Inter-laboratory comparison of HITU power measurement methods and capabilities

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Abstract. High Intensity Therapeutic Ultrasound (HITU) is gaining in importance among the spectrum of therapeutic options to combat cancer. HITU has already been approved and is in clinical use for the treatment of organs like the prostate, the liver and the uterus. Nevertheless, the metrology of the applied high power ultrasound fields, and in consequence, reliable treatment planning and monitoring, is still a challenge. As part of a European Metrology Research Programme project, the four National Metrology Institutes from the UK, Germany, Italy and Turkey conducted an inter-laboratory comparison of their power measurement capabilities at power levels of 5, 25, 75 and 150 W each at frequencies of 1.1, 1.5 and 3.3 MHz. The task was to measure the total, time-averaged ultrasonic output power, emitted by the circulated transducers under specified electrical excitation conditions into an anechoic water load, and the actual rms transducer input voltage. The output value to be reported was the electro-acoustic radiation conductance including the associated standard and expanded uncertainties. Several different measurement techniques were applied to gain further insight into HITU power measurement. The deviations from the calculated comparison reference value found for the different techniques are discussed and conclusions for the further improvement of measuring procedures are drawn.

1. Introduction

High Intensity Therapeutic Ultrasound (HITU) procedures compromise, amongst other things, the non-invasive treatment of tumourous tissue. The procedure with the highest intensities applied to the tissue (> 10,000 W/cm²) [1] is HIFU (High Intensity Focused Ultrasound, also referred to as Ultrasound Ablation or Focused Ultrasound Surgery) [2], used for the treatment of organs like the prostate, the liver and the uterus, by inducing localized necrosis of the tissue. Even though HITU has already been clinically approved, the metrology of the applied high power ultrasound fields, and in consequence, reliable treatment planning and monitoring, is still a challenge. A crucial step for the prediction of the desired temperature rise in an HITU-treated region is the measurement of the total ultrasound output power and the sound field distribution.

This paper describes the measurements and results of an inter-laboratory comparison of HITU power measurement methods and procedures. One goal of this comparison was the investigation of different approaches to the determination of the acoustic output power. The participants, thus, offered...
to use different methods available in their laboratories. The comparison was part of a European Metrology Research Programme project “External Beam Cancer Therapy (EBCT)” [3] and comprised the measurement of the time-averaged ultrasonic output power of two HITU ultrasonic transducers in the nominal frequency range from 1.1 MHz to 3.3 MHz and the measurement of the applied excitation voltage. The pilot laboratory was the PTB (Germany) and the other participants were UME (Turkey), INRIM (Italy) and NPL (UK). The measurements of this inter-laboratory comparison, including the re-measurements at the pilot laboratory, were carried out between June and December 2009.

2. The measurement task
The task was to measure the total, time-averaged ultrasonic output power $P_{\text{out}}$, emitted by the provided transducers under specified conditions of electrical excitation into an anechoic (i.e., free-field) water load, and the rms value of the input voltage $U_{\text{in}}$ applied to the transducer socket.

Finally, the electro-acoustic radiation conductance $G$ was to be calculated according to

$$G = \frac{P_{\text{out}}}{U_{\text{in}}^2}. \quad (1)$$

Three acoustic frequencies (1.1 MHz, 1.5 MHz and 3.3 MHz) and four power levels (very low - 5 W, low - 25 W, medium - 75 W and high - 150 W) were selected for the comparison, resulting in eleven different combinations of transducer type, frequency and power level. Two types of HITU transducers (Sonic Concepts H-102 and Imasonic 5706A), capable of providing the necessary frequencies and power levels, were used as travelling standards.

The participants applied different ultrasonic power measurement methods available in their laboratories. The reported output power was to relate to the transducer surface, which corresponds to the rim of the focusing bowl. For the measurement of the rms transducer input voltage $U_{\text{in}}$ the participant was to use his own methods and instruments.

3. Measurement setup of the participating laboratories

3.1. PTB
The PTB primary standard radiation force balance setup was used with absorbing targets according to IEC61161 (2007) [4]. The HITU transducers were mounted at the bottom of water tanks, radiating upwards to the targets (two layers with diameters of 136 mm and 110 mm) suspended from the balance (Mettler Toledo A250) by a thin wire.

The excitation voltage of the transducers was generated by a signal generator (R&S SMX) and amplified by an rf power amplifier (amplifier research 500A100A). Additionally, the supplied electrical power was monitored by a power reflection meter (R&S NRT-Z8). The input voltage on the transducer connecting port $U_{\text{in}}$ was measured with a calibrated 100:1 sensor head connected to an rms level voltmeter (RD 9303).

The applied measurement cycles consisted of two on-periods embedded in off-periods. The on-time lasted from 16 s to 12 s and the off-time from 48 s to 118 s depending on the applied power. The transducer target distances varied between 3 – 9 mm, including sub-wavelength variations of $\lambda$/4. For the estimation of the power at zero distance, the measured power was corrected for the attenuation in the water path (half of the absorption coefficient in the water path due to the recovering of the acoustical streaming momentum). Additionally, correction factors based on the curved geometry of the focusing transducers were applied to the measured power values.

3.2. INRIM
The device used for the ultrasonic power measurements is based on the radiation force balance method [4]. The absorbing target was made of two polyurethane rubber discs, superimposed on each other and connected by means of a mechanical coupler. The lower disc is 14 mm thick and has a diameter of 80
mm, the upper one is 10 mm thick and its diameter is 120 mm. The target was connected to a load cell (Honeywell mod. 31) which measured the apparent target mass variation due to ultrasonic field on-off-cycles. The signal produced by the load cell was conditioned by a strain gauge amplifier (Sensotec mod. UV-10) and then measured by a nano-voltmeter (Agilent 34420A). The load cell was screwed onto the bottom of the tank (volume approx. 15 l) and the transducers were mounted above, radiating downwards.

The excitation voltage of the transducers was generated by a signal generator (Agilent 33220A) and amplified by an rf power amplifier (amplifier research 500A100A). The rms values of the transducer driving signals were acquired by means of an rms voltmeter (R&S URE-3).

The applied measurement schema consisted of two on-cycles embedded in off-cycles. The on-time was from 16 s to 12 s and the off-time from 48 s to 118 s. For the calculation of the power at zero distance (rim of the transducer), the attenuation coefficient of water was applied. Correction factors were applied to the measured power values incorporating the curved geometry of the focusing transducers.

### 3.3. UME

A modified radiation force balance equipped with a reflecting target [4] was used for the measurements. The ultrasound power was applied to one scale beam where the reflecting target (stainless steel conic reflecting target with 100 mm in diameter) was mounted and the corresponding force was measured on the other scale beam which was connected to the balance (Mettler Toledo PR 2004) with a thin wire. The transducers were mounted at the bottom of the water tank, emitting upwards in the direction of the reflecting target. Absorbers prevented multiple reflections inside the tank.

The driving voltage of the transducers was supplied from a combination of a signal generator and an rf power amplifier (Agilent 33250A and ENI 3100L for low power levels, Agilent 33220A and E&I for high power levels). A calibrated digital scope (Agilent 54820A Infinium) with a 1:10 scope probe was used for measurements of the input voltages.

Balance read outs were acquired during power on/off time intervals between 15/30 seconds (5 W) and 12/120 seconds (150 W) and for different target-transducer distances between near zero and the focal point. The obtained power values were extrapolated to zero distance.

### 3.4. NPL

For the measurements, a modification of the NPL secondary standard setup was used. A castor oil target with its entry membrane facing vertically upwards was suspended beneath the balance (Sartorius CC1200) in a tank of water (volume approx. 20 l). The transducer was mounted on a retort stand with the radiating surface facing vertically downwards on to the castor oil target. The castor oil target was used to determine the total output power simultaneously from the radiation force and the thermal expansion of the target (buoyancy method) [5].

A programmable signal generator (HP3336C) provided the transducer drive through an rf power amplifier (amplifier research 150A100B). The measurement of the driving voltage was carried out with a digital storage oscilloscope (Tektronix DPO7254) fitted with a high impedance 100:1 probe. Since non-linearity of the drive signal was observed for medium and high power levels, the rms value of the fundamental frequency component of the rf voltage was taken into account for further calculations.

The ultrasound power was determined from the measurement of the radiation force [4] and from the change in buoyancy [5] of the target. The same data sets were used for both methods so the insonation conditions were identical. In all cases, the rf drive to the transducer was turned on and off with a period of 72 seconds (i.e. ON for 12 seconds; OFF for 60 seconds). For the estimation of the power at zero distance the measured power was corrected for the attenuation in the water path. For radiation force measurements, also the recovery of streaming momentum was taken into account for the estimation of the correction factor. Additionally, correction factors were applied to the measured power values due to the geometry of the focusing transducers.
4. Results

In table 1 the final results for the radiation conductance $G$ of the participants are listed. The uncertainties are generally understood as relative uncertainties in $\%$ (or in $10^{-2}$). The stated expanded uncertainties $ku(G)$ are based on a coverage factor $k=2$. The level of confidence is 95.45 $\%$.

**Table 1.** Values for the radiation conductance together with the expanded uncertainty stated by the participants (Lab 1 – PTB, Lab 2 – UME, Lab 3 – INRIM, Labs 4 and 5 – NPL) and the determined reference values.

| Transducer | $f$ | $P$-level | Lab 1 | Lab 2 | Lab 3 | Lab 4 | Lab 5 | Ref. value |
|------------|-----|-----------|-------|-------|-------|-------|-------|------------|
| No. MHz    |     |           | $G$   | $ku(G)$ | $G$ | $ku(G)$ | $G$ | $ku(G)$ | $G$ | $ku(G)$ |
| 1 1.1 vl   | 18.69 | 7.2       | 21.04 | 14.0   | 19.89 | 12.3   | 18.60 | 6.1   | 18.90 | 6.7   |
| 1 l        | 18.85 | 7.2       | 20.84 | 14.0   | 19.61 | 8.5    | 18.60 | 6.1   | 19.50 | 4.6   |
| 1 m        | 19.07 | 7.3       | 20.73 | 15.2   | 19.81 | 8.2    | 18.50 | 5.9   | 19.30 | 4.5   |
| 1 H        | 19.25 | 8.1       | 20.41 | 15.2   | 20.71 | 8.2    | 18.50 | 6.0   | 19.40 | 4.7   |
| 3 3.3 vl   | 13.00 | 7.4       | 15.73 | 14.0   | 14.31 | 13.0   | 13.20 | 6.1   | 14.30 | 6.2   |
| 1 l        | 13.23 | 7.4       | 15.62 | 14.0   | 13.70 | 8.5    | 13.40 | 6.1   | 14.00 | 4.9   |
| 1 m        | 13.61 | 7.6       | 15.55 | 15.2   | 14.18 | 8.2    | 13.60 | 6.0   | 14.50 | 5.0   |
| 2 1.5 vl   | 15.29 | 7.2       | 16.98 | 14.0   | 15.61 | 14.1   | 15.00 | 5.6   | 16.00 | 5.8   |
| 1 l        | 15.33 | 7.2       | 16.64 | 14.0   | 15.69 | 8.5    | 15.00 | 5.5   | 16.40 | 4.7   |
| 1 m        | 15.28 | 7.3       | 16.71 | 15.2   | 15.47 | 8.2    | 14.80 | 5.5   | 15.90 | 4.7   |
| 1 H        | 15.27 | 8.1       | 16.37 | 15.2   | 15.59 | 8.2    | 14.50 | 5.5   | 15.50 | 4.6   |

The uncertainties were derived in accordance with the “Guide to the Expression of Uncertainty in Measurement” [6]. The analysis of the reported radiation conductance followed the guidelines for the evaluation of key comparison data [7]. The reference values $G$ for each combination of frequency and power level were calculated as weighted means, incorporating the submitted measurements $G_i$ and standard uncertainties $u(G_i)$ of the participating laboratories.

![Figure 1. Consistency test - result of the applied chi-squared test.](image-url)
As the measurements are consistent (figure 1), the calculated reference values are valid estimates of the radiation conductance (table 1).

The degree of equivalence of each applied measurement method is given by the pair of values \( d_i \) and \( ku(d_i) \) \((k=2)\). The values were calculated using

\[
d_i = G_i - G \quad \text{and} \quad u(d_i) = \sqrt{u^2(G_i) - u^2(G)},
\]

with \( G_i \) the reported values and \( G \) the reference value (figures 2 and 3).

![Figure 2. Degrees of equivalence \( d_i \) of the participating laboratories with the reference value for the radiation conductance \( G \) of transducer 1 (Sonic Concepts H-102) and associated expanded uncertainties \( ku(d_i) \) \((k=2)\).](image)

5. Discussion and conclusion

With respect to the reported uncertainties of the participating laboratories, the circulated transducers appeared sufficiently stable over the measurement period from June to December 2009. For trans-
ducer 1 @ 1.1 MHz, the uncertainty contributions are much smaller than the uncertainty of the reference values. As reported by the participants, transducer 1 @ 3.3 MHz showed instabilities during measurements at higher power levels (drop in output) and transducer 2 @ 1.5 MHz experienced a leakage, which was successfully fixed. In summary, these facts induced an increase of the uncertainty contributions due to temporal instabilities, which are still smaller than the uncertainty of the reference values.

Figure 3. Degrees of equivalence \( d_i \) of the participating laboratories with the reference value for the radiation conductance \( G \) of transducer 2 (Imasonic 5706A) and associated expanded uncertainties \( \text{\( ku(d_i) \)} \ (k=2) \).

The participants’ relative expanded uncertainties for the radiation conductance at the various combinations of transducer type, frequency and excitation level range from 4.5 % to 15.2 %. The majority of deviations from the reference value were below 5 %, except the results obtained by means of a radiation force balance equipped with a reflecting target (max. deviation 15 %). This leads to the conclusion that the use of reflecting targets in strong focusing fields is not recommended.

6. Summary
The outcome of this first inter-laboratory comparison of power measurement methods provides an insight into the current state of HITU power measurement capabilities. The obtained agreement between the results of the participants can generally be considered satisfactory. Based on the experience of this comparison, a repetition with more participants is recommended.

7. References
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