Dissemination of the Acoustic Pascal: The Role and Experiences of a National Metrology Institute

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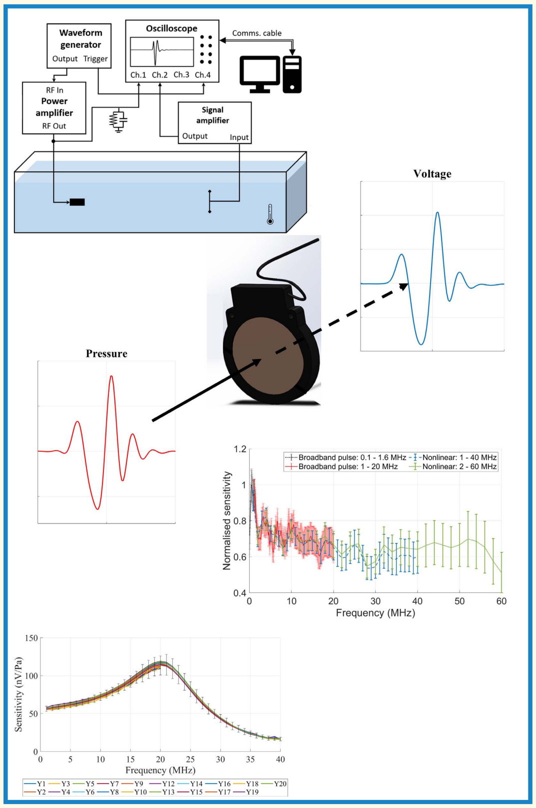
***Abstract*—Hydrophones are pivotal measurement devices ensuring medical ultrasound acoustic exposures comply with the relevant national and international safety criteria. These devices have enabled the spatial and temporal distribution of key safety parameters to be determined in an objective and standardized way. Generally based on piezoelectric principles of operation, to convert generated voltage waveforms to acoustic pressure, they require calibration in terms of receive sensitivity, expressed in units of V·Pa^{-1}. Reliable hydrophone calibration with associated uncertainties plays a key role in underpinning a measurement framework that ensures exposure measurements are comparable and traceable to internationally agreed units, irrespective of where they are carried out globally. For well over three decades, the U.K. National Physical Laboratory (NPL) has provided calibrations to the user community covering the frequency range 0.1–60 MHz, traceable to a primary realization of the acoustic pascal through optical interferometry. Typical uncertainties for sensitivity are 6%–22% (for a coverage factor *k* = 2), degrading with frequency. The article specifically focuses on the dissemination of the acoustic pascal through NPL's calibration services that are based on a comparison with secondary standard hydrophones previously calibrated using the NPL primary standard. The work demonstrates the stability of the employed dissemination protocols by presenting representative calibration histories on a selection of commercially available hydrophones. Results reaffirm the guidance provided within international standards for regular calibration of a hydrophone in order to underpin measurement confidence. The process by which internationally agreed realizations of the acoustic pascal are compared and validated through key comparisons (KCs) is also described.**



***Index Terms*—Acoustic pascal, calibration, comparison, hydrophones, primary standard.**

I. INTRODUCTION

THE SI system or the International System of Units [1] that forms the basis of the metric system of measurement is the only system of measurement with official status in nearly every country in the world. Widely employed in science, technology, industry, and everyday commerce, it ensures global comparability and traceability in measurement. The SI system comprises a coherent set of measurement units with seven base units and 22 derived units that are intimately linked to the base units. Important quantities related to the safe use of medical ultrasound [2], [3], [4], such as acoustic pressure and acoustic power, are two examples of such derived quantities [5], [6], [7]. Acoustic pressure, or dynamic force per unit area – represented dimensionally as $M \cdot L^{-1} \cdot T^{-2}$ – is specified in

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Highlights

- **For the first time, the stability in the sensitivity of a number of commercially available ultrasonic hydrophone designs over typical timescales of a decade is demonstrated, determined using National Physical Laboratory (NPL)'s secondary calibration services.**
- **The results demonstrate the stability of the calibrations systems available at NPL for calibrations over the frequency range of 0.1 to 60 MHz with uncertainties of 6 to 22%, providing traceability to the SI unit of the acoustic pascal.**
- **The paper underlines the importance of regular calibration with subtle but significant changes in the frequency-dependent hydrophone sensitivity, potentially leading to significant errors in acoustic output measurement, if unnoticed.**

pascals and is linked to three SI base units: mass, length, and time. The original Special Issue on Ultrasound Exposimetry [8] detailed progress up to that time in developing measurement methods characterizing important exposure parameters. An excellent case can be made that the major development in measurement instrumentation that has underpinned the current metrological infrastructure that allows users to undertake measurements in a comparable way has been the membrane hydrophone [9], [10]. The broadband nature of their response, the ability to manufacture devices with miniature poled active elements [11], [12] able to spatially resolve transducer fields and their well-understood performance [13], has meant that measurements made using these devices have been embodied in a range of international and national standards [2], [3], [4], [10], [14], supporting the regulatory framework [15]. While a range of hydrophone devices exist [13] and the choice of which one to use may be dependent upon features of the acoustic field being characterized, membrane hydrophones have generically become the gold standard for measurement.

Although the behavior of ultrasonic hydrophones is indeed well understood and can be modeled [16], [17], their receive sensitivity cannot be calculated due to manufacturing tolerances and uncertainties in key material input parameters. They must, therefore, be calibrated to allow quantitative acoustic field measurements to be made. The key quantity of importance is the hydrophone sensitivity expressed in units of $\mathrm{V{\cdot}Pa^{-1}}$. The frequency-dependent sensitivity is defined as the ratio of the output voltage to the input acoustic pressure existing at the spatial location of the device in its absence [10]. Deriving the sensitivity of the hydrophone, therefore, depends on the realization of the acoustic pascal unit. This is carried out through primary methods of measurement.

At a handful of National Metrology Institutes (NMIs), optical interferometer-based primary standards have been configured to measure either the local displacement [18], [19] or local particle velocity [20], [21] to provide traceability to the SI units of length, through the wavelength of the laser used, mass, and time. Primary measurement setups are operated under tightly controlled experimental conditions. Although hydrophones calibrated on primary standard setups provide the lowest uncertainties achievable in terms of hydrophone calibration, in general, their use for direct dissemination of the pascal to the user community is impractical. Instead, general dissemination is undertaken through secondary methods, where hydrophones previously calibrated using a primary method are used to calibrate test hydrophones through direct comparison. Secondary methods employed at the National Physical Laboratory (NPL) are based on a substitution technique, in which the response of the hydrophone under test and that of a reference hydrophone are compared when exposed to the same ultrasound field at the same spatial location. This calibration technique is lower in the dissemination chain as the test hydrophone is now traceable to the SI units only via hydrophones calibrated on the primary standard. As a result, the test hydrophone inherits both the inherent uncertainties of the secondary approach as well as the uncertainties of the primary method. However, secondary approaches maintain efficiency in terms of the work and resources (in terms of time and cost) needed to accomplish a calibration while still providing end users with access to traceable calibrations.

This article describes the range of methods used at NPL that has enabled the dissemination of the acoustic pascal to the worldwide user community for approaching four decades (Fig. 1). The article is organized as follows: Section II provides more details on how the acoustic pascal is realized at the primary level and Section III details how comparability of the primary-level realizations at the world's NMIs is assured. Section IV describes secondary calibration methods employed at NPL, Section V describes the bulk of hydrophone types that NPL calibrates, with Section VI providing typical results of a selection of devices. This demonstrates the stability of the calibration protocols employed but examples are also provided of changes in hydrophone sensitivity which the calibration techniques at NPL have been able to detect.

It should be noted that in addition to the frequency-dependent sensitivity response of a hydrophone, there are other key device-specific characteristics that affect performance. These include quantities derived from relative measurement techniques such as noise equivalent pressure and directional response (from which the effective element diameters are derived) [22]. These properties affect not only the end application of the hydrophone, but also the uncertainties achievable from their calibration. The robustness of hydrophones in withstanding damaging effects of cavitation at high-intensity therapeutic ultrasound (HITU) pressures is an important consideration when measuring such fields. It should additionally be noted that the sensitivity response referred to in this article only refers to the magnitude part of the complex frequency response of the hydrophone. The phase component of the frequency response is essential when measuring broadband ultrasound signals using a hydrophone with a nonuniform

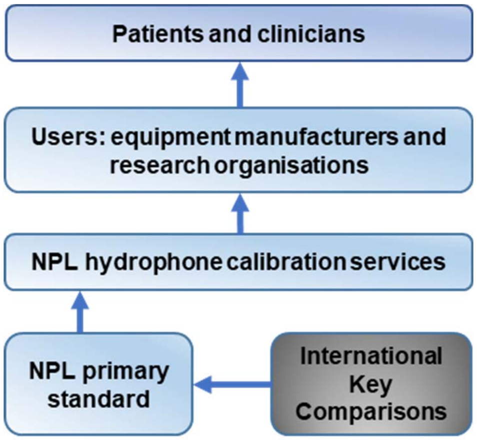

Fig. 1. Schematic representation of the way in which the acoustic pascal in water, as realized at NPL using the primary standard, is disseminated to the user community.

frequency response. In such cases, to accurately recover a broadband pressure signal, a temporal deconvolution of the measured hydrophone voltage signal is performed by using its complex-valued frequency response. This need is currently recognized in the revision to the IEC 62127-1 standard [10]. Fiber-optic hydrophones based on Fabry–Perot interferometry or reflectance at the tip of a cleaved fiber [23], [24] have not been considered in this article as they are very rarely calibrated at NPL.

More information on topics such as hydrophone designs, directivity calibrations, signal processing techniques for spatiotemporal deconvolution, considerations when using hydrophones for HITU, and how to choose a hydrophone for a given application is covered in a tutorial article published within this Spotlight Issue and the references contained therein [13].

Throughout this article, unless otherwise stated, all uncertainties (including error bars shown in the various figures) are expressed as combined (random and systematic) expanded uncertainties for a confidence interval of 95% (coverage factor $k = 2$). At NPL, the uncertainty analysis is carried out consistent with the ISO/IEC document: Guide to the expression of uncertainty in measurement [21].

II. REALIZING THE ACOUSTIC PASCAL

The unit of acoustic pascal [kg·m^{-1}·s^{-2}] is realized at a handful of global NMIs using a primary measurement standard (or primary standard) that provides direct traceability to fundamental units of measurement, that is, the SI. Free-field hydrophone calibrations obtained on the primary standard are also sometimes referred to as "absolute" calibrations and hydrophones calibrated on the primary standard can be known as reference, transfer, or secondary standard hydrophones. According to the International Vocabulary of Metrology [25], a primary standard is defined as a measurement standard established using a primary reference measurement procedure in which the derived measurement has no relation to another measurement standard for a quantity of the same kind. This is to say that the derived hydrophone sensitivity does not make reference to another hydrophone, regardless of its transduction mechanism.

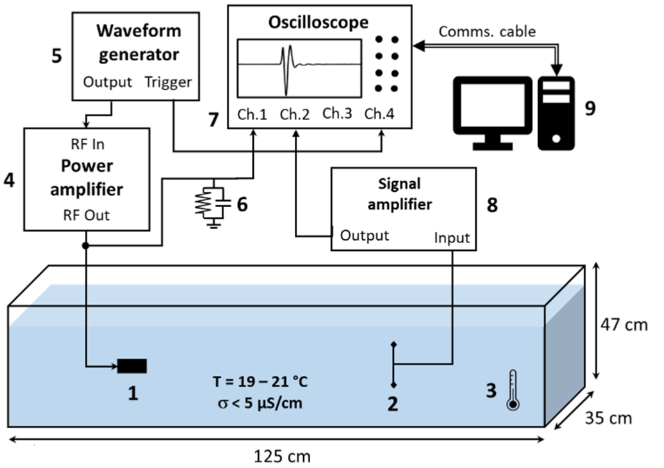

Fig. 2. General layout of the secondary standard hydrophone calibration setup. The details of various parts of the calibration setup identified by their corresponding numeric are listed in Table I. RF – radio-frequency (signal). Comms. Cable – General-purpose interface bus communications cable.

Various techniques have been explored for calibrating hydrophones [6], [18], [21], [26], [27], [28]. Optical interferometers are capable of measuring broadband and finite amplitude distorted ultrasound fields several megapascals in amplitude. The general arrangement consists of a thin plastic membrane (pellicle) made of polyethylene terephthalate film (1–5-μm thick) coated with a layer of gold (<25 nm in thickness) on one side, stretched over an annular ring [29]. The acoustic field from the source transducer is incident on the uncoated side, and the interrogating laser beam (beam waist ~ 50 μm) from the interferometer is reflected from the gold-coated surface. The laser interferometer is used to measure the motion of the pellicle as it moves in sympathy with the acoustic wave [29]. For a pellicle positioned in the transducer far-field, the sinusoidal acoustic displacement d [m] can be related to the acoustic pressure amplitude p under conditions approximating to an acoustic plane wave

$$p = \rho c \omega d \tag{1}$$

where ω [rad·s^{-1}] is the angular frequency and ρ [kg·m^{-3}] and c [m·s^{-1}] are the temperature-dependent mass density and speed of sound in water, respectively. The optical interferometer can, therefore, be used to measure the acoustic displacement at a spatial location in the field (thereby realizing the acoustic pascal); hydrophone calibration involves positioning the device to be calibrated at exactly the same point in the field and measuring its output voltage. Optical interferometers have been used to calibrate hydrophones at NPL in the frequency range of 100 kHz–60 MHz [18], [30], [31], [32]. Primary calibration of hydrophones typically requires acoustic displacements to be measured from a few tens of nanometers to a few tens of picometers. At NPL, the primary standard is used to calibrate several secondary standard membrane hydrophones with uncertainties that increase from typically 3% to 18% over the frequency range 100 kHz–60 MHz with the lowest uncertainty achieved in the range 0.5–20 MHz. These secondary standard hydrophones are then used to disseminate the acoustic pascal through the suite of services described in Section IV.

III. International Perspective

In terms of ensuring measurement comparability, it is clearly critical that the equivalence of primary realizations of units of technological significance at NMIs is validated. One of the central objectives of the mutual recognition arrangement (MRA) drawn up by the International Committee of Weights and Measures (CIPM) and signed by representatives of Member States of the Bureau International des Poids et Mésures (BIPM) is to establish degrees of equivalence of the national measurement standards maintained by NMIs [33]. Underpinning the basis for mutual recognition of calibration and measurement certificates issued globally, this provides governments and other parties with a secure technical foundation, which supports wider agreements related to international trade, commerce, and regulatory affairs (CIPM-MRA 2003) [34]. The BIPM is an international organization established by the Metre Convention, through which Member States act together on matters related to measurement science and measurement standards.

Degrees of equivalence of national measurement standards are established through international comparisons known as key comparisons (KCs) organized by various consultative committees of the CIPM such as the Consultative Committee for Acoustics, Ultrasound and Vibration (CCAUV). For the area of ultrasound exposimetry at medical ultrasound frequencies, these KCs address measurement of acoustic power using reference sources of ultrasound power circulated to NMIs [35] as well as the realization of the acoustic pascal in water using reference hydrophones. The latter involves circulating stable and well-characterized reference hydrophones between participating Laboratories. Frequency-dependent sensitivity values are compared using a strict KC protocol that involves NMIs declaring their full uncertainty budgets before participating in the KC. Taking place periodically over an eight–ten-year time frame, the frequency span of the last hydrophone KC was 0.5–20 MHz [36]. It involved the participation of four NMIs (NPL, PTB-Germany, NIM-China, and NMI-Japan) wherein NPL, PTB, and NMI-Japan provided calibrations using optical interferometry, and NIM-China provided calibrations using two-transducer reciprocity. Comparison results are used to derive degrees of equivalence between the NMIs. These support the CIPM MRA whose primary outcome is internationally recognized (peer-reviewed, validated through KCs, and finally approved) calibration and measurement capabilities (CMCs) at the NMI level which are publicly available in the CIPM MRA database (KCDB) [33]. BIPM defines a CMC as "the highest level of calibration or measurement normally offered to clients, expressed in terms of a confidence level of 95%, sometimes referred to as best measurement capability." The CMC tables enable parties interested in securing access to the calibration capability for various physical and chemical quantities to compare uncertainties and calibration scope declared by NMIs.

IV. Dissemination Methods at NPL

At NPL, secondary hydrophone calibration involves two methods employing multiple frequency intercomparison techniques (nonlinear distortion and broadband pulse). Together, these techniques can cover the range of 100 kHz–60 MHz. The comparison techniques are conceptually simple to understand: positioning the device under test and any reference device at exactly the same point in the acoustic field sequentially and comparing their output signals. However, a strict protocol is followed to ensure that the effects of short-term drifts in the calibration, for example, generated by fluctuations in the transducer output, are identified. An important feature of the calibration services is the use of two reference hydrophones whose calibration is traceable to the primary standard, which mitigates against changes in the reference hydrophone sensitivity in between primary calibrations. Reference hydrophones are calibrated regularly on the primary standard and must meet criteria related to stability over time and use. To ensure stable calibration conditions, the second reference hydrophone is used to assess if the results obtained using the first reference measurement are correct (the likelihood of both changing by the same amount being remote), thereby validating the test or user hydrophone results acquired between the two reference hydrophone acquisitions. This is done by determining the frequency-dependent ratios of the output voltages derived from the two secondary standard hydrophones and comparing them with historical values for these ratios. The nonlinear method generates calibration data with coarse frequency increments of 1 MHz (1–40 MHz) and 2 MHz (2–60 MHz). The broadband pulse method generates data with higher frequency resolutions. The standard increment for commercial services is 50 kHz over the frequency range 100 kHz–20 MHz. The hydrophone–transducer separation is chosen to ensure that the −6-dB beamwidth at each frequency within the calibration frequency range is at least three times the effective sensitive element size, to minimize spatial averaging errors. In both methods, four independent measurements are carried out, at different transducer–hydrophone separations, which results in four different frequency spectra. The actual transducer–hydrophone separation is maintained via fixed time-of-flight.

A. Calibration Setup

A general overview of the secondary standard hydrophone calibration setup is shown in Fig. 2 and the details of the various items of the setup are listed in Table I. The specific information related to nonlinear and broadband pulse methods is covered in Sections IV-B and IV-C, respectively. The dimensions of the polymethyl methacrylate water tank are 125 × 35 × 47 cm (length × width × height). The tank is filled with fresh deionized water (electrical conductivity, $\sigma < 1.5\ \mu\mathrm{S}\cdot\mathrm{cm}^{-1}$). The water quality degrades gradually over time as contaminants present on surfaces such as hydrophones, mounting structures, and operator hands (due to device handling) are transferred to the water. Therefore, the water is replaced every two weeks or sooner if σ approaches close to 5 $\mu\mathrm{S}\cdot\mathrm{cm}^{-1}$ [10]. The dissemination and primary standard facilities are resident in temperature-controlled laboratories and calibrations using both are carried out typically in the range of 19 °C–21 °C. Outside of this range, temperature-dependent sensitivity corrections may need to be applied [18], [31].

TABLE I
DETAILS OF EQUIPMENT USED IN THE SECONDARY STANDARD HYDROPHONE CALIBRATION

I.D.	Equipment	Nonlinear Distortion	Broadband Pulse
1	Transducer	i. Plane piston ⌀ = 50 mm, 1 MHz / Precision Acoustics Ltd., UK. ii. Plane piston V397, ⌀ = 29 mm, 2.25 MHz: / Olympus Keymed, Essex, UK.	i. Plano-concave 0.1-1.6 MHz custom transducer [37], ⌀ = 40 mm / Precision Acoustics Ltd, UK. ii. Planar and broadband V306, ⌀ = 13 mm, 2.25 MHz / Olympus Keymed, Essex, UK. iii. Planar and broadband V313, ⌀ = 6 mm, 15 MHz / Olympus Keymed, Essex, UK.
2	Hydrophone	Various membrane type hydrophones including GEC Marconi. For example, see ref [13].	
3	Thermometer	Spirit-in-glass thermometer IP39C / G. H. Zeal Ltd., UK.	
4	Power amplifier	150A100B / AR UK Ltd., Milton Keynes, UK.	
5	Waveform generator	33250A / Keysight Technologies, Wokingham, UK.	
6	100 MΩ scope probe	P5100A / Tektronix Inc., Bracknell, UK.	
7	Oscilloscope	TDS7104 / Tektronix Inc., Bracknell, UK.	
8	Small signal amplifier	0.1 – 100 MHz custom broadband amplifier for hydrophone signals / Cooknell Electronics Ltd, Weymouth, UK.	
9	Desktop computer	GX1 Optiplex installed with custom acquisition and analysis software written in LabVIEW® / Dell Inc., Round Rock, USA.	

All electrical equipment is turned on for at least 1 h before starting measurements to ensure that their thermal equilibrium is reached for stable operation. Similarly, the transducer, reference, and user hydrophones are all left immersed in the water tank to ensure they are completely wetted, that is, free of surface bubbles and have reached thermal equilibrium with the water.

The transducer is excited using a tone burst (nonlinear distortion method) or pulse signal (broadband pulse method) generated by the combination of a waveform generator and power amplifier at a pulse repetition rate (PRR) of 200 Hz. To ensure that the transducer is excited under nominally identical conditions, the transducer drive voltage at the output of the power amplifier is monitored using a scope probe with an input impedance of 100 MΩ. If the transducer voltage drifts by more than 1% from the voltage level recorded for the first reference hydrophone measurement, then the amplitude of the signal to the power amplifier for the subsequent user and second reference hydrophone measurements is accordingly adjusted on the waveform generator.

The signal amplifier shown in Fig. 2 is a small signal amplifier present between the output of the hydrophone and the oscilloscope. It has a voltage gain of ×5, high input impedance, output impedance matched to 50 Ω, and −3-dB bandwidth ranging from 100 kHz to 100 MHz. This amplifier is always present in the measurement chain and is used to improve the signal-to-noise ratio of hydrophone signals. For GEC Marconi type and hydrophones without an inbuilt amplifier, the small signal amplifier acts as a voltage buffer amplifier transforming the electrical impedance at the input of the hydrophone to the same as the input of a voltage measuring device such as the oscilloscope. For such hydrophones, a loading correction is applied by knowing the input impedances of the hydrophone and buffer amplifier, and the sensitivity is quoted as end-of-cable open-circuit sensitivity. The necessary equations for calculating loading corrections are mentioned in Annex C of the IEC 62127-2 standard [6].

B. Nonlinear Distortion

In this technique, broadband ultrasonic fields are produced by the nonlinear propagation of quasilinear single-frequency tone burst acoustic waves over a large distance [38]. To cover the frequency range of 1–60 MHz, two plane piston narrowband transducers are used (see Table I), with their center frequencies at 1 and 2 MHz. The transducer is excited with a tone burst signal consisting of 15 cycles at a peak-to-peak voltage of approximately 150 V. The minimum time-of-flight (transducer–hydrophone) propagation delays at a water temperature of 20 °C for 1 and 2 MHz transducers are 400 μs (equivalent to a distance of 593 mm) and 220 μs (or 326 mm), respectively. The acoustic pressure profile perpendicular to the transducer beam-alignment axes is broad enough such that the spatial-averaging corrections are negligible. An integer number of cycles (usually 5) from the constant amplitude region of the tone burst indexed at the same time offset for reference and user hydrophones is used for analysis. Harmonic frequencies at the integer multiples of the fundamentals obtained by Fourier transform (magnitude components) of the selected tone burst signals are used for comparisons. The maximum useable harmonic frequency for 1 and 2 MHz transducers is 40 and 60 MHz, respectively, which is based on the signal-to-noise and beamwidth, in conjunction with the upper-frequency limit of NPL's current primary standard capability. Typical acoustic pressure amplitudes generated for the calibration are 1–2 MPa. Here, coplanar-type broadband reference hydrophones are used with active element diameters in the range of 0.1–0.5 mm.

C. Broadband Pulse

The broadband pulse method provides calibration data at higher frequency increments and covers the frequency range of 0.1–20 MHz [37]. Three single-element, planar, and broadband transducers are necessary to cover this frequency range. The useable bandwidth of the transducers employed overlaps to provide increased confidence in the calibration data. The transducers are excited using a single-cycle sine wave at a peak-to-peak voltage of approximately 200 V. The first transducer, which has a relatively flat transmit response in the mid-frequency range of 0.1–1.6 MHz, is driven at both 500 kHz and 1 MHz. The second and the third transducers are driven at 2 and 9 MHz, respectively. The minimum time-of-flight transducer–hydrophone propagation delay at a water temperature of 20 °C for the first transducer is 200 μs (or 296 mm) and it is 120 μs (or 178 mm) for the second and the third transducers, respectively. In contrast to the method exploiting nonlinear distortion (see Section IV-A),

TABLE II

BEST ACHIEVABLE EXPANDED UNCERTAINTIES (*U*) FOR COMMERCIAL HYDROPHONE CALIBRATIONS AT NPL

Nonlinear		***Broadband***	
Frequency range	**U (%)**	**Frequency range**	**U (%)**
1 MHz – 8 MHz	6	0.10 MHz – 0.20 MHz	15
9 MHz – 12 MHz	7	0.25 MHz – 1.00 MHz	9
13 MHz – 16 MHz	8	1.05 MHz – 8.00 MHz	9
17 MHz – 20 MHz	11	8.05 MHz – 12.00 MHz	10
21 MHz – 30 MHz	12	12.05 MHz – 16.00 MHz	11
31 MHz – 40 MHz	15	16.05 MHz – 20.00 MHz	12
42 MHz – 50MHz	18		
52 MHz – 60 MHz	22		

peak-positive acoustic pressures generated using the broadband pulse technique are less than 250 kPa. The sampling frequency of the oscilloscope is fixed at 250 MS$\cdot$s^{-1}. The record length of the waveform is adjusted to provide the user-desired frequency increment. The magnitude components of the Fourier transform of the recorded reference and user hydrophone waveforms truncated over the useable frequency range for each transducer are employed for voltage signal comparisons. At least one of the two reference hydrophones is of Marconi bilaminar design with a 1 mm active element diameter. The bilaminar membrane presents a good signal-to-noise ratio of up to 20 MHz and its shielded nature means that it is typically less prone to electrical pick-up [39]. At frequencies below 0.1 MHz, the acoustic wavelength is significant in relation to the dimensions of characteristic construction features of the device (needle dimensions or the size of the supporting ring for a membrane) [30] and reflections may be important with the free-field assumption not being valid. This has been recently studied for needle hydrophones [40].

Currently available transducer technologies do not allow this technique to extend to frequencies beyond 20 MHz as it is difficult to generate planar acoustic fields relative to the maximum diameter of hydrophone used in biomedical ultrasound with an acceptable signal-to-noise ratio. Recently, the use of laser-generated ultrasound sources has shown significant promise in this regard [41].

Good agreement between the various calibration methods is exhibited, with random (Type A) uncertainties derived from a set of four repeat measurements being typically less than 3% expanded uncertainty for both the techniques described in this section. The best achievable expanded uncertainties for each frequency range and method are described in Table II. Fig. 3 shows an example of an NPL-calibrated hydrophone using the two methods covering the range of 0.1–60 MHz. The sensitivities in the overlapping frequency range, considering their respective expanded uncertainties, demonstrate good agreement between the broadband pulse and nonlinear distortion calibration methods.

V. TYPES OF COMMERCIAL HYDROPHONES

Worldwide, there are relatively a few manufacturers of high-quality hydrophones appropriate for use in the characterization of acoustic fields. This perhaps reflects the limited market size, but also the manufacturing difficulties in fabricating devices that approach the performance of an ideal hydrophone with regard to key performance features such as high sensitivity, small element size, stability, broadband, and uniform frequency response. Fig. 4 shows some of the typically available commercial devices.

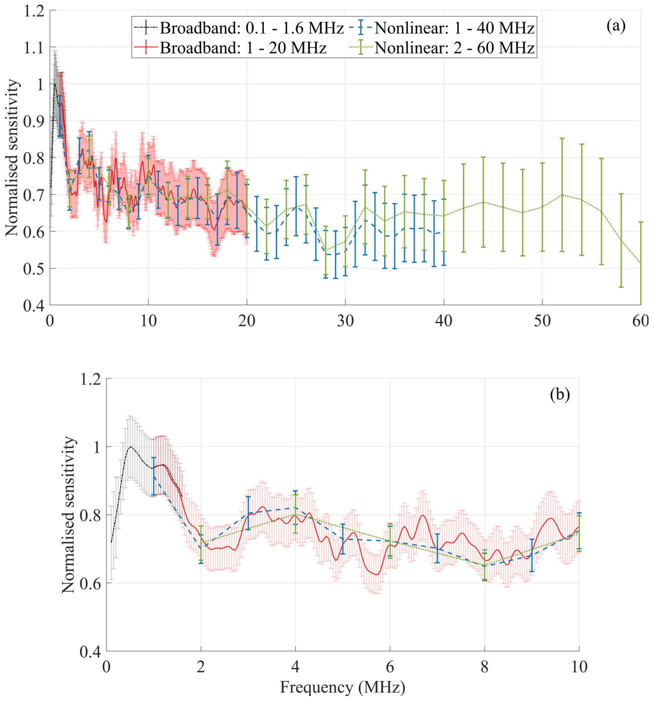

Fig. 3. Variation in sensitivity of a probe hydrophone with a nominal active element diameter of 0.085 mm using the broadband pulse and nonlinear calibration methods in use at NPL over the frequency range of (a) 0.1–60 MHz and (b) 0.1–20 MHz shown for the purpose of clarity.

The most common piezoelectric material used to manufacture high-quality hydrophones is based on polyvinylidene difluoride (PVDF) polymer. One of the main advantages of PVDF over other materials employed such as devices based on piezo-ceramics is the close acoustic impedance match to water. Earlier studies indicate that PVDF devices are additionally more stable than ceramic types [42]. Fig. 5 illustrates typical sensitivity curves for some of the hydrophones pictured in Fig. 4.

The hydrophones NPL calibrates are ultimately applied to quantify the acoustic output of clinical instrumentation. Aspects of their performance affecting the acoustic output measurement uncertainties are also clearly pertinent to how the devices are calibrated and the specific choice of calibration technique as covered in Section IV. IEC standard 62127-3 [22] recommends technical characteristics to be considered when using hydrophones for ultrasonic fields up to 40 MHz. These relate to the following:

1) The frequency response of the hydrophone.
2) *The directional response:* The frequency-dependent angular sensitivity gives rise to an effective active element radius, which deviates significantly from a geometrical radius below 5 MHz [43], [44], [45].
3) *Effective radius:* The effective radius of the element dictates spatial-averaging corrections during calibration and can be frequency-dependent [43], [44].

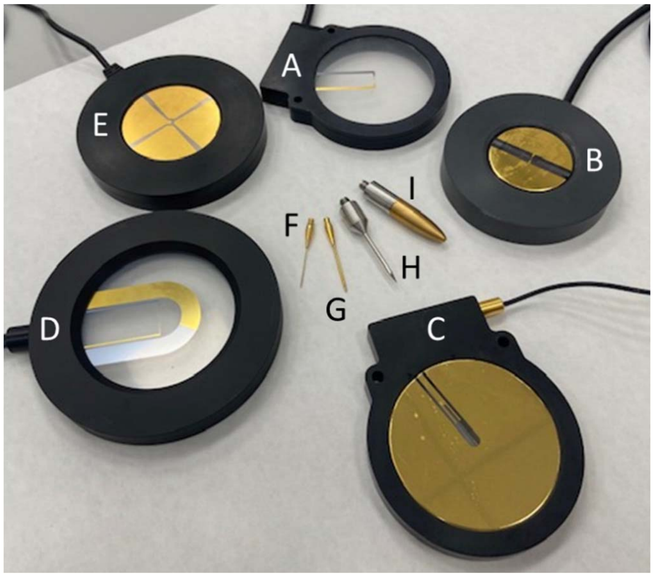

Fig. 4. Typical commercially available hydrophones. (A) Precision Acoustics Ltd. (PA), Dorchester, U.K., 0.2-mm-diameter differential-type membrane hydrophone (MH). (B) Onda Corporation, Sunnyvale, CA, USA, 0.2-mm side dimension backed MH. (C) PA 0.4-mm-diameter MH. (D) GAMPT mbH, Merseburg, Germany, 0.2-mm-diameter differential-type MH. (E) Acertara Acoustics Laboratory, Longmont, CO, USA, 0.4-mm-diameter MH. (F) and (G) PA 0.2- and 0.5-mm diameter needle hydrophones (NH). (H) Onda Corporation, 0.2-mm-diameter NH. (I) Onda Corporation, 0.2-mm probe or generally known as "Capsule"-type hydrophone. (These are only some examples and do not cover the range of all available devices.)

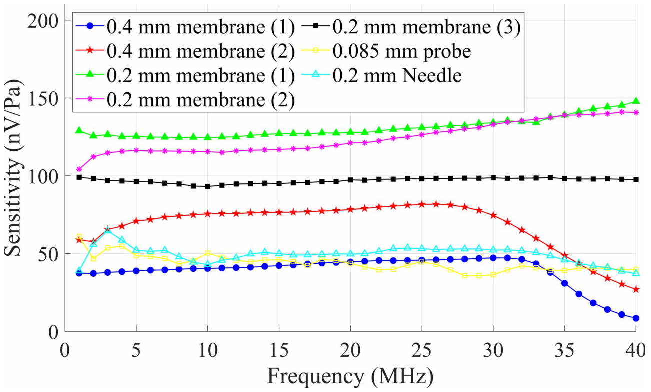

Fig. 5. Sensitivities of typical commercially available hydrophones. (These are only some examples and do not cover extensively the range of all available devices.)

4) *Environmental aspects:* The temperature of the water and its electrical conductivity are the main environmental factors that will affect both the hydrophone's performance and the calibration results.

Membrane hydrophones are often preferred because they exhibit both broadband and smooth frequency response. However, at low frequencies (<5 MHz), these hydrophones will present large sidelobes in their directional response due to the radial propagation of Lamb waves [46]. In contrast, probe (or needle) hydrophones do not have the directional response so strongly accentuated. The strong directionality of all hydrophones makes the acoustic alignment of these devices a crucial factor during calibration.

TABLE III

MAIN CHARACTERISTICS OF PIEZOELECTRIC POLYMER/CERAMIC HYDROPHONES

Hydrophone type	**Application - advantages**	**Application – disadvantages**
Membrane	- Less pulse distortion - Uniform sensitivity - Stability - Robustness - Higher bandwidth	- Bulky design - Coherent reflections, affecting continuous-wave measurements. - Strong directional response - Cost
Needle/Probe	- Access to device - No strong directional response - Cost - Suitable for continuous wave	- Soaking issues - Strong frequency dependent sensitivity at low frequencies - Fragile

All the parameters listed above directly affect the calibration uncertainties (Type B systematic), which need to be quantified and applied in the overall uncertainty estimation [38].

Table III summarizes the main characteristics of hydrophone types with regard to their application and the calibration techniques typically applied by NPL to determine their frequency-dependent sensitivity.

VI. PERIODIC CALIBRATIONS AND DEVICE STABILITY

While all hydrophone model types have characteristic frequency responses, their sensitivity cannot be known *a priori*, and hydrophones of nominally the same type can have differences in sensitivity by up to 100%. While 1-D analytical models for membrane hydrophones have been developed [16], [17], the significant uncertainties in input parameters mean that they can only be used to identify qualitative trends such as how design characteristics affect its frequency response. For this reason, for traceable measurements of acoustic field characteristics, each hydrophone must be individually calibrated. Most hydrophone manufacturers provide calibration data with their devices. These calibrations must be traceable through an unbroken chain of comparisons back to national standards maintained by an NMI, where the manufacturer's reference hydrophone is calibrated. Many modern hydrophones are coupled with integral or external amplifiers with the output signal terminated into a 50-Ω electrical impedance. Additional amplification stages are also common components of the measurement configuration. The calibration is normally performed on the combination, and a variation in any one component will require a new calibration.

It is worth remarking that the hydrophone's sensitivity is strictly valid only at the time of calibration and for the laboratory conditions in which the hydrophone is calibrated. The calibration certificate is not a guarantee that the device will perform in the same way in the future. However, two consecutive calibrations with comparable results can be reassuring to the user that their device has performed consistently during the interval between calibrations. For this reason, the IEC standard 62127-3 [22] recommends annual calibration of hydrophones as appropriate in most cases. However, to provide continued confidence in the performance of the device, it is

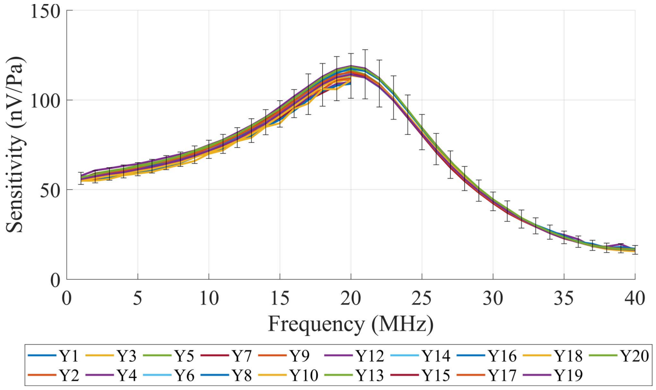

Fig. 6. Historical calibrations obtained from the nonlinear method (see Section IV-B) of a 1-mm diameter bilaminar membrane hydrophone over a period of 20 years, with data from 20 to 40 MHz only available from the year (Y) 12 onward. In Y11, the hydrophone was not returned to NPL for calibration.

clearly good practice to perform internal checks in a reference acoustic field before each use.

Typically, membrane hydrophones are very stable devices and, generally, very resilient. In our experience as a calibration laboratory, we have seen scratched or dented membranes, those that have suffered the loss of metallic coatings of both hydrophone and preamplifiers, without changes in sensitivity. IEC standard 62127-1 [10] recommends that when a single layer, electrically unshielded PVDF membrane hydrophone is used, the electrical conductivity of the water should be less than 5 μS$\cdot$cm^{-1}. For those devices that are regularly calibrated at NPL, the stability in the derived frequency-dependent sensitivity is both an indication of the continuity in the working condition of the device but also the stability of the calibration protocols employed to disseminate the acoustic pascal through secondary standard hydrophones. Fig. 6 shows the calibration results from the nonlinear method (described in Section IV-A) for a bilaminar membrane with a 1-mm-diameter active element, which has been calibrated on an annual basis almost continually for 20 years.

The normalized sensitivities (relative to historical averages) for selected frequencies of 1, 5, 10, 15, and 20 MHz are shown in Fig. 7. The root mean square (rms) variation is approximately 4.5% for all frequencies. In Y11, the hydrophone was not returned to NPL for recalibration. But in Y12, there was a 5%–10% increase in sensitivity relative to Y10 with a weak dependence on frequency. The rms value for the datasets before and after Y11 is approximately 3.1% at all frequencies. Though this suggests there was a step change in the overall sensitivity of the hydrophone, the two sensitivities from Y10 and Y11 are within their respective expanded uncertainties. The historical sensitivity data in Fig. 8 also shows that stability is a consistent characteristic among different models and manufacturers. While membrane hydrophones are generally considered more durable, probes can also show stable sensitivity over extended time periods.

Despite the demonstrated potential stability of hydrophones, issues do arise. Catastrophic failure (i.e., a complete absence of the electrical output signal) is only one of the possible issues and in other cases, a hydrophone can change its sensitivity and continue to produce output signals. It is, therefore, important that a calibration system is sensitive enough and the quality regime put in place is robust enough to be able to detect these changes, which can sometimes be quite subtle. A series of examples of sensitivity changes are reported in Fig. 9.

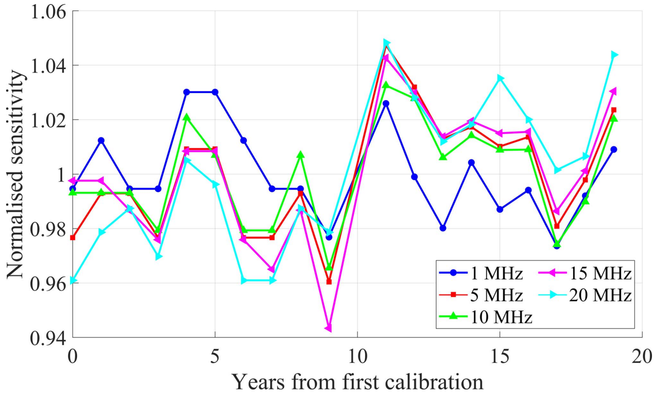

Fig. 7. Historical calibrations normalized to the historical average of selected frequencies from Fig. 6. Error bars representing relative uncertainties on each trace are not shown for clarity. The rms variation in the calibration trend is 4.5% for all frequencies, which is within the expanded calibration uncertainty at each frequency (refer to Table II).

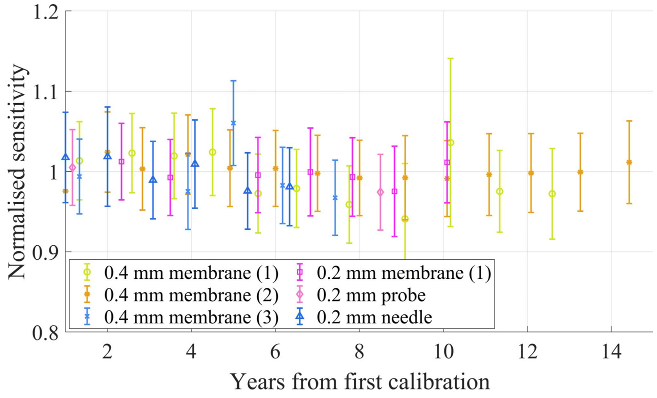

Fig. 8. Normalized sensitivity at 10 MHz for different commercial hydrophones. The horizontal axis represents the time from the first calibration. For each hydrophone, values were normalized to the average value computed from all calibrations for that hydrophone.

Fig. 9(a) shows a hydrophone whose sensitivity shifted downward by approximately 20% while still maintaining the same frequency response shape. This device continued to provide a good signal-to-noise ratio and a realistic waveform shape, but using the previous values of sensitivity will invariably result in an underestimation of the pressure parameters. Fig. 9(b) shows a hydrophone whose sensitivity changed only at high frequencies. This will result in an error in the estimation of the peak positive pressure of high-frequency pressure pulses. Fig. 9(c) shows a hydrophone whose frequency response changed only within a frequency band, in the example between 9 and 13 MHz. These variations might be difficult to spot but have significant effects if the measured acoustic wave has components within this frequency range. Fig. 9(d) shows a hydrophone whose frequency response has changed both in magnitude and shape. The changes will result in a different waveform, which cannot be reconciled with previous measurements from the same ultrasound device. It is interesting to observe that the sensitivity at 2 MHz has not changed, so a spot check at that frequency would have resulted in a pass test.

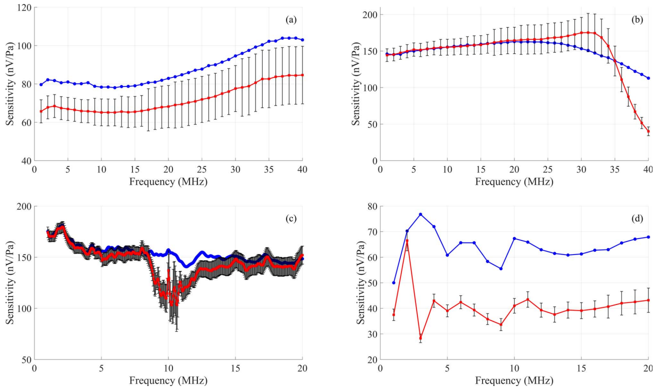

Fig. 9. Four example scenarios in which the sensitivity of a hydrophone was changed between two consecutive calibrations, performed one year apart. Red traces and corresponding error bars refer to the latest calibration and blue traces correspond to the preceding calibration. (a) Hydrophone whose sensitivity shifted downward by approximately 20% while still maintaining the same frequency response shape. (b) Hydrophone sensitivity changed only at high frequencies. (c) Hydrophone whose frequency response changed only within a small frequency band between 9 and 13 MHz. (d) Hydrophone whose frequency response has changed both in magnitude and shape. Refer to the main text for more details.

VII. DISCUSSION

In this article, the experiences of the U.K. NMI, NPL, in disseminating the standards for acoustic pressure through the realization of the acoustic pascal measured by a hydrophone, are shared with the user community. To the authors' knowledge, it is the first time that data on the long-term stability of a wide range of commercially available hydrophones have been published. At NPL, the realization of the acoustic pascal to the highest accuracy achievable is based on a primary standard utilizing a displacement sensing laser interferometer providing direct traceability to the fundamental base units of measurement, that is, the SI. Confidence in the primary standard is crucially established by deriving degrees of equivalence between global NMIs through KC exercises. The applications of biomedical ultrasound extend well beyond the frequency range of the last KC, which was from 0.5 to 20 MHz. This was the second KC in the Ultrasound area, which was extended down to 0.5 MHz to overlap with the primary standard capabilities of the Underwater Acoustics area [47]. Currently, NPL is looking to extend the lower frequency limit of its optical primary standard down to 100 kHz. Therefore, there is a need to establish degrees of equivalence from a lower limit of 100 kHz up to at least 40 MHz, which aligns with the requirements of current IEC standards [6], [10], [22]. NPL services that have disseminated the pascal have spanned a duration of almost four decades. Over this time, the primary standard has seen several evolutions [18], [29], [30], [31], [32] and in parallel, dissemination techniques have been developed and validated in order to respond to user requirements for frequency range coverage, frequency resolution, and the calibration of relative phase. The examples given in terms of the stability of various commercially available devices also demonstrate the stability of the comparison methods employed to disseminate the acoustic pascal. They also point to the ability of the techniques described in Section IV, to detect small and subtle changes in hydrophone frequency response.

It is clear from the incorporation of hydrophones in a range of international and national standards that these devices play a pivotal role in the traceability of the acoustic pascal in various biomedical applications. However, they remain artifacts and not primary standards in themselves and as such there are a number of key performance characteristics [13], [22] of which its stability is really central to ensuring accurate measurements are made each and every time a hydrophone is used. The historical calibration data shared in this article for a range of example hydrophone models provide confidence in their long-term stability (see Fig. 8). The recommendation of IEC standard 62127-3 [22] for annual calibration of hydrophones traceable to national standards appears to be appropriate in most cases for the reference devices described in this article. Although this is good practice, there may be instances where the hydrophone sensitivity could change in-between periodic calibrations at an NMI. If the in-house quality regime only involves single-frequency checks, then, in some cases, it may not reveal the complete change in device behavior [see Fig. 9(d)], which could lead to errors in the performance evaluation of biomedical ultrasound devices. In our experience, in only in few cases were users (primarily equipment manufacturers) aware of performance changes to their hydrophones before sending them to NPL. Therefore, it is of utmost importance to have a robust in-house quality regime such as multiple frequency stability checks in reference broadband acoustic fields and also by maintaining multiple hydrophones of different designs, which may be calibrated at staggered intervals at NMIs.

Looking to the future and to meet the requirements of increasingly broadband hydrophones being developed, the dissemination of hydrophone calibrations up to 100 MHz will become more important as this is presently under consideration in the future editions of IEC standards 62127-1 and 62127-2. PTB has already developed its primary standard to satisfy the anticipated increase in the upper limit of traceable calibrations [21]. NPL has made some progress in this regard with the development of a 100-MHz bandwidth planar laser-generated ultrasound source for hydrophone calibration [41]. Similar to PTB, NPL's new interferometer is based on a 600-MHz bandwidth laser vibrometer together with the laser-generated ultrasound source will be evaluated in extending its traceable frequency range from its current upper limit of 60 MHz. NMI-China and NMI-Japan have also extended their primary standards based on optical interferometry up to at least 40 MHz [19], [20], [26]. Taking into consideration of the latest development across NMIs, there will be a need to extend the frequency range of future KCs, underpinned by the availability of high-quality, stable reference hydrophones.

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REFERENCES

[1] *The International System of Units (SI), Bureau International des Poids et Mesures*. Accessed: Jul. 20, 2022. [Online]. Available: https://www.bipm.org/en/publications/si-brochure

[2] *Medical Electrical Equipment—Part 2-37: Particular Requirements for the Basic Safety and Essential Performance of Ultrasonic Medicaldiagnostic and Monitoring Equipment*, document IEC 60601-2-37:2007+AMD1:2015 CSV, Int. Electrotechnical Commission, Geneva, Switzerland, 2015.

[3] *Medical Electrical Equipment—Part 2-62: Particular Requirements for the Basic Safety and Essential Performance of High Intensity Therapeutic Ultrasound (HITU) Equipment*, document IEC 60601-2-62:2015, Int. Electrotechnical Commission, Geneva, Switzerland, 2015.

[4] *Medical Electrical Equipment—Part 2-5: Particular Requirements for the Basic Safety and Essential Performance of Ultrasonic Physiotherapy Equipment*, document IEC 60601-2-5:2015, Int. Electrotechnical Commission, Geneva, Switzerland, 2015.

[5] *Quantities and Units—Part 8: Acoustics*, document ISO 80000-8:2020, Int. Electrotechnical Commission, Geneva, Switzerland, 2020.

[6] *Ultrasonics—Hydrophones—Part 2: Calibration for Ultrasonic Fields Up to 40 MHz*, document IEC 62127-2:2007+AMD1:2013+AMD2:2017 CSV, Int. Electrotechnical Commission, Geneva, Switzerland, 2017.

[7] *Ultrasonics—Power Measurement—Radiation Force Balances and Performance Requirements*, document IEC 61161:2013, Int. Electrotechnical Commission, Geneva, Switzerland, 2013.

[8] G. R. Harris, "Progress in medical ultrasound exposimetry," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 52, no. 5, pp. 717–736, May 2005, doi: 10.1109/TUFFC.2005.1503960.

[9] G. R. Harris, R. C. Preston, and A. S. DeReggi, "The impact of piezoelectric PVDF on medical ultrasound exposure measurements, standards, and regulations," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 47, no. 6, pp. 1321–1335, Nov. 2000, doi: 10.1109/58.883521.

[10] *Amendment 1-Ultrasonics—Hydrophones—Part 1: Measurement and Characterization of Medical Ultrasonic Fields up to 40 MHz*, document IEC 62127-1:2007+AMD1:2013, Int. Electrotechnical Commission, Geneva, Switzerland, 2013.

[11] S. Robinson, R. Preston, M. Smith, and C. Millar, "PVDF reference hydrophone development in the U.K.—From fabrication and lamination to use as secondary standards," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 47, no. 6, pp. 1336–1344, Nov. 2000, doi: 10.1109/58.883522.

[12] V. Wilkens, S. Sontag, and O. Georg, "Robust spot-poled membrane hydrophones for measurement of large amplitude pressure waveforms generated by high intensity therapeutic ultrasonic transducers," *J. Acoust. Soc. Amer.*, vol. 139, no. 3, pp. 1319–1332, 2016, doi: 10.1121/1.4944693.

[13] G. R. Harris *et al.*, "Hydrophone measurements for biomedical applications: A review," *Adv. Ultrasound Exposimetry*, to be published, doi: 10.1109/TUFFC.2022.3213185.

[14] *Amendment 1—Ultrasonics—Field Characterization—Test Methods for the Determination of Thermal and Mechanical Indices Related to Medical Diagnostic Ultrasonic Fields*, document IEC 62359:2010/AMD1:2017, Int. Electrotechnical Commission, Geneva, Switzerland, 2017.

[15] (2019). *Marketing Clearance of Diagnostic Ultrasound Systems and Transducers, Guidance for Industry and Food and Drug Administration Staff*. Accessed: Jul. 19, 2022. [Online]. Available: https://www.fda.gov/regulatory-information/search-fda-guidance-documents/marketing-clearance-diagnostic-ultrasound-systems-and-transducers

[16] P. N. Gélat, R. C. Preston, and A. Hurrell, "A theoretical model describing the transfer characteristics of a membrane hydrophone and validation," *Ultrasonics*, vol. 43, no. 5, pp. 331–341, Mar. 2005, doi: 10.1016/j.ultras.2004.08.003.

[17] C. Koch and W. Molkenstruck, "Primary calibration of hydrophones with extended frequency range 1 to 70 MHz using optical interferometry," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 46, no. 5, pp. 1303–1314, Sep. 1999, doi: 10.1109/58.796135.

[18] R. C. Preston, S. P. Robinson, B. Zeqiri, T. J. Esward, P. N. G. Lat, and N. D. Lee, "Primary calibration of membrane hydrophones in the frequency range 0.5 MHz to 60 MHz," *Metrologia*, vol. 36, no. 4, pp. 331–343, Aug. 1999, doi: 10.1088/0026-1394/36/4/13.

[19] Y. Matsuda, M. Yoshioka, T. Uchida, and T. Kikuchi, "Absolute calibration of membrane hydrophones up to 40 MHz in ultrasonic far-field," in *Proc. IEEE Int. Ultrason. Symp.*, Oct. 2012, pp. 374–377, doi: 10.1109/ULTSYM.2012.0092.

[20] P. Yang, G. Xing, and L. He, "Calibration of high-frequency hydrophone up to 40 MHz by heterodyne interferometer," *Ultrasonics*, vol. 54, no. 1, pp. 402–407, Jan. 2014, doi: 10.1016/j.ultras.2013.07.013.

[21] M. Weber and V. Wilkens, "Using a heterodyne vibrometer in combination with pulse excitation for primary calibration of ultrasonic hydrophones in amplitude and phase," *Metrologia*, vol. 54, no. 4, pp. 432–444, Aug. 2017, doi: 10.1088/1681-7575/aa72ba.

[22] *Ultrasonics—Hydrophones—Part 3: Properties of Hydrophones Forultrasonic Fields up to 40 MHz*, document IEC 62127-3:2007+AMD1:2013 CSV, Int. Electrotechnical Commission, Geneva, Switzerland, 2013.

[23] P. Morris, A. Hurrell, A. Shaw, E. Zhang, and P. Beard, "A Fabry–Pérot fiber-optic ultrasonic hydrophone for the simultaneous measurement of temperature and acoustic pressure," *J. Acoust. Soc. Amer.*, vol. 125, no. 6, pp. 3611–3622, Jun. 2009, doi: 10.1121/1.3117437.

[24] S. M. Howard, "Calibration of reflectance-based fiber-optic hydrophones," in *Proc. IEEE Int. Ultrason. Symp. (IUS)*, Sep. 2016, pp. 2–5, doi: 10.1109/ULTSYM.2016.7728572.

[25] *International Vocabulary of Metrology—Basic and General Concepts and Associated Terms (VIM)*, document ISO/IEC GUIDE 99:2007, Int. Org. Standardization, Geneva, Switzerland, 2007.

[26] Y. Matsuda, M. Yoshioka, and T. Uchida, "Absolute hydrophone calibration to 40 MHz using ultrasonic far-field," *Mater. Trans.*, vol. 55, no. 7, pp. 1030–1033, 2014, doi: 10.2320/matertrans.I-M2014814.

[27] G. Ludwig and K. Brendel, "Calibration of hydrophones based on reciprocity and time delay spectrometry," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. UFFC-35, no. 2, pp. 168–174, Mar. 1988, doi: 10.1109/58.4167.

[28] E. G. Oliveira, R. P. B. Costa-Felix, and J. C. Machado, "Primary reciprocity-based method for calibration of hydrophone magnitude and phase sensitivity: Complete tests at frequencies from 1 to 7 MHz," *Ultrasonics*, vol. 58, pp. 87–95, Apr. 2015, doi: 10.1016/j.ultras.2014.12.006.

[29] D. R. Bacon, "Primary calibration of ultrasonic hydrophone using optical interferometry," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. UFFC-35, no. 2, pp. 152–161, Mar. 1988, doi: 10.1109/58.4165.

[30] S. Rajagopal, B. Zeqiri, and P. N. Gélat, "Calibration of miniature medical ultrasonic hydrophones for frequencies in the range 100 to 500 kHz using an ultrasonically absorbing waveguide," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 61, no. 5, pp. 765–778, May 2014, doi: 10.1109/TUFFC.2014.2969.

[31] T. J. Esward and S. P. Robinson, "Extending the frequency range of the national physical laboratory primary standard laser interferometer for hydrophone calibrations to 80 MHz," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 46, no. 3, pp. 737–744, May 1999, doi: 10.1109/58.764860.

[32] C. J. Bickley, B. Zeqiri, and S. P. Robinson, "Providing primary standard calibrations beyond 20 MHz," *J. Phys., Conf.*, vol. 1, pp. 20–25, Jan. 2004, doi: 10.1088/1742-6596/1/1/007.

[33] *Calibration and Measurement Capabilities—CMCs*. Accessed: Jul. 19, 2022. [Online]. Available: https://www.bipm.org/kcdb/cmc/advanced-search

[34] *Technical Supplement to the Arrangement: Mutual Recognition of National Measurement Standards and of Calibration and Measurement Certificates Issued by National Metrology Institutes*, document CIPM Revision 2003, Bureau international des poids et mesures, Paris, France, 2003.

[35] C. Koch and K.-V. Jenderka, "Final report on key comparison CCAUV.U-K3 for ultrasonic power," *Metrologia*, vol. 51, no. 1A, Jan. 2014, Art. no. 09001, doi: 10.1088/0026-1394/51/1A/09001.

[36] S. Rajagopal *et al.*, "Report on BIPM/CIPM key comparison CCAUV.U-K4: Absolute calibration of medical hydrophones in the frequency range 0.5 MHz to 20 MHz," *Metrologia*, vol. 53, no. 1A, Jan. 2016, Art. no. 09004, doi: 10.1088/0026-1394/53/1A/09004.

[37] A. M. Hurrell and S. Rajagopal, "The practicalities of obtaining and using hydrophone calibration data to derive pressure waveforms," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 64, no. 1, pp. 126–140, Jan. 2017, doi: 10.1109/TUFFC.2016.2594770.

[38] R. A. Smith and D. R. Bacon, "A multiple-frequency hydrophone calibration technique," *J. Acoust. Soc. Amer.*, vol. 87, no. 5, pp. 2231–2243, May 1990, doi: 10.1121/1.399191.

[39] S. Robinson, R. Preston, M. Smith, and C. Millar, "PVDF reference hydrophone development in the U.K.—From fabrication and lamination to use as secondary standards," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 47, no. 6, pp. 1336–1344, Nov. 2000.

[40] S. Rajagopal *et al.*, "On the importance of consistent insonation conditions during hydrophone calibration and use," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, early access, Sep. 12, 2022, doi: 10.1109/TUFFC.2022.3205851.

[41] S. Rajagopal and B. T. Cox, "100 MHz bandwidth planar laser-generated ultrasound source for hydrophone calibration," *Ultrasonics*, vol. 108, Dec. 2020, Art. no. 106218, doi: 10.1016/j.ultras.2020.106218.

[42] R. C. Preston, Ed., *Output Measurements for Medical Ultrasound*. London, U.K.: Springer, 1991.

[43] K. A. Wear, C. Baker, and P. Miloro, "Directivity and frequency-dependent effective sensitive element size of membrane hydrophones: Theory versus experiment," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 66, no. 11, pp. 1723–1730, Nov. 2019, doi: 10.1109/TUFFC.2019.2930042.

[44] K. A. Wear, C. Baker, and P. Miloro, "Directivity and frequency-dependent effective sensitive element size of needle hydrophones: Predictions from four theoretical forms compared with measurements," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 65, no. 10, pp. 1781–1788, Oct. 2018, doi: 10.1109/TUFFC.2018.2855967.

[45] K. A. Wear and S. M. Howard, "Directivity and frequency-dependent effective sensitive element size of a reflectance-based fiber-optic hydrophone: Predictions from theoretical models compared with measurements," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 65, no. 12, pp. 2343–2348, Dec. 2018, doi: 10.1109/TUFFC.2018.2872840.

[46] D. R. Bacon, "Characteristics of a PVDF membrane hydrophone for use in the range 1–100 MHz," *IEEE Trans. Sonics Ultrason.*, vol. SU-29, no. 1, pp. 18–25, Jan. 1982, doi: 10.1109/TSU.1982.31298.

[47] *Underwater Acoustics—Hydrophones—Calibration of Hydrophones—Part 1: Procedures for Free-Field Calibration of Hydrophones*, document IEC 60565-1:2020, Int. Electrotechnical Commission, Geneva, Switzerland, 2020.

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Dr. Zeqiri, in 2021, was elected as a fellow of the Royal Academy of Engineering. In 2021, he has received the U.K. Institute of Physics James Joule Medal and Prize for distinguished contributions to the development of acoustic measurement techniques and sensors.