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THE IMPORTANCE OF THE FREQUENCY RESPONSE OF A HYDROPHONE WHEN CHARACTERISING MEDICAL ULTRASONIC FIELDS

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INTRODUCTION

There is an increasing need to make accurate measurements of the acoustic output of medical diagnostic ultrasound equipment. A major difficulty in meeting this need is that finite-amplitude distortion of the pulse waveform [1]-[6] when the ultrasound is propagating in water can lead to considerable uncertainties in measurements made with hydrophones. To ensure reliable measurements of the acoustic parameters used for the characterisation of medical diagnostic equipment [7, 8], it is necessary to record such distorted waveforms using a hydrophone with a very wide bandwidth (up to 70 MHz). Furthermore, if a single value for the pressure sensitivity of the hydrophone, obtained at the fundamental frequency of the pulse, is to be used to convert the voltage waveform into a pressure waveform, then it is necessary to use a hydrophone with a flat frequency response over the whole range of frequencies contained in the waveform and this often extends to 100 MHz. There are many designs of miniature piezoelectric hydrophone in regular use for making this type of measurement; some of these have a bandwidth of only 10 MHz, whilst others have resonances within the range 1 to 15 MHz which grossly distort the true acoustic waveform.

In this paper a comparison is made between the frequency responses of various types of hydrophone, followed by a comparison between the acoustic pulse waveform recorded using these hydrophones when making measurements at the focus of a mechanical sector scanner. Finally, values for peak pulse parameters calculated from these waveforms show that large errors in some of the measured parameters can result from the use of hydrophones having an inadequate frequency response. However, it is possible to reduce these uncertainties considerably by a suitable choice of instrumentation.

FREQUENCY RESPONSE MEASUREMENTS

The technique used to determine the frequency response of hydrophones [9] utilises the sawtooth waveform produced by finite-amplitude acoustic propagation in water. A high-amplitude toneburst with centre frequency 1 MHz (Figure 1) contains Fourier components at harmonic frequencies having amplitudes inversely proportional to frequency (Figure 2). By recording the waveform received by a number of different hydrophones (including a standard hydrophone) and performing a fast Fourier transform, their sensitivities can be compared with the standard hydrophone at frequencies which are multiples of 1 MHz. The standard hydrophone used was a coplanar shielded membrane hydrophone [10] and it was calibrated at 1, 2, 3, 5, 7, 10 and 15 MHz using an optical interferometer [11]. At the other required frequencies in the range up to 25 MHz the sensitivity was calculated using the theoretical frequency response model of Bacon [9]. The overall uncertainty in this technique is largest at lower frequencies and is estimated to be less than 10% at all frequencies within the range of interest.

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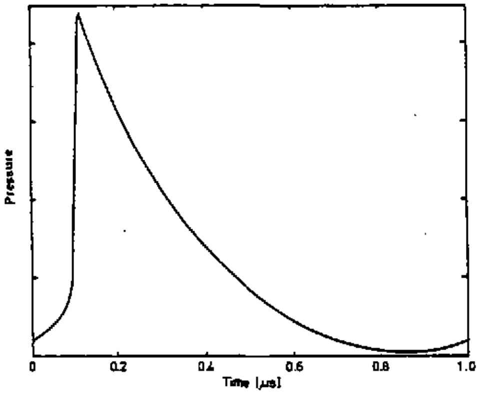

Figure 1. Pressure waveform exhibiting finite-amplitude distortion.

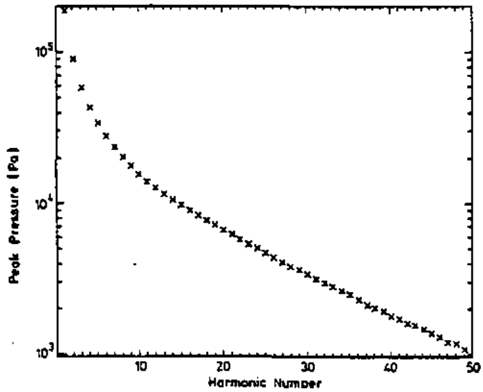

Figure 2. Frequency spectrum of a typical distorted waveform.

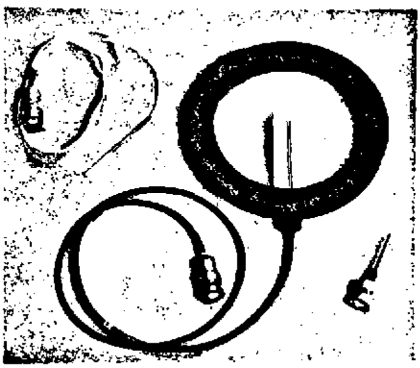

Figure 3. From left to right: PVDF needle probe; PVDF membrane and ceramic probe.

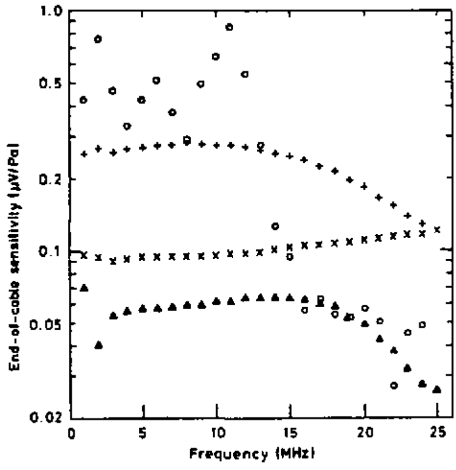

Figure 4. Frequency responses of o Type N, + Type L ▲ Type K and x Type C.

Three fundamentally different designs of hydrophone are referred to in this paper: polyvinylidene fluoride (PVDF) membrane hydrophones [10]; PVDF needle probe hydrophones; and ceramic probe hydrophones [12]. These are illustrated in Figure 3.

To facilitate reference within this paper, the different types of hydrophone used are classified in Table 1. It should be noted that not all of these hydrophones were used to measure peak pulse parameters.

The frequency responses of the main designs of hydrophone are compared in Figure 4. The membrane hydrophone of type C has a constant sensitivity over the

Table 1. Classification of hydrophones.

Type	Category	Membrane Thickness (μm)	Element Diameter (mm)	Cable Length (cm)
A	PVDF Membrane	9	1	3
B		9	0.5	15
C		9	1	65
D		25	0.5	15
E		25	0.5	75
F		25	1	65
G		25	2	30
H		50	0.5	75
I		50	1	75
J	PVDF Needle Probe	(Early Type)	1	90
K		-	1	90
L		-	1	100
M	Ceramic Probe	-	0.2	0
N		-	0.6	0
O		-	1	190

whole range of frequencies covered. Several other membrane hydrophones were used to illustrate the variation of frequency response with element size, membrane thickness and cable length [9,10]. Figure 5 shows that the element size only affects the absolute sensitivity of the hydrophone, the frequency response remaining constant. However, Figure 6 shows that the frequency response is affected by both the thickness of the membrane and the length of cable. The thickness-mode resonance of a 50 μm membrane is expected theoretically to be between 20 and 25 MHz and, as shown in Figure 6, in fact occurs at about 24 MHz. A 25 μm membrane has a resonance at twice this frequency so the gradual rise in sensitivity with frequency is less marked and the rise is even less for a 9 μm thick membrane, which has a resonance frequency above 100 MHz [10].

The length of cable between the hydrophone and the preamplifier is also important in determining the frequency response. The sensitivity of the hydrophone increases with frequency due to the presence of the cable, reaching a peak at 75 MHz for a cable of length 65 cm. Shortening the cable to 3 cm increases the resonant frequency and gives a flatter frequency response; this is illustrated by the lower two curves in Figure 6.

Three PVDF needle probes from the same manufacturer were calibrated; the two of type K have very similar frequency responses, although the sensitivities differ by a factor of two (Figure 7). Apart from a resonance below 3 MHz there is no obvious peak in the frequency response, merely a smooth fall-off in sensitivity above 15 MHz giving a -6 dB bandwidth of 23 MHz. The third hydrophone (type J) has a smaller bandwidth of about 14 MHz, which suggests that this earlier

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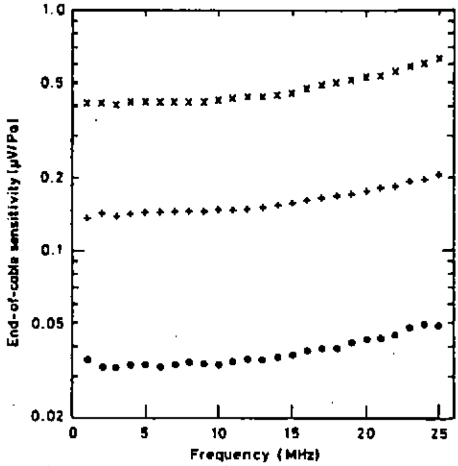

Figure 5. Frequency responses of ● Type E, + Type F, and x Type G.

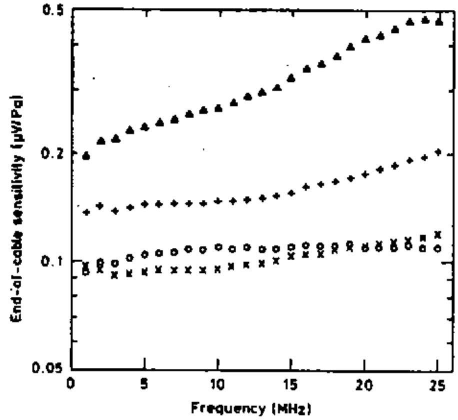

Figure 6. Frequency responses of ▲ Type I, + Type F, x Type C and o Type A.

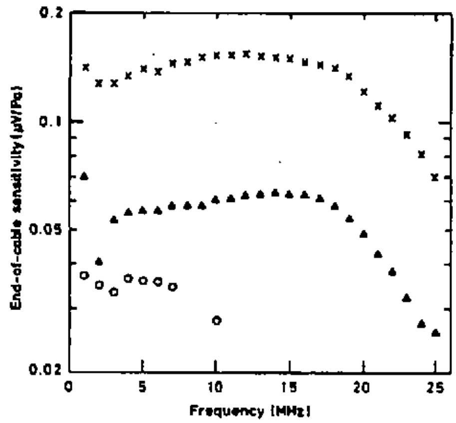

Figure 7. Frequency responses of x Type K, ▲ Type K and o Type J.

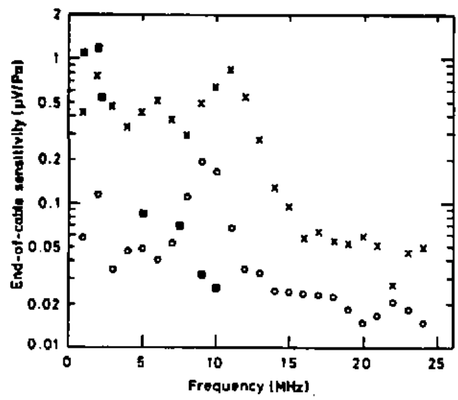

Figure 8. Frequency responses of o Type M, x Type N and ■ Type O.

design may have used a thicker PVDF element. The 1 mm diameter PVDF needle probe (type L), from another manufacturer, has a similar frequency response to the other PVDF probes with a -6 dB bandwidth of 23 MHz, see Figure 4.

The ceramic probes have resonances in the 1 to 10 MHz range, giving rise to variations of up to 3 dB over a 1 MHz frequency interval. These fluctuations in response would give rise to very large uncertainties if such a device were used for the characterisation of pulsed ultrasonic fields, as these contain components at many different frequencies. Another important feature of the frequency response is the -6 dB point, which occurs at 13 MHz for the 0.6 mm diameter probes type N, and at 11 MHz for the 0.2 mm diameter probes type M. This is illustrated in Figure 8, where the frequency responses of the two sizes of ceramic probes are compared with another ceramic probe of diameter 1 mm (type O), which was found to have a -6 dB point at about 3 MHz.

To summarise, the ceramic probe hydrophones studied have resonances within the 1 to 10 MHz frequency range and their sensitivity falls off at higher frequencies. The PVDF needle probes studied have a flatter response with a 20 MHz bandwidth whilst the PVDF membrane hydrophones have a smooth frequency response and -6 dB bandwidths up to over 100 MHz with thickness-mode resonances and cable resonances at even higher frequencies.

MEASUREMENT OF PEAK PULSE PARAMETERS

The acoustic pressure waveform at the focus of the acoustic field of a commercial 5 MHz sector scanner was recorded using various different hydrophone and amplifier combinations. The waveforms, shown in Figures 9 to 13, were recorded using a Tektronix 7D20 programmable digitiser using the sensitivity of the hydrophone at 5 MHz to derive the values for acoustic pressure. The values for various peak pulse parameters, defined in references [7] and [8], are given in Table 2 and have been corrected for spatial averaging over the active element by up to +16% and +4% for peak-positive and peak-negative pressures respectively, and by up to +32% for spatial-peak temporal-peak (SPTP) intensities. The spatial-peak pulse-average (SPPA) intensities have not been corrected.

Membrane hydrophones

Figure 9 shows the recorded waveform for a membrane hydrophone type A, which has both thickness-mode resonance and cable resonance above 100 MHz and a flat frequency response (± 3 dB) from 1 to 70 MHz [13]. Thus its sensitivity is well represented by a single value and Figure 9(a) can be taken as an accurate representation of the true waveform excluding only harmonics above 70 MHz. Use of a 23 MHz bandwidth amplifier with such a hydrophone leads to the waveform shown in Figure 9(b) with a reduction of 20% in the measured peak-positive pressure.

Figure 10 illustrates the effect of cable resonance on the recorded waveform. The waveform shown in Figure 10(a) was obtained using a 15 cm length of cable and the resultant resonance is well above the bandwidth of the amplifier, giving an accurate estimate of peak-positive pressure (see Table 2). Figure 10(b) illustrates the much more significant resonance caused by a 65 cm length of cable; in this case the peak-positive pressure is overestimated by 35% if a 70 MHz bandwidth amplifier is used but leads to an underestimate of only 7% if a 23 MHz bandwidth amplifier is used.

Figure 11 demonstrates the use of a hydrophone made from a 25 μm thick membrane and with a short cable. This hydrophone has a thickness-mode resonance at 45 MHz, which gives rise to an overestimate of 6% in peak-positive pressure. Table 2 shows that if a longer cable is used (75 cm), the measured peak-positive pressure is 50% too large because the cable resonance overshadows the effect of the film thickness. Again, the 23 MHz bandwidth amplifier reduces the measured peak-positive pressure. Figure 12(a) shows the waveform obtained with a 50 μm thick membrane hydrophone (bilaminar shielded) with a 75 cm cable. Here the thickness mode resonance at 24 MHz, shown in Figure 8, is visible and

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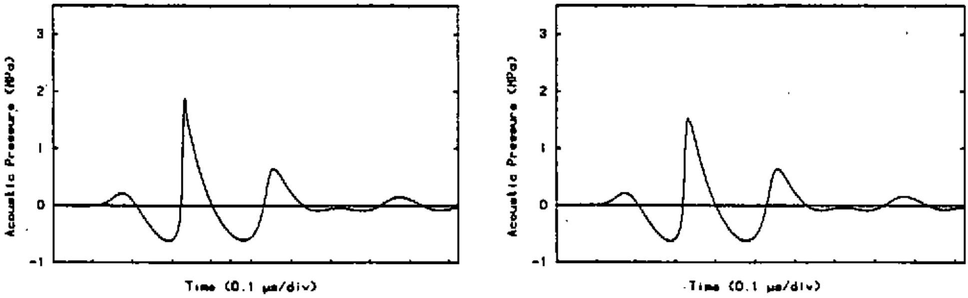
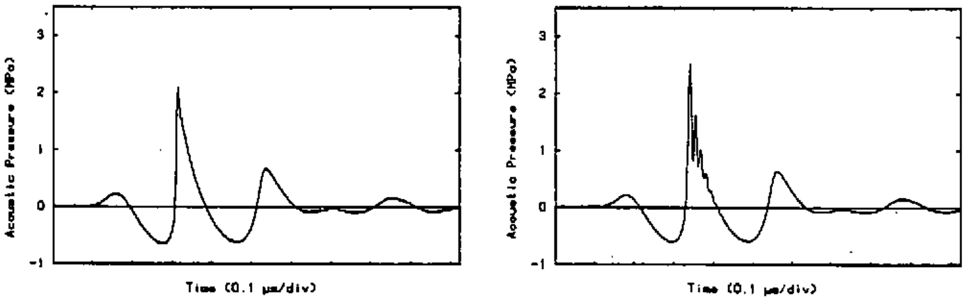


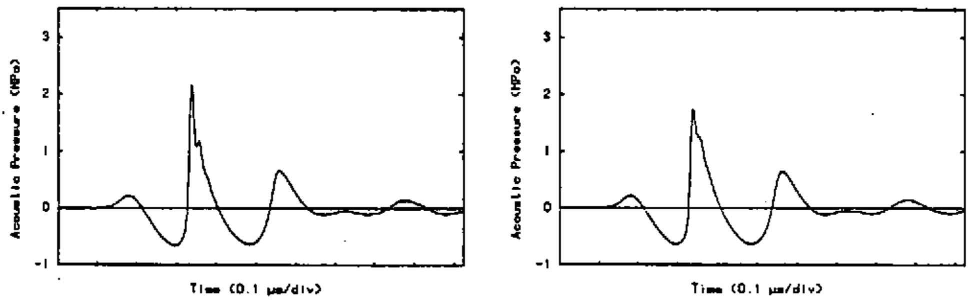
(a) (b)

Figure 9. Waveforms recorded using hydrophone type A: (a) with a 70 MHz bandwidth amplifier and (b) with a 23 MHz bandwidth amplifier.



(a) (b)

Figure 10. Waveforms recorded using hydrophone: (a) type B and (b) type C, both with a 70 MHz bandwidth amplifier.



(a) (b)

Figure 11. Waveforms recorded using hydrophone type D: (a) with a 70 MHz bandwidth amplifier and (b) with a 23 MHz bandwidth amplifier.

Table 2. Measurements of peak pulse parameters.

Type	Amplifier Bandwidth (MHz)	Peak Pressure +ve (MPa)	Peak Pressure -ve (MPa)	SPTP Intensity (W/cm^2)	SPPA Intensity (W/cm^2)	Pulse Duration (ns)	Maximum Intensity (I_m) (W/cm^2)
A A	70 23	2.17 1.76	-0.63 -0.65	320 210	28 27	335 341	60 56
B B	70 23	2.21 1.62	-0.65 -0.65	330 180	32 29	330 336	68 60
C C	70 23	2.92 2.02	-0.64 -0.65	580 280	31 27	329 339	68 58
D D	70 23	2.30 1.84	-0.67 -0.65	360 230	32 30	331 335	68 62
E E	70 23	3.21 2.42	-0.64 -0.62	700 400	35 30	315 328	87 65
F F	70 23	2.93 1.98	-0.69 -0.64	580 270	32 27	326 339	72 55
H H	70 23	2.63 2.35	-0.65 -0.63	470 370	36 33	326 328	86 77
I I	70 23	2.55 2.03	-0.63 -0.63	440 280	32 27	329 341	79 60
J J	70 23	1.49 1.51	-0.60 -0.65	150 150	22 24	355 358	43 47
M* M*	70 70	1.47 1.86	-1.03 -1.14	150 230	29 51	393 413	46 102
N* N*	70 70	2.22 0.63	-1.32 -0.76	340 28	65 6	260 540	121 15
O	23	0.61	-0.59	25	4	1840	11

* In these cases two nominally identical hydrophones were used.

has resulted in a 20% overestimate of peak-positive pressure; however, the cable resonance has been completely suppressed. Table 2 shows that by using a 23 MHz bandwidth preamplifier, a value of the peak-positive pressure is obtained which is nearer to the value given by the 9 µm thick membrane; this is because the decrease in response with increasing frequency due to the amplifier compensates for the hydrophone resonance at 24 MHz.

To summarise, the cable resonance has a greater effect on the measured pressure than does the thickness-mode resonance, so it is beneficial to have a short (15 cm) cable on membranes of thickness 25 µm or less. The use of an amplifier with reduced bandwidth (23 MHz) is beneficial both for 50 µm thick membranes and for thinner membranes with long cables. In this study, reliable measurements were obtained with a hydrophone made from 25 µm or thinner film with 15 cm or less cable attached, provided an amplifier with 70 MHz bandwidth was used.

PVDF needle probe hydrophones

Figure 12(b) shows the waveform recorded by a 1 mm diameter PVDF needle probe of type J which is of an earlier design than type K, and its frequency response has a -6 dB point at about 14 MHz. This has resulted in attenuation of the second and higher harmonic frequencies, leading to a reduction in steepness and amplitude of the shock front. It is expected that a PVDF needle probe with either of the frequency responses shown in Figure 4 would not underestimate the peak-positive pressure to the same extent, but it has not been possible to verify this. As shown in Table 2, the underestimate of peak-positive pressure is 30% due to the decrease in sensitivity at higher frequencies.

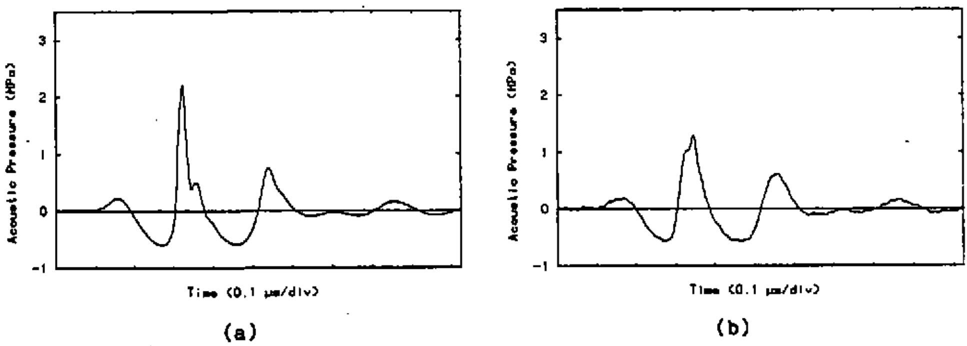
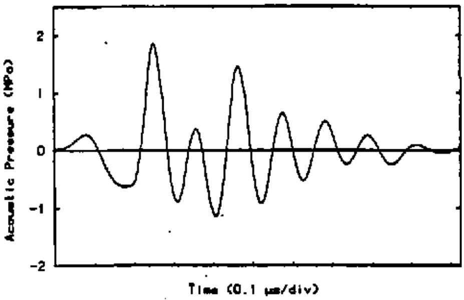


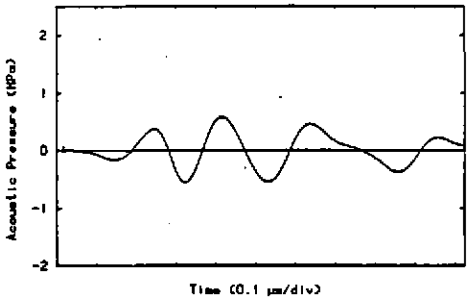
Figure 12. Waveforms recorded using hydrophone: (a) type I and (b) type J, with a 70 MHz bandwidth amplifier.

Ceramic probe hydrophones

The waveforms recorded by two types of ceramic probe are shown in Figure 13 whilst the corresponding frequency responses are given in Figure 5. The 0.2 mm diameter hydrophone has a resonance at 9 MHz, which obviously dominates the waveform in Figure 13(a). No higher frequencies are detected because the sensitivity falls away above 11 MHz, which means that the distortion due to nonlinear propagation is not revealed [1]. The type O probe has a 10 dB fall-off in sensitivity between 5 and 10 MHz (Figure 8), and the effect of this response is seen in the waveform of Figure 13(b) which exhibits no distortion and is dominated by the fundamental frequency at 5 MHz. Both hydrophones, therefore, give unrepresentative waveforms and underestimate the peak-positive acoustic pressure. The peak-negative pressure is overestimated by the 0.2 mm probe (type M) because the sensitivity increases by a factor of 4 between frequencies of 5 and 10 MHz.



(a)



(b)

Figure 13. Waveforms recorded using hydrophone: (a) type M and (b) type O, both with a 70 MHz bandwidth amplifier.

Maximum intensity (I_m)
Table 2 also gives values for I_m [8], which is the mean acoustic intensity averaged over the largest half-cycle within the acoustic pulse. It can be seen that this parameter is affected by resonances in hydrophones in a far less predictable fashion than is the peak-positive pressure. This is illustrated by noting that the 9 µm membrane hydrophones give the same value for I_m whether the cable is 15 cm or 65 cm long, whereas the 25 µm membrane hydrophones give a 30% higher value for a 75 cm cable compared with that for a 15 cm cable.

CONCLUDING REMARKS

The ceramic probe hydrophones used in this study only give reliable results in acoustic fields where a single, well-defined frequency is present. Such a situation occurs in relatively few of the current diagnostic ultrasound units. PVDF needle probe hydrophones give an underestimate of the peak-positive acoustic pressure because their sensitivities are reduced at frequencies above 20 MHz where there is still an appreciable harmonic content in the field of diagnostic equipment.
In general, PVDF membrane hydrophones overestimate the peak-positive pressure, particularly if a significant length of cable is used between the hydrophone and the amplifier. However, in this study it was possible to reduce this overestimate to 10% by limiting the cable length to 15 cm. Finally, it appears that it is difficult to predict the accuracy of the measured values of I_m, even if the frequency response of the hydrophone is known.

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