ULTRASONIC METROLOGY II – THE HISTORY OF THE MEASUREMENT OF ACOUSTIC POWER AND INTENSITY USING RADIATION FORCE

Francis Duck

Formerly, University of Bath and the Royal United Hospital Bath NHS Trust

I. INTRODUCTION

When a solid object is placed in a sound beam, it experiences a force perpendicular to the interface with the surrounding medium. This force is proportional to local energy density.

This phenomenon has been used in ultrasonic metrology in two ways. If a small object is placed within an acoustic beam, the force on that object can be used to measure the acoustic intensity. If the object is large enough to cover the whole beam, then the radiation force is proportional to the total acoustic power W. In this case the force $F = kW/c$, where c is the speed of sound in the medium and k is a constant depending on the nature and shape of the object, and the form of the acoustic wave. For an object with a plane surface perpendicular to the direction of propagation, k=2 if it is fully reflecting, and k=1 if it is fully absorbing.

It will be seen in this article how this very simple principle has been used in the design and use of ultrasound power balances of a wide variety of designs and sensitivities.

II. THE TORSION PENDULUM

The measurement of acoustic power using radiation force in an ultrasound beam is as old as the use of ultrasound for pulse-echo detection. Paul Langevin had started to investigate the use of ultrasound for submarine detection very early in the First World War. By July 1915 he reported an intensity of about 100 mW cm^{-2}, measured using a radiation force method.

'During the course of operations it was necessary to be guided constantly by the intensity of the ultra-sonic emissions produced, and for this purpose a convenient and valuable process based on the existence of *"pressure of radiation"* was used. …. When this radiation is directed onto a palette suspended by a torsion wire, the palette, if its thickness be appropriate, is pushed by the ultrasound and the torsion of the wire permits the measurement of the power emitted. ' [1]

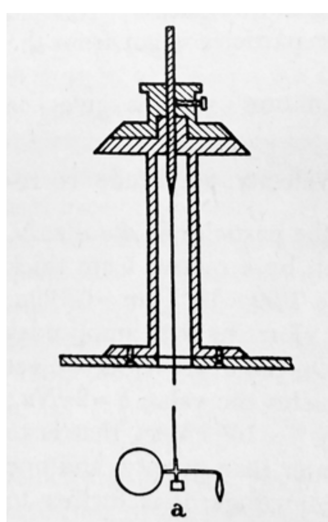

Fig 1. A torsion pendulum for the measurement of acoustic intensity.

Langevin himself gave no further details of his measurement method. However, in his 1941 book about ultrasound, Pierre Biquard, a student and subsequently close colleague of Langevin, confirmed that he had verified his first attempts at producing ultrasound with a torsion pendulum, describing the instrument as follows (Figure 1)

‘A circular disc, the diameter of which must be large compared to the wavelength of the ultrasound, is fixed to a horizontal beam attached to a rigid rod T suspended from a fine wire f. (Quartz and phosphor bronze are particularly suitable, since they do not retain any residual twist.) A counterweight m balances the disc. A mirror M, attached to the rod T, allows optical observation of the rotation of the pendulum' [2].

The angle of rotation is proportional to the radiation pressure, and hence the intensity averaged over the area of the disc target. Counter-rotation of the twisted wire gives greater precision than the optical measurement of the angle of twist. The addition of a damping weight aided stability. Biquard added that the method had been since widely used for research in laboratory ultrasound studies, which included his own investigations into the loss of energy in finite-amplitude waves.

Langevin also gave values for the total power emitted by his transducers. It seems doubtful that his targets were large enough to encompass the whole beam, and so he must have estimated the power from the ratio of areas of the quartz transmitter to the target.

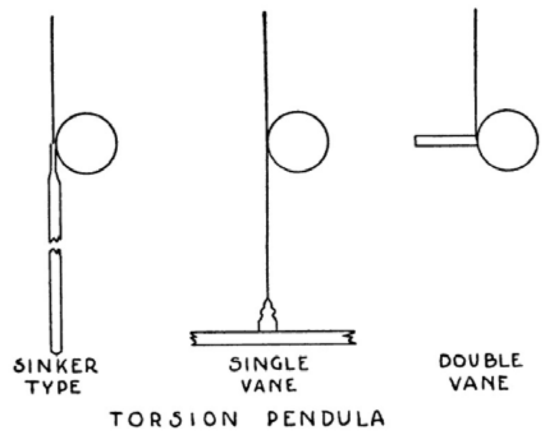

Fig 2. Various designs of torsion pendulum targets. [4]

When Langevin’s wartime colleague, Robert Boyle, returned in 1919 from Britain to Alberta University in Canada, he established an ultrasonics laboratory in which he carried out many studies in ultrasonic acoustics. Amongst these, he used a torsion pendulum to investigate relative axial and radial intensity profiles of his ultrasound beams [3]. Figure 2 shows his various designs. By traversing the vane through the beam, Boyle was able to compare observed with predicted intensity profiles [4] (Figure 3).

Alternative targets to reflecting plates were investigated. The first power estimates in the USA were made using an absorbing target less than one wavelength across. In a report dated 1 April 1919, from the Throop College of Technology (later Caltech) Anderson et al reported that they had explored reflecting and absorbing targets, plates, cylinders and bulbs, their selected target being a small, absorbing cylinder made of blotting paper. They estimated the intensity by measuring the force it experienced close to the face of the transducer. Intensities up to 11.0 W cm^{-2} were reported [5].

Interest in the use of very small targets to measure local intensity continued, particularly in the USA, particularly once it was appreciated that the finite size of the disc target introduced diffraction errors for which corrections were required [6]. As an alternative, Elias Klein proposed measuring the radiation force on a suspended spherical target by observing its displacement [7]. Such direct methods were never widely adopted for intensity mapping, however, especially once high-fidelity calibrated hydrophones became available from which intensity could be calculated.

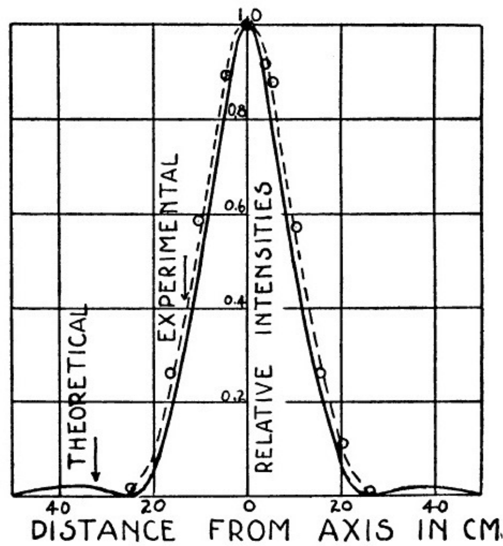

Fig 3. Measured and calculated intensity profiles using the torsion balance. Boyle 1928. [4]

III. Acoustic power in a standing wave

At the same time as some were mapping ultrasound beams using radiation force, others wanted to measure the total ultrasonic power used in laboratory experiments into the chemical, physical and biological effects of ultrasound. The physicist Robert Wood and the ex-banker Alfred Lee Loomis were notable among the early ultrasound investigators in the 1920's [8]. They soon discovered that it was challenging to measure the total emitted power by determining the force on a large plane reflector placed above a quartz plate. Their sketch (Figure 4) showed the problem. Reflected sound between the target and the quartz transducer set up standing waves in the exposed water bath. The energy density varied with position and the force on the reflector varied with the separation. Only with careful adjustment of the separation could a full standing wave be created, and only then could the force be related to the total acoustic power. This applied equally to Elias Klein's novel spring balance design in which the incident beam of ultrasound lifted a spring-loaded disc against gravitation forces, the spring being so designed that a very small contraction introduces a large axial rotation [9]. The standing-wave power balance principle continued to retain interest until well into the 1950s. For example, Walter Cady developed an interesting design at Caltech, which required a standing wave to be established between the plane face of the transducer and a liquid/air interface above it. In this case the transducer and not the target formed one arm of a balance, and its apparent change of weight was measured when the beam was switched on [10].

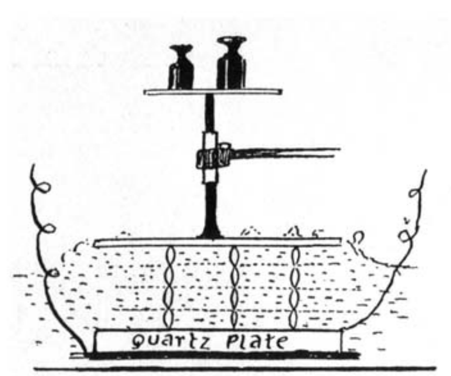

Fig 4. Sketch diagram showing the principle of weighing the variation of radiation force in a standing wave. Wood, 1939. [11]

IV. Acoustic power in a travelling wave: early developments

The standing-wave approach was only appropriate for specific applications. The face of the transducer had to be plane. The acoustic load on the transducer depended on the experimental design. It could not be used for measuring insertion loss when investigating the frequency-dependent attenuation of liquids. Other designs emerged, arranged to inhibit or eliminate acoustic reflections and standing waves.

Sörensen's balance used a beam travelling in the vertical direction in oil, exerting force from beneath a target whose position was restored by the addition of weights, the use of oil inhibiting the creation of standing waves [12]. In 1937, in Paris, Ernest Baumgardt devised a balance using a conical target, absorbing the reflected waves in an acoustic lining (Figure 5) [13]. He used this balance to explore the linearity and resonant behaviour of quartz transducers. Ultrasonic laboratories in Japan [14] and in the USSR [15] similarly developed ultrasonic measurement devices based on radiation force.

It was not only laboratory scientists who needed to measure acoustic power. This pre-war period was also one during which underwater applications of sound continued, accelerating as war became increasingly inevitable. The large power balance shown in Figure 6, now in the PTB collection, was constructed at Atlas-Werke, Bremen during the 1930s. Its cone-shaped target is large enough to span the full beam width of a marine transducer, including perhaps one operating in the audio spectrum.

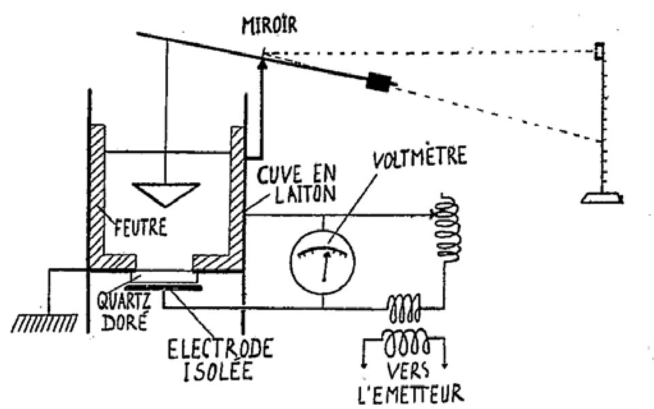

Figure 5. Ernest Baumgardt's balance with vertical beam and conical target. 1937. [13]

Fig 6. 1930s Radiation-force balance of Atlas-Werke, Bremen. Physikalische-Technischen Bundesanstalt, Brauschweig.

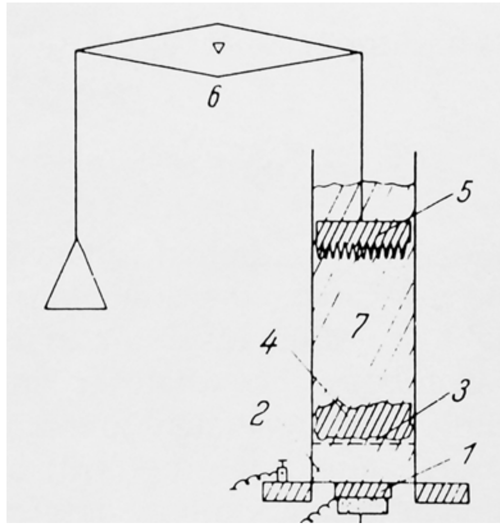

Fig 7. Pohlman's use of radiation force to measure ultrasound transmission loss in samples of tissue. 1 & 2 quartz fixed to tin foil: 3 & 4 tissue sample laid on a paper sheet: 5 scattering target: 6 arm of a sensitive balance: 7 sodium chloride solution. Pohlman, 1939. [17]

V. Commercial portable power meters

The rapid growth in the use of ultrasound for therapy in the late 1940s generated a significant interest in the measurement acoustic power. This resulted in commercial power balances becoming available by 1950 from two of the larger German companies selling ultrasound therapeutic equipment [16].

Reimar Pohlman(n) had joined Siemens in Berlin after completing his PhD in physics in 1932. As head of the ultrasound laboratory, he started to explore the therapeutic use of ultrasound, investigating the frequency-dependent attenuation of various body tissues, comparing adipose, muscle and mixed fat and muscle tissue samples [17]. Transmission loss was measured using radiation force (Figure 7).

Fig 8. The Siemens Sonotest c 1950. Physikalische-Technischen Bundesanstalt, Brauschweig.

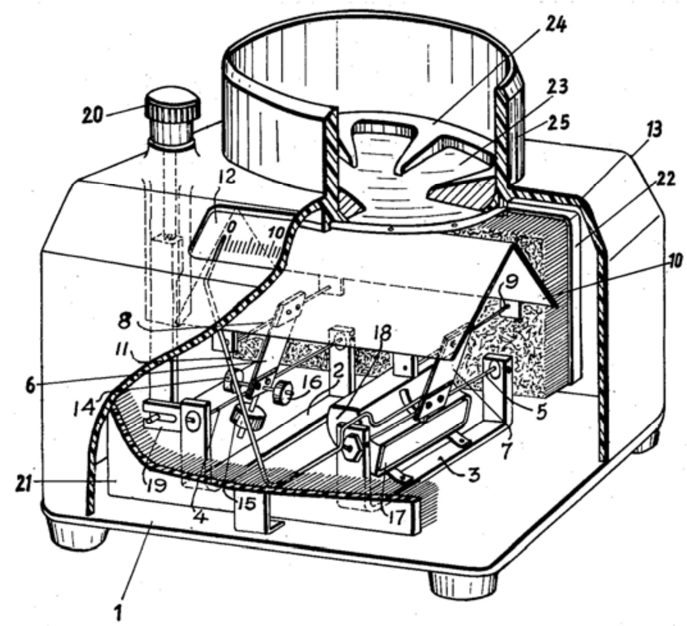

Fig 9. Cutaway plan of the Fiedler portable power balance as shown in the patent. Hueter & Bolt [18].

The beam was oriented in a vertical direction so that the force on the target could be ‘weighed’ directly. The target was large enough to encompass the whole beam so that the total acoustic power might be estimated. Standing wave formation was inhibited by deep indentations in the target creating a scattering surface. Pohlman had no need to measure absolute power: he was only concerned with the loss caused by the introduction of the tissue sample. Among the possible sources of error, Pohlman recognised that secondary phenomena such as streaming and acoustic cavitation could distort his results, and he made measurements with the quartz transducer driven at several voltages to check for any deviation from linearity.

Pohlman’s initiatives for the therapeutic use of ultrasound flowered with the renewal of European economies after the war. Under Pohlman’s guidance at the Seimens-Reiniger-Werke in Erlangen, Siemens launched their commercial therapy unit, the Sonostat, in 1947. It was designed to operate quartz transducers at two frequencies, 800 kHz and 2.4 MHz, with two transducers sizes, 10 cm^2 and 40 cm^2. The average intensity at the transducer was limited to 3 W cm^2, based on Pohlman’s pre-war safety assessments.

A simple means was required for calibration and maintenance. At Siemens, Georg Fiedler, working with Pohlman, developed and patented a rugged compact power balance with a roof-shaped reflecting target, which was sold by Siemens as the Sonotest (Figures 8,9) [18,19]. In Pohlman’s words:

‘The device consists of an open coupling chamber and a closed measuring chamber, which are separated from each other by a thin membrane. The coupling chamber accommodates the transducer to be measured either on a star-shaped guide grate or in simple retaining rings. To couple the transducer to the device, the coupling chamber is filled with degassed water. The measuring chamber contains the measuring system. It consists of a roof-shaped reflector that measures the radiation force, which is connected to a torsion spring parallelogram and a pointer. The pointer moves over a scale, calibrated in watts. Laterally attached absorbers prevent standing waves from occurring. A damping device shortens the settling times of the power meter. The measuring chamber is completely filled with distilled and degassed water. There is a rotary knob next to the coupling chamber, which allows the pointer to be readjusted to the zero point on the scale. The equilibrium of the system is so compensated that it is possible to measure in the main working position (irradiation from above) and in the horizontal position (instrument lying down). This means that horizontal sound fields can also be recorded by immersing the entire instrument in the water using a handle that can be attached for this purpose, as can be desired with permanently installed sound sources (marine transmitters) or water-bath treatments.

Fiedler had adapted a balance used by his colleague Theodor Hueter, who was investigating ultrasound transmission through solid rods in Erlangen at the time. In Hueter's design, the apex of the rooftop target was oriented towards a horizontal beam, and it was suspended from a vertical, counter-balanced arm [20].

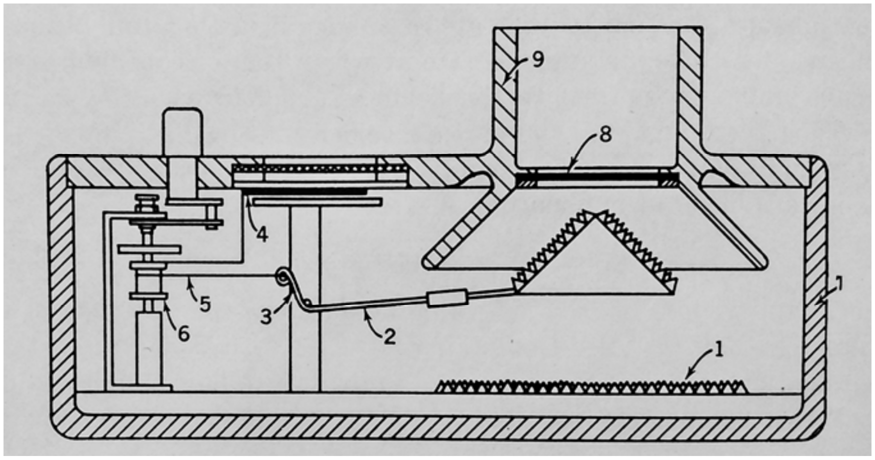

Fig 10. The Atlas-Werke portable power balance c 1950. Hueter & Bolt [21].

The chamber in the Sonotest was rendered anechoic using two panels of a brush-type lining material, one on each side of the target. The operating range was 0 to 50 W, and the maximum transducer outside diameter that could be accommodated was 80 mm. The angled target not only prevented standing waves, it was also less prone to error from poor alignment, and Pohlman claimed that misalignment of up to 8° could be tolerated. The radiation force acted against springs, rather than gravitational force, so the balance could be turned on its side so as to measure power with a horizontal beam in a water bath.

The reflector could be made from two metal plates separated by a sheet of dry paper, to approximate more closely to a complete reflector [21]. However, Fiedler's patent left open the possibility of a 'reflecting and/or absorbing target' and anticipated future designs that might use reflecting targets consisting of sheet metal enclosing an air space.

A different portable power balance was developed at the same time by Krupp Atlas-Werke in Bremen. It was designed to be used with their therapy unit, the 'Supersonic', a magnetostricitive device operating at 175 kHz. The balance is shown in Figure 10. The target was surfaced with small absorbing rubber cones, a material also used as the anechoic lining material. The target formed one arm of a balance; the other arm (3) actuated a pointer (4) by means of a string (5) wound on a drum (6) attached to the pointer axle.

VI. National laboratory calibrations for medical ultrasound

The growth in therapeutic ultrasound during the second half of the 1940s, particularly in Germany, created the need for a centralised ultrasound calibration and type-testing service [22]. This need was explored further by the specialist group for electro-medicine in the Central Association of the Electrotechnical Industry (Zentralverband der electrotechnischen Industrie, ZVEI). In 1948, an approach was made to Dr W Engbert, then working for Atlas-Werke, for advice. It was decided that type-testing should be carried out in a neutral laboratory rather than contracting a single manufacturer, so Engbert's patented design of power balance was taken up by the national standards laboratory, Physikalische-Technischen Bundesanstalt (PTB) in Braunschweig, under the lead of Paul Rieckmann. The requirements and test procedures that permitted manufacturers to label equipment as having achieved a standard of performance included one for acoustic power [23]. The selected design was for a free-floating target of neutral buoyancy (Figure 11). The beam was directed vertically downwards in a water bath onto a hollow-cone-shaped reflector. The shallow opening angle, 25°, ensured that reflected sound was deflected away from the transducer to be absorbed in the lining of the chamber. The floating target, or 'swimmer', was air-filled with a thin-walled cover surface, assumed to be a perfect reflector. Below the target there was a hollow stem with a scale, which was lowered into a volume of carbon tetrachloride giving the whole assembly neutral buoyancy. When exposed, the radiation force caused the target to sink by an amount proportional to the force, and hence the total power.

One novel aspect of the design was the concave hollow cone. This resulted in a self-centring property, any tendency for lateral displacement resulting in an asymmetric restoring force. Calibration of the displacement was achieved using small aluminium weights in the range 1 g to 7 g. For a reflecting target, the force in the direction of the beam depends on $\cos^2\alpha$, where α is the angle of incidence.

Several experimental details helped to improve the fidelity of the measurements. Cavitation was prevented by degassing the water under vacuum for 24 hours, which was then pumped through a closed system to the measurement chamber. The temperature was controlled at 30°C, so managing the neutral buoyancy and the sound velocity. An aluminium foil was placed obliquely over the target to protect it from streaming, still perceived as a 'quartz wind' generated by the transducer.

The balance was used for the certification of medical ultrasound therapy equipment by PTB, starting in about 1952. It would appear that Pohlman had a close informal relationship with PTB at this time because he mentions in his 1950 book that he had obtained a PTB performance certificate, which showed 'a display error of ± 5%' certificate. In their 1952 account, Oberst and Rieckmann reported that measurements using the PTB balance were broadly equivalent to those made using the Sonotest, and that both PTB and Pohlman had also calibrated their power balances at higher powers against a calorimetric method.

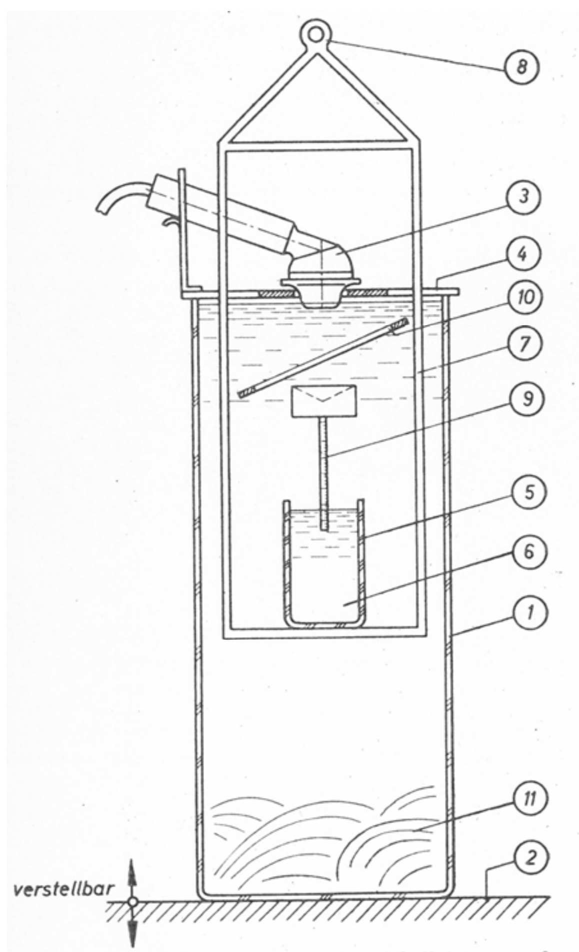

Fig 11. The PTB floating target power balance. 1952. The transducer 3, is centred over the streaming screen 10 above the buoyant target 9. The lower calibrated stem is lowered into carbon tetrachloride 6. Oberst & Rieckmann [22].

A. Development of the PTB buoyancy method

During the 1950s, others used the buoyancy technique in their own laboratories. George Henry was working for the General Electric Company in Schenectady, New York, when he published his review of power measurement in 1957. He selected radiation force as his preferred method for measuring ‘gross acoustic power transfer’ to a liquid load. He set out the criticisms of the two alternative methods, to use a hydrophone to plot of acoustic pressure from which power could be calculated from integrating the calculated intensity, and calorimetric methods calculating power from the rate at which sound energy is degraded into heat. In order to apply radiation force measurement for his applications, which included ‘degassing, impregnation, emulsification and certain chemical processes’, he used a neutral buoyancy, absorbing float target (Fig 12) [24].

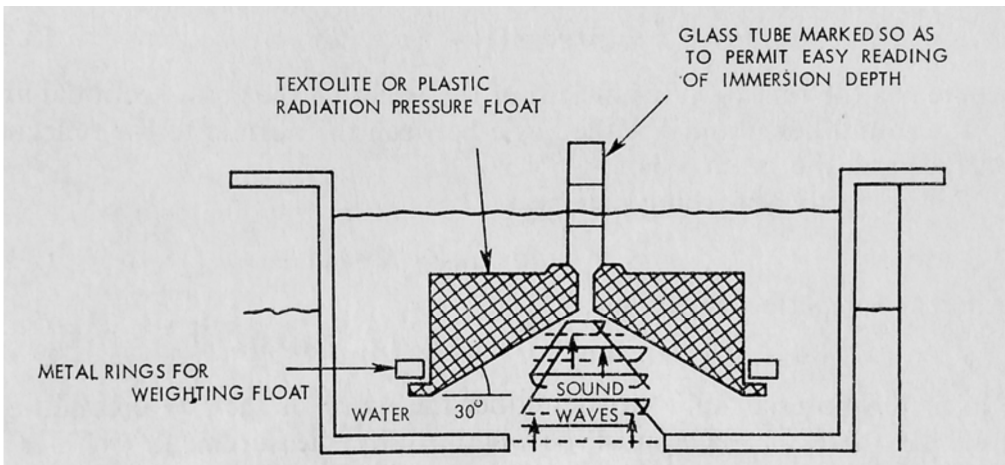

Fig 12. Henry’s design for a power balance using a neutral buoyancy absorbing float target. 1957. [24] (©Iliffe Books Ltd)

The solid target was made from Textolite, a machinable laminated electro-insulation material made from resin-embedded fabric, probably chosen for its availability more than for its acoustic properties. The density is less that 1.0, so metal rings were added to give neutral buoyancy. A marked glass tube allowed changes in immersion depth to be read. The weighted floating target was freely suspended in water above the quartz transducer, and the displacement measured using a marked glass tube.

The absorbing target mitigated the some uncertainties resulting from reverberations but introduced new challenges of calibration. The Textolite was not a perfect absorber of sound, so Henry still had to use a re-entrant cone. There remained the difficulty of the calibration factor appropriate to a partially reflecting target. Henry proposed two methods for correction, neither entirely satisfactory. The first was to compare the force using two cones, one angled at 30° and a second at 15°. The second method involved evaluating the changed force as the target was progressively misaligned.

Mostly, others could not improve on Engbert’s design as implemented at PTB. In 1962, George Kossoff, in Sydney Australia, described a variation of the float target in which a self-centring 30° cone was suspended under the transducer, with the beam oriented downwards. The target was made from a reflecting metal shell suspended in carbon tetrachloride [25]. The US National Bureau of Standards in Washington copied the PTB design for their own power balance [26]. The National Physical Laboratory (NPL) in the UK used the same principle in its later ‘tethered float radiometer’, with a downward vertical beam impinging on a floating, reflective target. In this case, however, the target was stabilised by attachment to three chains hanging partially below the float. As with other balances using a downward-directed beam, calibration was achieved using weights placed on the target. The stated range was 200 mW to 9W [27].

VII. MILLIWATT BALANCES FOR DIAGNOSTIC ULTRASOUND

A. Gavitational balances

The best sensitivity of the balances so far described was limited to about 100 mW. Newell's balance, in 1963, in which power was derived from the displacement of a fully immersed target, was still limited to a sensitivity of 60 mW [28]. This was entirely satisfactory for therapeutic ultrasound equipment but, by this time, new considerations about exposure and the safety of ultrasound for diagnostic purposes, and especially for obstetric applications, drove a need for the design of power balances with improved sensitivity. By the end of the decade, several balance designs had been reported for which sensitivity of about 1 mW was claimed. Peter Wells and Maurice Bullen, in Bristol in the UK, used a plane aluminium box target suspended by two fine wires about 1 m long, and set at 45° to the downward beam (Figure 13). A horizontal beam caused displacement of the target, which was measured using a travelling microscope. By using a horizontal beam, Wells and Bullen avoided the uncertainties associated with surface tension tethering of the suspending threads. For a reflecting target at 45°, $\cos^2 \alpha = 1$, so the force is the same as that would have been experienced by a fully absorbing target. ±3% accuracy was claimed in a 2 mW beam [29].

At the same time, George Kossoff pointed out that most laboratories were equipped with chemical microbalances that could be adapted to measure ultrasonic power [30]. Such balances were well able to resolve to 0.01 mg, so making measurements in the 1 mW range possible. One example was described in 1970 by Kit Hill, from the Institute of Cancer Research in the UK. (Figure 14) [31]. In his simple design, an aluminium reflector was hung using three very fine nylon filaments from one balance arm, minimising surface tension effects. The target was set at 45° to the downward beam. Reflected sound was trapped by a scattering and absorbing composition of glass wool and rubber at the end of the water-bath. Small amounts of paraffin wax were added to compensate for temperature variations in the weight of the plate. The balance was initially brought to equilibrium and then rebalanced when the downward radiation force was exerted on the target. A calibration of 67 mg W^{-1} was assumed. In Kossoff's review in 1972 he compared the sensitivity of microbalance systems with an absorbing target, an inverted cone reflecting target and an oblique target, concluding that Hill's gave the greatest sensitivity [32].

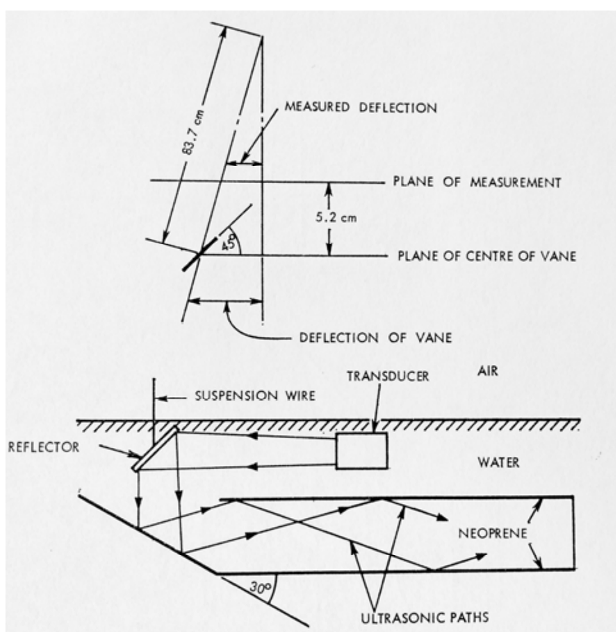

Fig 13. The Wells and Bullen balance. 1964. [31] (©Iliffe Books Ltd)

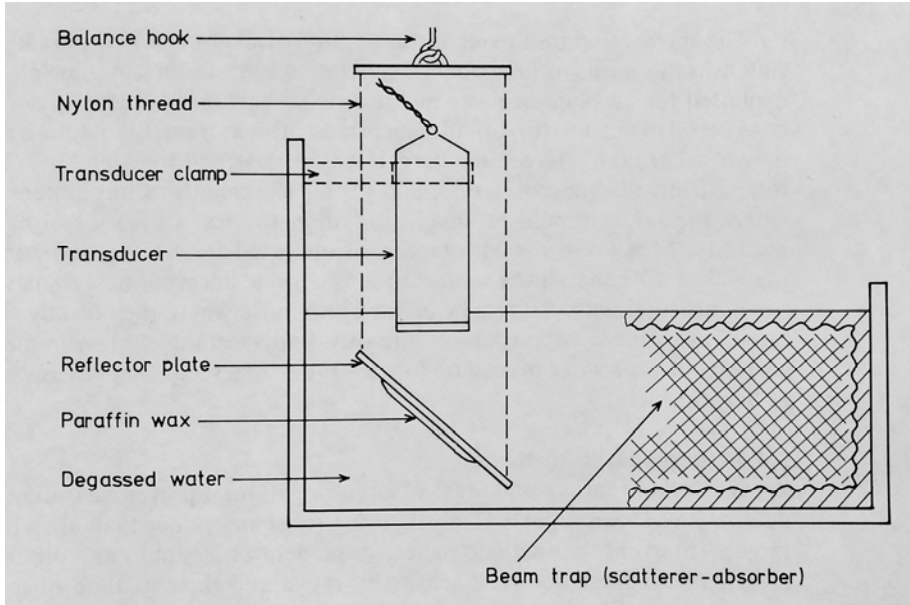

Fig 14. Hill's sensitive power balance based on a chemical microbalance, 1970. [32]

During the 1970s, numerous other laboratories reported their own experiences of approaching the design of sensitive power balances by weighing, with various degrees of success [33,34,35,36,37,38]. In due course, the general availability of force transducers has given rise to simpler, electronic measurement of weight, leading to portable commercial power balances of simpler designs. Nevertheless, sufficient sensitivity for diagnostic measurement remains challenging, and the inherent issues of acoustic design and calibration remain important.

B. Servo-controlled balances

Quantification of the radiation force in the systems so far reported used one of two approaches. In some cases the target was allowed to move under the effect of the incident ultrasonic beam, and the radiation force calculated by computing the mechanical forces associated the new position of equilibrium. Alternatively a mechanical force was applied, typically by the use of weights, to hold the target in a null position.

Force feedback methods developed on these approaches in two ways. First, a sensor was added to detect movement: and an electromagnetic means was introduced to restore the target to its null position.

André Dognon, professor of medical physics at the Faculty of Medicine in Paris, first introduced the concept of force feedback in his laboratory measurements in 1953 (Figure 15), probably as part of his work with Yvonne Simonot on the chemical and biological effects of acoustic cavitation [39]. The target was suspended by a fine wire attached to the coil of a milliameter, causing it to rotate when the target experienced a force. An adjustable current compensated the radiation force by the electromagnetic coupling. Whilst the experimental arrangement, using a small target and subject to standing waves, was never intended to measure total acoustic power, it demonstrated the first attempt to use a null method to measure radiation force by applying an equal an opposite electromagnetic one [40]. Incidentally, Dognon mentioned the problem of measuring power under conditions in which cavitation was an intended consequence, using degassed water and lower powers to calibrate his equipment.

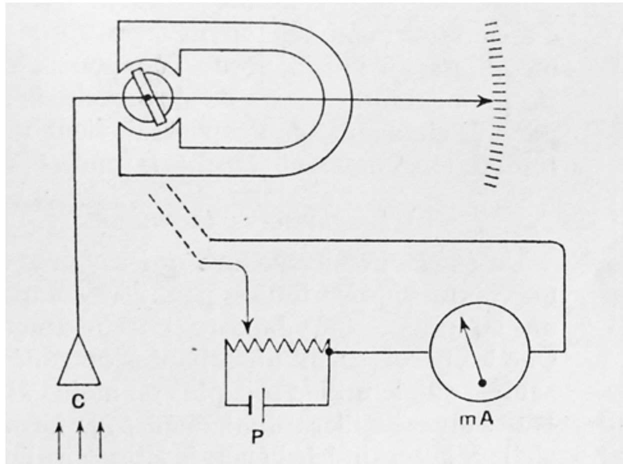

Fig 15. Dognon's electromagnetic feedback technique to measure radiation force. 1953. [39].

A fully servo-controlled balance for ultrasound power was described by Wemlen in 1968 [41]. A portable balance, capable of measuring down to 3 mW, by Lee Dunbar of Grumman Health Systems, New York, was described in 1976 [42]. His design reflected a vertical beam through 45º onto an angled reflecting target, made from a plastic washer with aluminium foil stuck to both sides, adjusted for neutral buoyancy. The target was mounted onto the mechanism of a taut-band meter and was held in a null position using amplified feedback from an occluding photocell, instead of Wemlen's capacitative detector. An alternative servo design was developed in 1982 for a small portable commercial force balance, primarily intended for the measurement of power up to 400 mW emitted from small Doppler transducers. This instrument, available from the UK company Doptek, used a plane absorbing target of Sorbothane® placed in a downward oriented beam [43]. The floating target had a stem holding a bar magnet, the whole tightly contained in a water-filled vessel. An optical position sensor generated a feedback voltage to an external coil, creating a force on the magnet equal and opposite to the downward radiation force. This design overcame the difficulty of placing the feedback coil in the water in the measurement chamber. However, independent calibration was essential since the target could not be assumed to be fully absorbing.

By the early 1970s several large medical physics departments had been established in the National Health Service in the UK, often on a networked regional basis. In some of these, physicists specialised in the technical support of the expanding clinical ultrasound services. They responded to the growing need for a robust and transportable instrument with which to carry out surveys of ultrasonic exposure in clinical use.

Working in the Regional Medical Physics Department in Newcastle, England, Tony Whittingham and Mick Farmery developed a servo-controlled balance to operate in the power range 1-100 mW. Whittingham presented a description of his first servomechanism balance in 1974. In this design, the beam was directed downward into a water bath. A horizontal balance arm carried a 45° degree reflecting target at one end and an opaque rectangular black plastic 'flag' (about 10 mm square) together with a small permanent bar magnet with its axis vertical at the other. Two light beams, partially blocked by the upper and lower edges of the flag respectively, were detected by photo-diodes. These responded to any movement of the flag, generating an out-of-balance signal which, when amplified, caused current to flow in a coil around the magnet, maintaining the balance in a null position. The restoring current was measured by an ammeter, calibrated in mW. This design allowed the use of water as a medium, did not require a plastic window and allowed the electronics to be completely out of the water [44].

Whittingham and Farmery subsequently patented a more rugged design in which the beam was aimed horizontally and, at Farmery's suggestion, the magnet and coil were replaced with the mechanism from a moving coil galvanometer. The reflecting target consisted of a Perspex box with a thin foil window attached to the pointer of the galvanometer and set at 45° to the incoming horizontal beam. The absorbing lining was made of carpet, as effective as the brush absorber in Fiedler's design. Analysis gave a calibration factor of 1.30±0.05 μA mW^{-1} [45,46] (Figures 16,17).

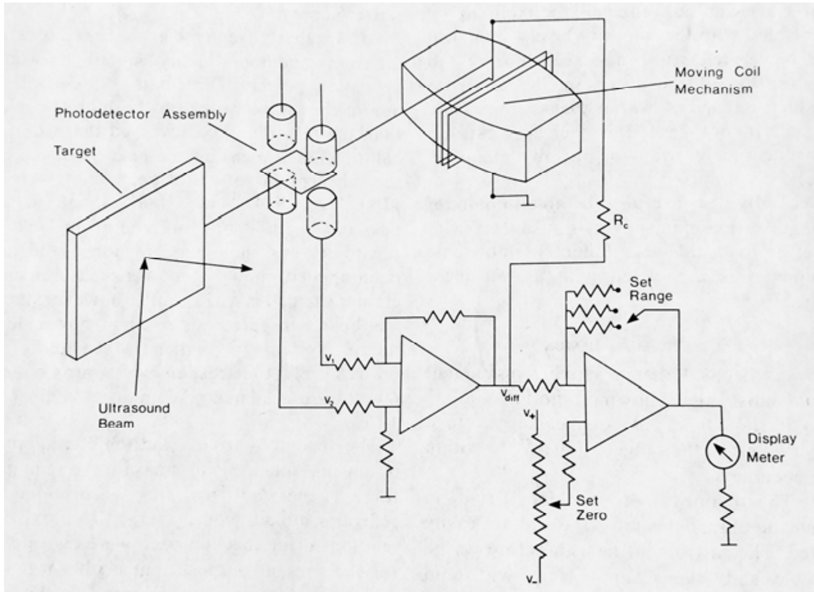

Fig 16. The servo-controlled circuit of Farmery and Whittingham. 1976 [45]. Permission to reproduce: Elsevier Inc.

The horizontal beam orientation introduced one very important attribute. Any sources of thermal instability, for example changed target buoyancy or convection currents, act in a direction orthogonal to the radiation force. By decoupling these forces from those from the ultrasound beam, greater stability could be achieved for measurements of powers down to 1 mW.

There were still some disadvantages with this design. A membrane was needed in order to couple the transducer to the measurement chamber, introducing uncertainties not only from coupling but also in positioning and angulation [47]. The meter mechanism had to be immersed in the liquid in the measurement chamber. Therefore it was no longer appropriate to use water as the transmission fluid, which was replaced with liquid paraffin. Whilst this served to dampen and stabilise the movement, it introduced a frequency-dependent transmission loss between the entry window and the target. Nevertheless, this design was a significant step towards a practical portable milliwatt balance.

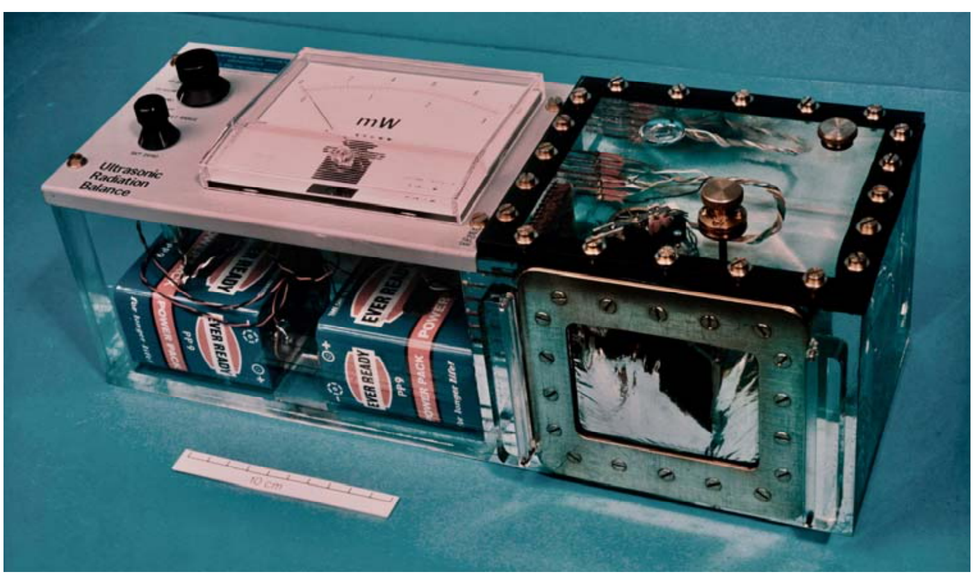

Fig 17. Farmery and Whittingham portable milliwatt power balance [45]

Following Whittingham's work, the first portable power balance to built in the Wiltshire Area Medical Physics Department, based at the Royal United Hospital Bath, UK, was based on the Newcastle design. Constructed by the senior engineer Mike Perkins it introduced a few changes. The transmission loss was minimised by making the overall size smaller and by using a low viscosity transformer oil. A mechanical iris was added to centre the transducer, so avoiding beam placement errors. Otherwise, the general design was the same, including an electronic damping circuit to aid the settling time. From this experience, Perkins carried out a design project for his Open University degree, creating a new design based on similar principles, but with changed geometry [48] (Figure 18).

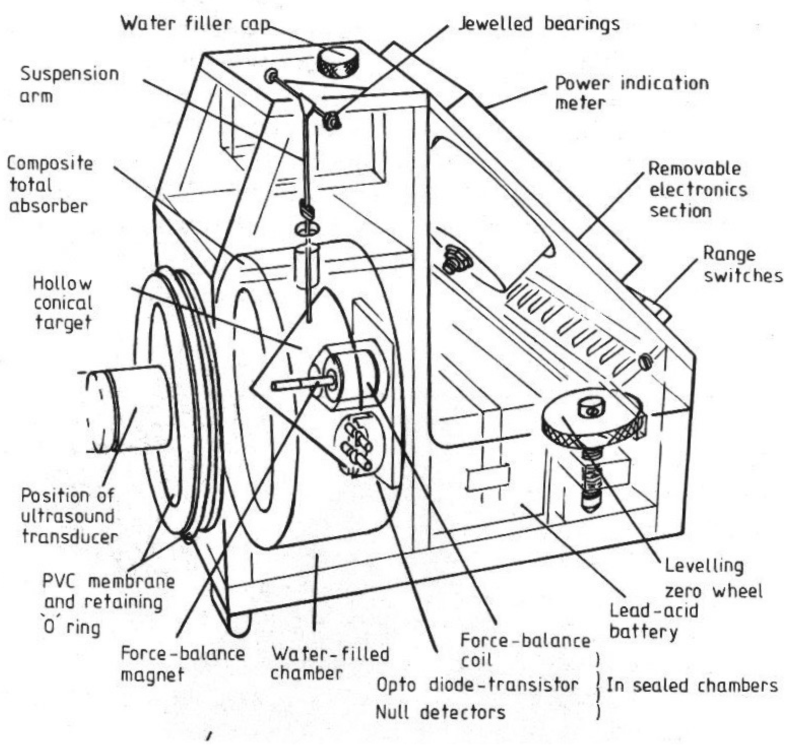

Fig 18. Ghost diagram of the Bath power balance. Perkins, 1989. (Michael Perkins)

The target of Mike Perkins' 'Bath' balance was made of a two cones of very thin monel metal separated by foam spacers. With a 70 mm diameter, it was large enough to ensure measurements could be made on the largest transducers. The cone was suspended from a jewelled bearing within a water-filled chamber with its apex towards an acoustic window. Reflected sound was absorbed in a cylindrical absorber made of carpet. Optical sensors detected movement. The restoring force operated through an external coil and a permanent magnet on the back of the target. The dynamic range enabled it to operate over scales from 0-1 mW up to 0-10W. Electronic zeroing was supplemented by an adjustable screw support, enabling the balance to operate on any surface. The horizontal beam arrangement minimised thermal instabilities. Absolute calibration was enabled using a horizontal balance arm attached to the top of the suspension, on which calibrating weights were hung. In a later simplifying adaptation, the conical reflecting target was replaced by a plane absorbing target made of carpet [49].

The balance was constructed in two compartments. Under normal use as a portable balance these were locked together. For work in the laboratory, it was possible to disconnect the measurement chamber from the electronics, allowing the target assembly to be placed into a separate larger water tank. This arrangement was used to study finite-amplitude loss in water [50]. Neither the Bath nor the Newcastle balance became a commercial product. Nevertheless, such was the interest in power measurement in other medical physics departments that ten more of the Bath design instruments were constructed and provided at cost, one being shipped as far as New Zealand.

With renewed interest in the calibration of ultrasound diagnostic equipment, National Standards laboratories invested in the development of primary standards for ultrasound metrology. For power measurement, this entailed the design of new sensitive radiation force balances, for which the servo feedback design offered significant advantages for sensitivity. One example was the balance developed in 1983 at the National Physical Laboratory in the UK, and designed for the measurement of powers below 200 mW [51].

In due course, the general availability of solid-state force transducers gave rise to simpler, electronic microbalances, leading to portable or semi-portable commercial balances of simpler designs. In one, the solid target was replaced by an absorbing liquid [52, 53]. Even so, in a wide review of radiation force balances that could operate in the diagnostic range, published in 1992, it was noted that 'there are relatively few off-the-shelf radiation force balances …. suitable for measurements of acoustic power of diagnostic equipment'. Only four out of a list of fifteen commercial balances offered measurement capability below 1 mW [54]. Sufficient sensitivity for diagnostic measurement remains a challenge, and the inherent issues of appropriate acoustic design, stability and calibration remain important.

Physiotherapy equipment was less of a challenge, with several reliable commercial balances becoming available. This area also gave rise to one of the simplest and cheapest power balances, designed for quick operational checks of the output of physiotherapy equipment, which soon earned the name of the 'tea caddy'. This was simply an open topped beaker with a balanced vane, set at 45º. An attached pointer gave an approximate indication of acoustic power.

VIII. Regulatory changes

Until the late 1970s it had been accepted that exposure to ultrasound was best quantified by measuring the total acoustic power. Calorimetric methods had failed to dislodge radiation force as the preferred method of measurement. Whilst it was understood that local intensity could be derived from hydrophones, from which total power could be derived by scanning through the beam and integrating, practical and theoretical challenges inhibited this approach as a technique that could be realistically implemented. Hydrophones were used to check frequency and bandwidth, pulse length and frequency, but no more.

Fig 19. The Perkins 'Bath" Balance fitted with a 1 cm aperture for measurements for Thermal Index for scanned beams.

The introduction of regulatory changes in the USA in 1976 served to move the emphasis away from the measurement of total acoustic power. Manufacturers were required to establish 'substantial equivalence' on acoustic output to equipment sold before that date through the Food and Drug Administration 510(k) process. Acoustic power was not included as one of the criteria on which equivalence would be based. Instead, local maxima of intensity anywhere in the exposed region were set, with a range- and frequency-dependent factor applied to compensate for transmission loss through tissue. This approach meant that the emphasis in acoustic metrology moved away from the measurement of acoustic power and towards the use of hydrophones for measuring acoustic pressure and derived intensity. Whilst those concerned with the safe use of diagnostic ultrasound in hospitals and universities continued their efforts to develop improved means for measuring acoustic power, there was no regulatory drive to develop better commercial instruments. The FDA has never added total acoustic power for regulatory purposes.

Regulatory interest in the measurement of power resumed with the publication, in 1992, of the Safety Standard for Diagnostic Ultrasound Equipment, by the American Institute of Ultrasound in Medicine and the National Electrical Manufacturers Association (AIUM/NEMA) [55]. This document established acoustic power as the basis for estimates of tissue temperature rise, creating a definition of the Thermal Index as W/W_{DEG}, in which W is the acoustic power used, and W_{DEG} is the power required to raise the tissue temperature by 1°C under identical conditions of exposure.

Power measurement was reinstated in the metrology agenda. However, the relationship between total acoustic power and tissue temperature rise is not straightforward, especially for focussed, scanned beams from arrays. Some formulae depended not on the total power from the whole array, but instead on the power through a region across the array limited to 1 cm. As a result, apertures to limit the beam had to be added to the means for measuring power (Figure 19).

IX. Accuracy and sources of error

Radiation force remains the preferred method for measuring total acoustic power for medical ultrasonic applications [56]. Decades of experience have given clear evidence of possible sources of error. Absorbing targets are now recommended, using a specified, fully absorbing material which may be used over the full range of medical frequencies. The use of degassed water is mandatory. The distance between source and target should be short to minimise transmission losses at higher frequencies and also from finite amplitude effects, and to limit acoustic streaming. Good temperature control means that the velocity of sound, required for calibration, is known accurately, and convection instabilities are limited. Closed measurement chambers prevent disturbing air currents. Shock-absorbing mounts prevent disturbance from vibrational noise. The relationship between radiation force and power holds in pulsed beams [57], so integration of total power in beams with short pulses may be achieved so long as the mechanical time constant of the balance is long enough. Errors associated with poor beam alignment may be mitigated by careful experimental technique. The most sensitive techniques, used for powers below 1 mW, generally compensate for base-line drift by cycling the power on and off, averaging the differences during each cycle.

Nevertheless, some systematic sources of inaccuracy may remain. The acoustic load on the transducer is different when coupling onto a membrane as opposed to water coupling. The simple relationship between acoustic power and radiation force assumes a plane wave front. As Klaus Beissner has pointed out, the focussed beams used for many medical applications can decrease the radiation force on a target for a given total power. He has proposed appropriate correction factors [58]. There remains the question whether practical targets, absorbing or reflecting, confirm to their ideals when calibration is carried out with an externally applied known force or weight. The design of an absorbing target that will transfer all the force in the direction of the beam remains a challenge. However carefully a reflecting target is manufactured, unsuspected surface acoustic effects may occur. For these reasons, standard test sources are now available to deliver known powers for periodic checks, and regular calibration traceable to a National Standards Laboratory is recommended. An International 'Key Comparison' now allows considerable confidence in this chain of traceability [59].

X. Summary

Radiation force was first used to measure ultrasonic power by Paul Langevin as part of his development of pulse-echo location during the 1914-18 war. The torsion balance was used in many early ultrasonic studies to investigate intensity. The substantial growth of ultrasound therapy in the late 1940s gave rise to new designs for the measurement of total acoustic power, especially in Germany. The standards laboratory at PTB created a balance with a floating target to support its programme of type-testing, widely copied by others. Robust portable commercial balances with mechanical force detectors were also available by 1950. In the 1960s, servo-controlled balances of various designs replaced chemical micro-balances for the measurement of powers in the mW range emitted by medical diagnostic equipment. Regulatory changes in the USA briefly inhibited interest in power measurement, which was reinstated following the establishment of the thermal index for safety management in the 1990s.

Author	Date	Measurement method	Beam direction	Target
Langevin[1]	c.1915	torsion pendulum	Horizontal	Reflecting 90° plane
Boyle [4]	1928	torsion pendulum	Horizontal	Reflecting 90° plane
Baumgardt[13]	1937	movement	Vertical up	Reflecting 30°cone
Atlas-Werke	c.1939	movement	Vertical up	Reflecting 30°cone
Pohlman[17]	1939	gravitational	Vertical up	Absorbing 90° plane
Fiedler[18]	1950	mechanical	Vertical down	Reflecting 45° roof
Atlas- Werke[20]	c.1950	mechanical	Vertical down	Absorbing 45° roof
Oberst & Rieckmann[22]	1952	float movement	Vertical down	Reflecting 30°cone
Dognon[40]	1953	servo feedback	Vertical up	Reflecting 90° plane
Henry[24]	1957	float movement	Vertical up	Absorbing 30°cone
Kossoff [30]	1962	float movement	Vertical down	Reflecting 30° cone
Wells [29]	1964	movement	Horizontal	Reflecting 45° plane
Hill [31]	1970	gravitational	Vertical down	Reflecting 45° plane
Dunbar[42]	1976	servo feedback	Horizontal	Reflecting 45° plane
Farmery & Whittingham[45]	1978	servo feedback	Horizontal	Reflecting 45° plane
Shotton [27]	1980	float movement	Vertical down	Reflecting 30° cone
Cornhill[43]	1982	servo feedback	Vertical down	Absorbing 90° plane
Perkins [48]	1989	servo feedback	Horizontal	Reflecting 45° cone

Table 1. Selected examples of radiation force balance designs. The angle given is that between the target and the beam direction.

Acknowledgements

I wish to add my sincere thanks to Dr Volker Wilkens from Physikalische-Technischen Bundesanstalt (PTB) in Braunschweig, for providing documents, photographs and further details from the earliest years of PTB's activities in metrology for medical ultrasound. In addition, Dr Bajram Zeqiri, of the National Physical Laboratory, Teddington UK, was kind enough to read and comment on an earlier draft. The kind permission of Illife Books Ltd to reproduce figures 12 and 13 from B Brown and D Gordon, *Ultrasonic Techniques in Biology and Medicine* (1967) is acknowledged.

References

1. (Langevin P). The employment of ultra-sonic waves for echo sounding. *Hydrographic Rev.* Nov 1924;2(1):57-91.
2. Draveil F (alias of Paul Biquard). *Les Ultrasons.* “Que sais-je?” Vol 21. Paris Presses Universitaires de France. 1941.
3. Boyle RW, Lehmann JF, Reid CD. Visualisation and energy survey of a high frequency diffraction beam. 1925; *Trans Roy Soc Canada* (3);19:167-196.
4. Boyle RW. Ultrasonics. *Science Progress* 1928;23:75-105.
5. Anderson JA, Babcock HD, Ryan HJ. Summary of a study of the Langevin supersound source-projector. Appendix B in Klein E. *Notes on underwater sound research and applications before 1939*. Office of Naval Reasearch Report ACR-135. 1967.
6. King LV. On the acoustic radiation pressure on circular discs. Inertia and diffraction corrections. *Proc Roy Soc Lond A* 1935;153:17-40.
7. Klein E. Absolute sound intensity in liquids by spherical torsion pendula. *J Acoust Soc Am* 1938;9:312-320.
8. Wood RW, Loomis AL. The physical and biological effects of high-frequency sound-waves of great intensity. *Phil Mag (7th ser)* 1927;4:417-436.
9. Klein E. Absolute sound measurements in liquids. *J Acoust Soc Am* 1938;10:105-111.
10. Cady WG, Gittings CE. On the measurement of power radiated from an acoustic source. *J Acoust Soc Am* 1953;25:892-896.
11. Wood RW. Supersonics: *The Science of Inaudible Sounds.* Brown University. 1939. 53.
12. Sörensen Ch. Absorptions-, Geschwindigkeits- und Entgasungsmessungen im Ultraschallgebeit. *Ann Phys* (5) 1936;26:121-137.
13. Baumgardt E. Sur le rendement ultrasonore des quartz piézoélectriques. *Comptes rendus (Paris)* 1937(10)204:751-754.

14. Oyama H. Generation and application of intense supersonic acoustic waves. Rep Radio Res Japan. 1934;4:41-55. (in Japanese: J Inst Elec Eng Japan 1933;545:1088-1094)
15. Malov NN, Rschevkin SN. Messungen der Schallisolationsfähigkeit bei ultraakustischen Frequenzen. Hochfrequennztechn Elektroakust 1932;40:134-136.
16. Pohlman R. *Die Ultraschalltherapie*. Med Verlag Hans Huber, Bern, 1950. 61-72.
17. Pohlmann R. Über die Absorption des Ultraschalls im menschlichen Gewebe und ihre Abhängikeit von der Frequenz. *Physik Z.* 1939;40:159-161. (English tr. F Dunn. *Ultrasonic Biophysics*. Stroudsberg. Dowden, Hutchinson & Ross. 1976. 14-18.)
18. Fiedler G. Instrument for measuring compressional wave radiation pressure. US Patent 2,531,844. Filed May 13 1949. Granted Nov 28, 1950.
19. Pohlmann R, Fiedler G. Über das Problem der Abstrahlungsmessung in der Ultraschalltherapie. *Ärztl Forsch* 1949;3:521.
20. Hüter Th. Über die Fortleitung von Ultraschallwellen in festen Stäben. *Z amgewandte Physik.* 1949;1:274-289.
21. Heuter Th F, Bolt RH. *Sonics.* Wiley. 1955. 45-47.
22. Oberst H, Rieckmann P. Das Messverfahren der Physikalisch-Technischen Bundesanstalt bei der Bauartprüfung medizinischer Ultraschallgeräte, *Amtsblatt der PTB*,1952;3,:106-109, and 1952;4:143-146.
23. *Amtsblatt der PTB* 1952;2:35.
24. Henry GE. Ultrasonic output power measurements in liquids. *IRE Trans Ultrasonic Eng.* 1957;6:17-31.
25. Kossoff G. Calibration of ultrasonic therapy equipment. *Acustica* 1962;12:84-90.
26. Stewart HF. Ultrasonic measurement techniques and equipment output levels. *Essentials of Medical Ultrasound*. Repacholi MH & Benwell DS (eds) Humana Press. Clifton NJ USA. 1982. 59-83.
27. Shotton KC. A tethered float radiometer for measuring the output from therapy equipment. *Ultrasound Med Biol* 1980;6:131-133.
28. Newell JA. A radiation pressure balance for absolute measurement of ultrasonic power. *Phys Med Biol* 1963;8:215-221.
29. Wells PNT, Bullen MA, Freundlich HF. Milliwatt ultrasonic radiometry. *Ultrasonic*s 1964;2:124-128.
30. Kossoff G. Balance technique for the measurement of very low ultrasonic power outputs. *J Acoust Soc Am* 1965;38:880-881.
31. Hill CR. Calibration of ultrasonic beams for bio-medical applications. *Phys Med Biol* 1970;15:241-248.
32. Kossoff G. Radiation force. I*nteraction of ultrasound and biological tissues.* Reid JM and Sikov MR (eds). DHEW publication (FDA) 73-8008. Rockville Maryland. 1972. 159-162.
33. Van den Ende H. Radiation force meter for small ultrasonic beams. *Med Biol Eng* 1969;7:411-417.
34. Rooney JA. Determination of acoustic power outputs in the microwatt-milliwatt range. *Ultrasound Med Biol*, 1973;1:13-16.
35. Carson PL, Fischella PR, Oughton TV. Ultrasonic power and intensities produced by diagnostic ultrasound equipment. *Ultrasound Med Biol* 1978;3:341-350.
36. Lunt MJ, Ashley B. A simple radiation balance for measuring ultrasonic power. *J Med Eng Tech*. 1979;3:194-197.
37. Bindal VN, Singh VR, Singh G. Acoustic power measurement of medical ultrasonic probes using a strain gauge technique. *Ultrasonics* 1980;18:28-32.
38. Reibold R. Microwatt ultrasonic power determination using laser interferometry. Ultrasound Med Biol 1982;8:191-197.
39. Dognon A, La cytolyse par ultra-sons. *Bull Acad nat Med*. 1953 13 Jan:36-38.
40. Dognon A. *Les ultrasons et leurs applications.* Paris. Presses Universitaires de France. 1953.
41. Wemlan A. A milliwatt ultrasonic servo-controlled balance. *Med & Biol Engng* 1968;6:159-165.
42. Dunbar LE. Torque feedback radiometer for ultrasonic power measurements. *J Clin Ultrasound* 1976;4:292-294.
43. Cornhill CV. Improvement of a portable radiation force balance design. *Ultrasonics* 1982;20:282-284.
44. Tony Whittingham, personal communication. Presentation at: Colloquium on Ultrasound Bioeffects and Dosimetry, Chelsea College, London, July 22-23, 1974
45. Farmery MJ, Whittingham TA. A portable radiation-force balance for use with diagnostic ultrasonic equipment. *Ultrasound Med Biol* 1978;3:373-379.
46. Whittingham TA, Farmery MJ. Ultrasonic radiation measuring instruments. UK Patent 1 542 419. Filed 3 Sep 1976, Published 21 March 1979.
47. Lunt MJ**,** Duck FA**.** Ultrasonic power balances -effect of a coupling window on the power measured from physiotherapy ultrasound units. Ultrasound Med Biol 2001;27:1127-1132.
48. Perkins MA. A versatile force balance for ultrasound power measurement. *Phys Med Biol* 1989;34:1645-1651.
49. Whittingham TA. The acoustic output of diagnostic machines. Ter Haar G, Duck FA. (eds) *The Safe Use of Ultrasound in Medical Diagnosis*. Ch 3. London. British Medical Ultrasound Society/ British Institute of Radiology. 2000. 20.
50. Duck FA Perkins MA, Amplitude-dependent losses in ultrasound exposure measurement, *IEEE Trans Ultrasonics Ferroelectrics & Freq Control,* 1988;UFFC-35: 232-241.
51. Livett AJ, Leeman S. Radiation pressure and its measurement. *Proc 1983 IEEE Ultrasonics Symposium.* 749.
52. Shaw A. How to measure HIFU output power properly. In: Clement GT, McDannold NJ, Hynynen K, ed. Therapeutic ultrasound. Proceedings of the 5th International Symposium on Therapeutic Ultrasound (AIP Conference Proceedings). Vol. 829. Melville, NY: American Institute of Physics. 2006;628–632.
53. Cunningham-Hill CJ, Pelmore JM. Evaluation of the Dorchester ultrasound power meter. *Physiotherapy* 1992; 78: 569-570.
54. Lewin PA. Practical implementations and technology of measurement devices. *Ultrasonic Exposimetry* (Eds Ziskin MC & Lewin PA) Ch 7 . CRC Press. 1992. 185-215.
55. American Institute of Ultrasound in Medicine/National Electrical Manufacturers Association. *Standard for Real-Time Display of Thermal and Mechanical Indices on Diagnostic Ultrasound Equipment.* Rockville MD USA. American Institute of Ultrasound in Medicine. 1992.
56. International Electrotechnical Commission. IEC 61161:2013 – *Ultrasonics – Power measurement - Radiation force balances and performance requirements*. IEC Geneva.
57. Beissner K. On the time-average acoustic pressure. *Acustica* 1985;57:1-4.
58. Beissner K. Radiation force calculations. *Acustica* 1987;62:255-263.
59. Koch C, Jenderka K-V. Final report on key comparison CCAUV.U-K3 for ultrasonic power. Metrologia. 2014;51 Suppl.