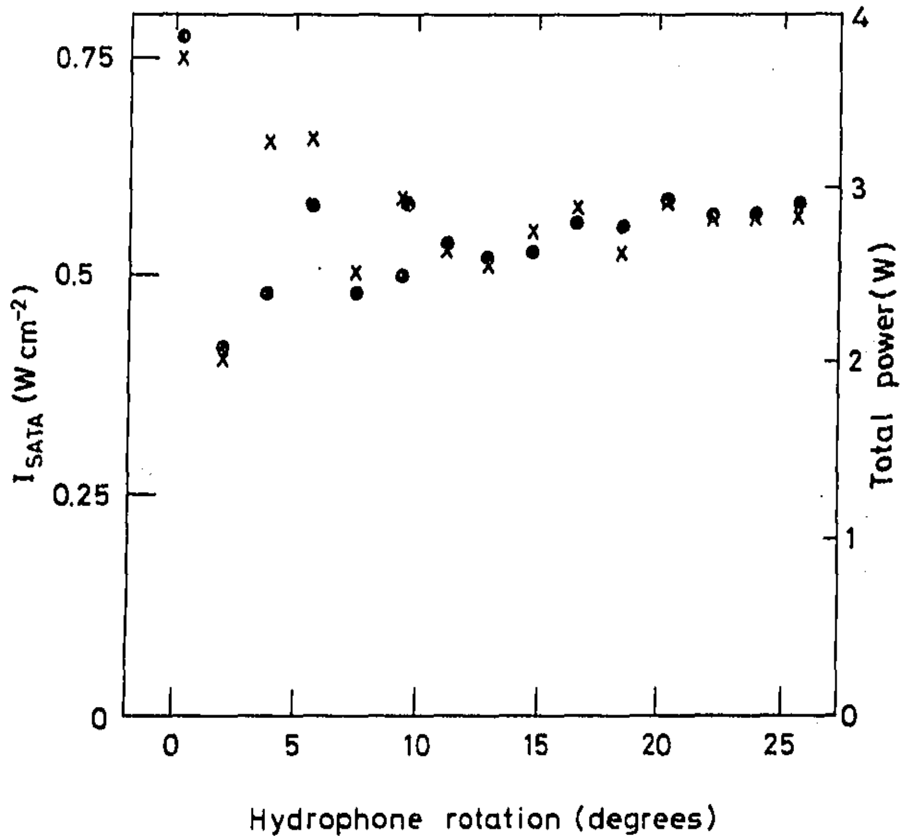

Figure 6 Variation of the results of measurements of two acoustical parameters with hydrophone rotation for a 1.5 MHz physiotherapy transducer after correcting for the directional response of the hydrophone.

● Total power,

x I_{SATA}.

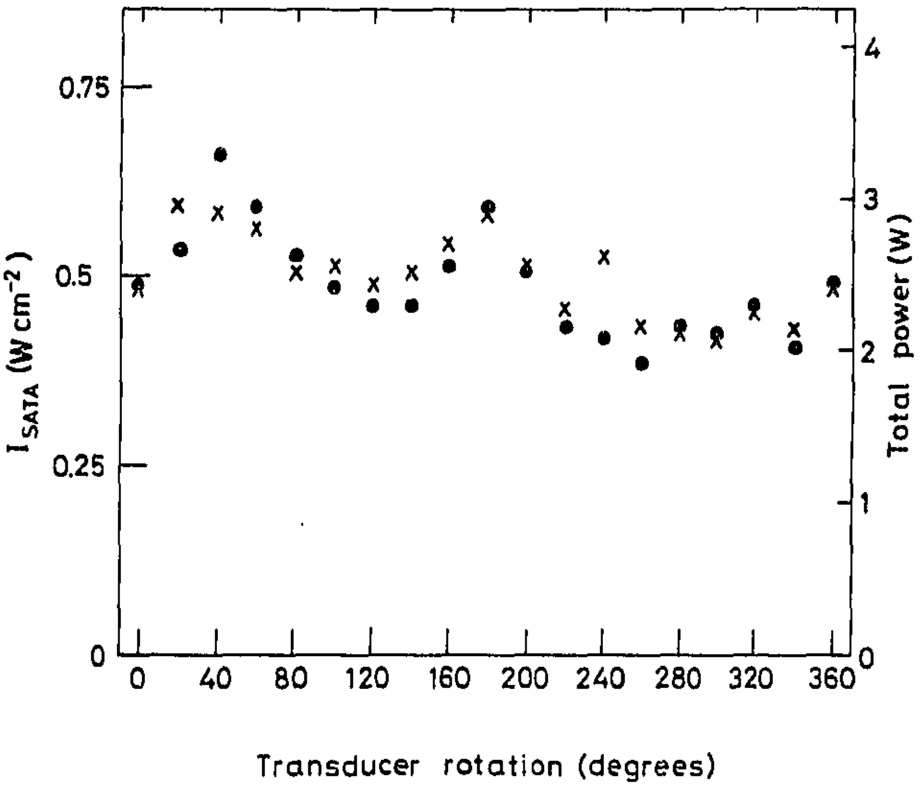

Figure 7 Variation of the results of measurements of two acoustical parameters with transducer rotation (determined at a distance of 20 mm from the face of a 20 mm diameter physiotherapy transducer operating at 1.50 MHz).

● Total power,

x I_{SATA}.