Technical note

Acoustic power measurement of high-intensity focused ultrasound transducer using a pressure sensor

Yufeng Zhou

Division of Engineering Mechanics, School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore 639798, Singapore

A R T I C L E   I N F O

Article history:
Received 20 October 2014
Revised 11 January 2015
Accepted 18 January 2015

Keywords:
High-intensity focused ultrasound (HIFU)
Acoustic power
Radiation force balance
Nonlinear effect

A B S T R A C T

The acoustic power of high-intensity focused ultrasound (HIFU) is an important parameter that should be measured prior to each treatment to guarantee effective and safe outcomes. A new calibration technique was developed that involves estimating the pressure distribution, calculating the acoustic power using an underwater pressure blast sensor, and compensating the contribution of harmonics to the acoustic power. The output of a clinical extracorporeal HIFU system (center frequency of ~1 MHz, \( p_r = 2.5–57.2 \text{ MPa} \), \( p = -1.8 \) to \(-13.9 \text{ MPa} \), \( I_{50\text{ppa}} = 513–22,940 \text{ W/cm}^2 \), -6 dB size of 1.6 × 10 mm; lateral × axial) was measured using this approach and then compared with that obtained using a radiation force balance. Similarities were found between each method at acoustic power ranging from 18.2 W to 912 W with an electrical-to-acoustic conversion efficiency of ~42%. The proposed method has advantages of low weight, smaller size, high sensitivity, quick response, high signal-to-noise ratio (especially at low power output), robust performance, and easy operation of HIFU dosimetry measurement.

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1. Introduction

High-intensity focused ultrasound (HIFU) originated in the 1940s as a therapeutic modality for noninvasive cancer and solid tumors. Technical development in the 1990s brought HIFU back to life for the ablation of prostate, pancreatic, breast, liver, and kidney cancers and uterine fibroids effectively and safely [1–3]. Ultrasound energy is focused onto a small volume to heat and destroy the target without causing damage to the intervening tissue. More than 100,000 cases have already been conducted in China and Europe with great success [4,5]. Therefore, HIFU technology has attracted the interests of ultrasound scientists, medical device engineers, physicians, patients, and health care administrators. Calibration of the acoustic power radiated by HIFU systems prior to clinical therapy is important for both effectiveness and safety.

The acoustic power of HIFU transducers, \( P \), can be determined based on the measured radiation force, \( F \), [6, 7]

\[
P = \frac{2c_0F}{1 + \cos \phi}
\]

(1)

where \( c_0 \) is the speed of sound in the medium, \( \phi \) is half of the beam convergence angle, \( \phi = \sin^{-1}(d/D) \), and \( d \) and \( D \) are the aperture radius and geometrical focal length of the focused transducer, respectively [8,9]. For a transducer made of \( N \) identical pistons placed on a common spherical surface, the equation becomes [10,11]:

\[
P = \frac{NFC_0(\text{corr})}{\sum_{i=1}^{N} \cos \theta_i}
\]

(2)

where \( \theta_i \) is the angle between the acoustic beam axis of the \( i \)th element and the main axis of the HIFU array, and \( \text{corr} \) is the planar wave correction factor:

\[
\text{corr} = \frac{1 - J_1(2ka)/ka}{1 - J_0^2(ka) - J_2^2(ka)}
\]

(3)

where \( k \) is the wave number, \( a \) is the radius of a single piston, and \( J_0(*) \) is an \( n \)-order Bessel function. The accuracy of radiation force measurement deteriorates for strong focusing (\( F \)-number < 1). Long sonication (>1 s) forms acoustic streaming, which leads to an 18% measurement difference at 30 W [7]. High power output results in acoustic cavitation, even in the prefocal region, and bubble shielding effects reduce the focal intensity significantly [12].

The buoyancy technique was developed as a new type of calorimetry for HIFU dosimetry [13]. Acoustic energy is absorbed by an oil-filled target immersed in a water bath and suspended from a balance. The change in volume during heating causes additional buoyancy force acting on the target, which is independent on the ultrasound incident angle. The uncertainties of the method are about ±3.4%. Longer sonication (~10 s) is required to achieve uniform thermal distribution and significant volume expansion.
Another method is to map the HIFU field by a hydrophone, such as a fiber optic probe hydrophone (FOPH) [14], which has a small sensing element (100 μm) and broad bandwidth (50 MHz or higher after convolution). FOPHs are also much more robust to cavitation damage than polyvinylidene fluoride (PVDF) membrane or needle hydrophones at high output. If the tip is damaged, a new fiber tip can be prepared easily with self-calibration. The acoustic power is determined by integrating the acoustic intensity derived from the measured pressure waveforms through a large area that covers the main lobe and significant side lobes [14]. Although calculated values are similar to those provided by the HIFU manufacturer, the scanning takes hours, and the sensitivity of FOPHs is so low (1–2 MPa) that averaging (>100) is needed to increase the signal-to-noise ratio (SNR).

In this study, an underwater pressure sensor was used to measure the spatial-averaged pressure waveform at the focus of a clinical HIFU system, and then the acoustic power was calculated by compensating the higher harmonics across the sensing area. The results were compared with measurements obtained using a radiation force balance, and similarities were found between them with acoustic power ranging from 18.2 W to 912 W. The proposed method can conveniently and reliably estimate the acoustic power of a fully calibrated HIFU system (i.e., increases of harmonics with acoustic intensity at the focus).

2. Material and methods

2.1. HIFU system

The transducer of a clinical extracorporeal HIFU system (FEP-BY02, Beijing Yuande Bio-Engineering, China) has an outer diameter of 33.5 cm and an inner diameter of 12 cm with an integrated ultrasound imaging probe (S3, Logiq S, GE, Seongnam, Korea) in the center. Two hundred fifty one individual PZT elements (center frequency of ~1 MHz and diameter of 16 mm) were positioned on a common spherical surface and all driven in phase. The electrical voltage to the transducer was measured by a high-voltage probe (PPE-2 kV, LeCroy, Chestnut Ridge, NY), which was registered to a digital oscilloscope (9304CM, LeCroy). The electrical input power was determined by:

$$P_e = \frac{V_{rms}^2}{G}$$

(4)

where $V_{rms}$ is the r.m.s. voltage, and $G$ is the conductance of the HIFU transducer, which was measured to be 17.56 mS using an impedance analyzer (4192A, Hewlett-Packard, Palo Alto, CA). The acoustic field of the HIFU transducer was characterized by a fiber optic probe hydrophone (FOPH-2000, RP Acoustics, Leutenbach, Germany), for which $p^+ = 2.5–57.2$ MPa, $p^- = -1.8$ to $-13.9$ MPa, $I_{SPPA} = 513–22,940$ W/cm$^2$ at an electrical input power of 43–2046 W (see Fig. 1). The peak positive pressure has an inflection at ~750 W, which was observed before [14,15] and may be due to the shock formation in the prefocal region. The ~6 dB beam size is about 1.6 × 10 mm.

2.2. Radiation force balance system

A radiation force balance was fabricated in the lab, and the acoustic absorbing target was 25.4 cm in diameter (see Fig. 2a). Nylon brush bristles (~3.5 cm in length and ~0.44 mm in diameter) were potted in a silicone elastomer (Sylgard 170, Dow Corning, Midland, MI) mixed with nickel powder (~400 mesh, Alfa Aesar, Ward Hill, MA) and plastic microspheres (PM6545, The PQ Corp, Valley Forge, PA) to absorb ultrasound energy. The absorbing target was suspended from a load cell (SML-100, Interface, Scottsdale, AZ) whose signal was digitized by a DAQ board (SCB-68, National Instruments, Austin, TX) with a sampling frequency of 1000 Hz. A LabVIEW (National Instruments) program was used to control the HIFU sonication and acquire the response of the radiation force balance via GPIB cable. The sensitivity of the radiation force balance was calibrated using a balance weight.

Fig. 1. The output of the HIFU system, peak positive and negative pressures, and the spatial-peak pulse-averaged acoustic intensity, at the focal point measured by a fiber optic probe hydrophone.

Fig. 2. Photos of (a) radiation force balance, (b) underwater blast sensor used in the measurement of HIFU acoustic power, and (c) B-mode ultrasound image with the underwater blast sensor aligned at the focal point of the HIFU system.
set (VWR, West Chester, PA). The alignment of the absorbing target was checked using the ultrasound imaging system. The discrepancy of stabilized responses between “on” and “off” stage of the HIFU (3 s and 5 s, respectively) was used to calculate the radiation force and the subsequent acoustic power. To minimize the bubble shielding effects, the interval time of sonication was at least 1 min for complete bubble dissolution.

2.3. Underwater sensor pressure

An underwater blast sensor (diameter \times length: 4.2 \times 7.6 mm, rise time \leq 3 \mu s, 138A38, PCB Piezotronics, Depew, NY) was fitted to the tip of a serological pipet (Fig. 2b), which was connected with a three-dimensional translational stage (LT3, Thorlabs, Newton, NJ). The stage was aligned with the focal point of the HIFU system initially under the guidance of ultrasound imaging (Fig. 2c) and then by manual scanning for the maximum output, which is not time consuming because of its high sensitivity. According to the manufacturer’s specifications, the electrical power input to the HIFU transducer needs 20 mW to reach its maximum and stable amplitude, so the measurement usually took at about 25 ms after transmitting HIFU pulses (which could be reduced to only a few cycles if the power amplifier, such as class A type, has a quick response time). Hollow polypropylene balls (KB-135, Excel Plastics, Byron Center, MI) were put on the water surface in order to reduce the reflection of the HIFU pulses from the interface.

2.4. Acoustic power calculation

The lateral beam profile of an annular focused source on the focal plane is

\[ \frac{p(r)}{p(0)} = \exp \left( \frac{ikr^2}{2D} \right) \frac{\{2J_1(\xi_1)/\xi_1\} \sin^2(\beta_1/2) - [2J_1(\xi_2)/\xi_2] \sin(\beta_2/2)}{\sin(\beta_1/2) - \sin^2(\beta_2/2)} \tag{5} \]

where \( p(r) \) is the acoustic pressure at a radial distance \( r \) from the axis, \( p(0) \) is the acoustic pressure at the focus, \( \xi_1 = (ka_1/D) \), \( \xi_2 = (ka_2/D) \), \( a_1 \) and \( a_2 \) are the outer and inner radii of the annular source, and \( \beta_1 \) and \( \beta_2 \) are the corresponding halves of the convergent angles, respectively. The distribution has good agreement with the HIFU simulation performed using the Khokhlov–Zabolotskaya–Kuznetsov (KZK) equation. The spatial averaging effect was expressed as:

\[ \bar{p}(r) = \frac{\int \int p(r, \rho) d\rho d\phi}{\int \int \rho d\rho d\phi} \tag{6} \]

where \( \bar{p}(r) \) represents the “effective” hydrophone response after the integration of the instantaneous acoustic pressure \( p(r, \rho) \) over the hydrophone’s active element area, and \( \rho \) and \( \phi \) are the polar integration coordinates. If the hydrophone is aligned to the focus exactly, the average pressure picked up is proportional to the acoustic focal pressure, \( p(0) \).

\[ \bar{p}(0) \propto p(0) \text{ or } p(0) = A_1 \cdot \bar{p}(0) \tag{7} \]

Thus the acoustic power is proportional to \( p(0)^2 \) and \( \bar{p}(0)^2 \) (i.e., \( P = A_2 \cdot p(0)^2 \)).

Harmonics show up in the pressure waveform and spectrum due to the acoustic nonlinearity in the HIFU field. Although the normalized pressure distributions of harmonics along the transducer have similar shape, the –6 dB beam size decreases with the harmonic number by \( n^{-1/2} \) (see Fig. 3) [14,16]. Therefore, the relationship between the acoustic power and the acoustic pressure is

\[ \frac{P_1}{P_n} = \frac{\int \int p_1^2(\rho)/2 \rho \rho_0 dS}{\int \int p_n^2(\rho)/2 \rho \rho_0 dS} = n \cdot \left[ \frac{p_1(0)}{p_n(0)} \right]^2 \tag{8} \]

where \( p_1(0) \) and \( p_n(0) \) are the acoustic pressures of the fundamental and nth harmonic at the focus, and \( P_1 \) and \( P_n \) are the corresponding acoustic powers, respectively. Due to the limited bandwidth of the underwater pressure sensor, no harmonics could be measured. Therefore, the contribution of harmonics to the total acoustic power should be compensated. The fundamental and harmonic components increase with the axial acoustic intensity almost constantly, regardless of the geometries and center frequency of the HIFU transducer [14,17,18]. Then the pressure of fundamental and harmonic components can be predicted as

\[ p_n(l, 0) = p_n(l_0, 0) \cdot \left( \frac{l}{l_0} \right)^{\eta_n} \tag{9} \]

where \( l_0 \) is the acoustic intensity at a low output, \( l \) is the acoustic intensity interpolated from Fig. 1 using the measured electrical power, and \( \eta_n \) is the slope of the nth harmonic. So the ratio of the nth harmonic to the fundamental at the measured electrical power can be determined as:

\[ \frac{p_n(l, 0)}{p_1(l, 0)} = \frac{p_n(l_0, 0)}{p_1(l_0, 0)} \cdot \left( \frac{l}{l_0} \right)^{\eta_n} = B_n \tag{10} \]

The total acoustic power can be calculated as:

\[ P(l, 0) = \sum n \cdot p_n(l, 0) = \sum n \cdot \frac{P_1(l, 0)}{P_1(0)} \cdot \frac{p_n(0)^2}{p_1(0)^2} \]

\[ = \sum n \cdot A_2 \cdot B_n \cdot p_n^2(l, 0) \]

\[ = \sum n \cdot A_2 \cdot B_n \cdot A_1^2 \cdot p_1^2(l, 0) \tag{11} \]

where \( \bar{p}_1(l, 0) \) is the average pressure at the fundamental measured by the blast sensor. Ten harmonics are included to compensate for the energy shift due to the nonlinear effect, which is limited by the SNR of the FOPH-2000 and the resolution of spectrum analysis.

3. Results

The radiation force balance measured output acoustic power of up to 900 W, which is the highest ever reported. However, the noise it picked up was large (see Fig. 4a). So the calculated electrical-to-acoustic energy conversion ratio is only 23% at the electrical power of 42.6 W. In comparison, at electrical power over 2000 W, the response of the radiation force balance becomes much clearer (Fig. 4c). But it takes about 1.3 s to reach a stable reading when HIFU pulses are delivered continuously, and a similar duration of decay was found in the

![Fig. 3. The normalized pressure distribution of fundamental and harmonics in the focal plane of the extracorporeal HIFU system simulated using Eq. (5).](image-url)
Fig. 4. The measured responses of the radiation force balance at electrical output power of (a) 42.6 W, (b) 492 W, and (c) 2120 W. HIFU pulses were delivered continuously for 3 s and then turned off. The measured spatial-average waveform of HIFU pulses by blast sensor at electrical output power of (d) 42.9 W and (e) 2045 W.
The computation took (40.0% vs. 41.2%) with electrical output power up to 2000 W (Fig. 5). After compensating the contribution of harmonics, the results become significant with the calculated electrical-to-acoustic energy ratio at 42.6 W using the radiation force balance). The most efficient to form lesions and to prevent all cancer cells from surviving otherwise, the thermal dose produced inside the target may be insufficient to cause thrombin generation, vessel puncture, and paralysis [21,22]. Although the radiation force balance has been used widely, transducer geometry and configurations are required to correct the beam convergence using different equations. Long sonication induces acoustic streaming, bubble shielding effects, and degradation of the transducer due to heat accumulation in the piezoelectric material, which may affect the accuracy of measurement, especially at high power. The underwater pressure sensor used here seems to be a good candidate for measuring the acoustic power of a clinical HIFU system with similar electrical-to-acoustic conversion efficiency to that obtained using the radiation force balance. Its high sensitivity and robustness to high pressure ensure operation at both low and high output levels. Much shorter sonication for pressure measurement could minimize the effect of HIFU-induced cavitation bubbles.

According to the established guidelines [10,23], when measuring the acoustic field the effective radius of the active element of the hydrophone should be equal to or less than a quarter wavelength. However, it is hard to find such a hydrophone for use in an acoustic field that is highly-focused and has high intensity and high frequency (with harmonics generation owing to the nonlinear effect). Although the FOPH is a good candidate [14], there is always a spatial-averaging effect on the active element that affects the measurement accuracy. A practical spatial averaging model was developed to correct the hydrophone calibration at up to 40 MHz [24]. Using a similar model, the acoustic power was calculated using a large and easily fabricated sensor in this study.

The alignment is always a critical issue in acoustic field characterization. It is recommended that the diameter of the acoustic absorbing target should be at least 1.5 times the acoustic beam size, and the distance between the target and HIFU transducer should be no greater than 0.7 times the focal length [9,10]. Although the alignment of absorbing target is much less critical to the measurement than the reflecting target [7], it is recommended that the HIFU beam to be aligned to the center of the absorbing target [11]. The position of our absorbing target needs to be adjusted to obtain excellent SNR, as well as to achieve the maximum acoustic power at the electrical output of about 300 W each time before full range measurement. The presence of friction in transporting the radiation force generated by the HIFU pulses to the load cell will also affect the reliability and accuracy of measurement. In contrast, the alignment of the underwater pressure sensor is much easier under the initial guidance of the B-mode ultrasound imaging and subsequent manual scanning in a much smaller range.

One method of characterizing HIFU transducers is measuring the acoustic field at low output and then extrapolating toward high output based on a linear propagation model, but this method has high error because of acoustic nonlinearities [25, 26]. However, waveform distortion could be simulated using the KZK equation in the extrapolation [15]. The boundary conditions and vibration pattern across the transducer surface may be determined by acoustic holography to improve the simulation accuracy. Although FOPH has broad bandwidth, the shock front may still be underestimated [15]. Using the established algorithm, the calculated acoustic power and simulated pressure waveform (data not shown) were similar to the measurements obtained using the radiation force balance and FOPH, respectively. The simulated pressure waveform alone is sufficient for evaluating the performance of the HIFU system. Due to the limitations of sampling frequency, the number of samples, and weak nonlinearity at low output levels, it is difficult to calculate the spectra of very high-order harmonics (n > 5). It was found that the amplitudes of the harmonics decay exponentially with the order of harmonics. So the first few harmonics were used to fit the exponential decay curve and then

![Graph](image_url)

**Fig. 5.** Comparison of the acoustic power measurement obtained using the radiation force balance and the underwater blast sensor.

HIFU “off” stage (Fig. 4c). In addition, there were some low-amplitude low-frequency fluctuations in even the stabilized reading, which may be due to vibration of the suspending target and the target heating effect [7]. Since there was great variation (~20%) in the electrical power using the same output setting (with hardware limitations in the signal generation circuit), performing an averaging operation to enhance the SNR was not feasible. So the electrical power to the transducer needed to be measured each time.

Before delivering HIFU pulses, the HIFU transducer of the FEP-BY02 system needs warming-up and emits low energy, which is shown as some weakly bright bands in the B-mode ultrasound images and could be picked up by the underwater pressure sensor. This leaking energy is due to the hardware design and is superimposed on the output HIFU waveform (especially on wave peaks and troughs; see Fig. 4). But it may not have a significant contribution to the HIFU treatment because of its low amplitude. In 1-month measurements, neither mechanical nor thermal damage was found in the underwater pressure sensor.

Measurements obtained using the radiation force balance and the underwater blast sensor were compared (Fig. 5). The higher sensitivity of the underwater pressure sensor leads to more reliable results at very low output (only 23% electrical-to-acoustic energy conversion ratio at 42.6 W using the radiation force balance). The most energy of the measured pressure waveform was concentrated on the fundamental frequency of the HIFU pulses with electrical power <400 W. Similar conversion ratios (~42%) were found between these two approaches. Because the nonlinear effects become more apparent and important at higher output levels, the discrepancy between those two results becomes significant with the calculated electrical-to-acoustic energy conversion ratio gradually decreasing to ~34.6%. After compensating the contribution of harmonics, the results are similar to those obtained using the radiation force balance technique (40.0% vs. 41.2%) with electrical output power up to 2000 W (Fig. 5). The computation took <1 min.

4. Discussion

Despite the promising outcomes of clinical HIFU treatment for a variety of solid tumors or cancers, the biggest concerns of the United States Food and Drug Administration (FDA) are its efficiency and safety. Prior to each treatment, the HIFU system should be calibrated conveniently, accurately, and reliably for appropriate planning. Otherwise, the thermal dose produced inside the target may be insufficient to form lesions and to prevent all cancer cells from surviving [19]. With a significantly low electrical-to-acoustic energy conversion ratio, the HIFU transducer may break down or defects may occur in the driving circuit. On the other hand, if higher power is delivered, more side effects (i.e., skin burn and pain) will be induced. Significant temperature rise and thermal diffusion in the target tissue can lead to overexposure [20]. Cavitation damage to perivascular structures and nerves adjacent to many large vessels has been demonstrated to cause thrombin generation, vessel puncture, and paralysis [21,22].

![Graph](image_url)

The simulated pressure waveform alone is sufficient for evaluating the performance of the HIFU system. Due to the limitations of sampling frequency, the number of samples, and weak nonlinearity at low output levels, it is difficult to calculate the spectra of very high-order harmonics (n > 5). It was found that the amplitudes of the harmonics decay exponentially with the order of harmonics. So the first few harmonics were used to fit the exponential decay curve and then
calculate the amplitudes of others. However, the behavior of harmonic generation used in this study may be invalid once a shock front forms or acoustic saturation occurs, which needs further investigation.

The proposed method requires simulation of the pressure distribution, calculation of the spatial-averaged pressure, and measurement of acoustic pressures at the focal point and the slopes of harmonics with respect to the acoustic intensity, which can be provided by the HIFU manufacturer or measured in the system calibration. So the method can be used to estimate the acoustic power of a fully calibrated HIFU transducer, as opposed to measuring the value of a new transducer. There are two error sources. One is due to the limited integration area and the number of harmonics included in the calculation. However, pressures of very high-order harmonics \((n > 10)\) and beyond the presented integration area are very low. Therefore, their contribution could be negligible. The other error source is associated with the alignment error. Manual scanning for the maximum pressure is helpful for minimizing it. For transrectal or interstitial HIFU transducers, which work at higher frequencies, an appropriate blast sensor should be chosen to pick up at least the fundamental component.

In summary, a novel method was developed to measure the spatial-averaged pressure at the focus of an extracorporeal HIFU transducer and then calculate the acoustic power of up to 912 W. With harmonic compensation, the proposed method has similar results to those obtained using a radiation force balance. This method has the advantages of low weight, small size, high sensitivity, high SNR (especially at low power output), robust performance, quick response, and easy operation. The method can be used to check the performance of a clinical HIFU system routinely and may be developed into a convenient and reliable tool for HIFU exposimetry measurement.

**Ethical approval**

Not required.

**Conflict of interest**

The author confirms that there is no conflict of interest in relation to this work.

**Acknowledgments**

The author thanks Mr. Byron W. Cunitz at the Center for Industrial and Medical Ultrasound, University of Washington, for designing and fabricating the radiation force balance.

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