Output beam characterization of medical diagnostic ultrasound systems using a thermal technique for intensity measurements

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1. Introduction

Ultrasound exposure measurements for medical ultrasound systems are essential as regards aspects of safety and quality assurance. International standards require the characterization of output beams regarding, for instance, power, intensity, peak pressure, and lateral dimension. Spatial-peak temporal-average intensities are particularly important, since they are related to the potential thermal hazard of the patient. Usually, local intensity parameters are derived from hydrophone measurements. However, in the case of modern multi-mode diagnostic ultrasound systems, the necessary measurement procedures can become technically very difficult, time consuming and expensive. Instead of running the actual operation mode used in medical practice, exposure measurements in these cases may only be realizable in special engineering modes and only by the manufacturer. In this paper, the practical applicability of a more simple and low-cost thermal intensity sensor technique recently developed [1] is demonstrated. The method is shown to be an adequate alternative for the precise determination of ultrasound time-averaged intensity distributions.

2. Sensor Principle

The thermal measurement technique used is based on the transformation of the incident ultrasonic energy into heat within a small-sized cylindrical absorber (Figure 1). The front face of the absorber is in contact with the surrounding water to allow the ultrasound wave to pass into the absorber. Due to this contact, the temperature at the absorber front face is the same as in the water bath. Since the absorber is in part thermally insulated by an air-filled housing, the temperature at the rear side increases during insonation. Part of the heat produced inside the absorber permanently flows through the front face to the water. After a period of insonation with constant intensity, thermal equilibrium will appear between the heat produced by absorption and the heat given off to the surrounding water. From the temperature enhancement ΔT at the rear side of the absorber at this equilibrium measured by a small resistor temperature probe, the ultrasound intensity averaged over the absorber cross section can be determined. Since all thermal processes are slow in comparison with the ultrasound frequencies and typical repetition frequencies used in diagnostics, the sensor inherently temporally averages over all waveforms incident. Therefore, in contrast to the hydrophone-based method, emission pulse pattern information about the ultrasound system to be measured is not necessary to determine the temporal-average intensity.

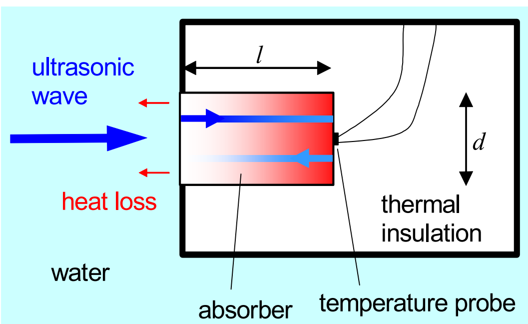

Figure 1: Thermal ultrasound intensity sensor.

3. Sensor Calibration

To enable quantitative intensity measurements, the prototype sensors manufactured were calibrated using a substitution calibration technique and comparison with membrane hydrophones [1]. In a first measurement run, the acoustic pressure in the far field of three different source transducers covering the frequency range from 1 MHz to 16 MHz was measured in a water tank by means of calibrated coplanar membrane hydrophones. From the measured pressure amplitudes, the time-averaged acoustic intensities $I(f)$ were calculated using plane wave assumptions and extrapolation from the finite burst lengths used to continuous waves. In a second run, the measurements were repeated for each frequency with the thermoacoustic sensor to be calibrated positioned at the same distance z from the source transducer as the hydrophone was before. The same electrical excitation conditions as in the hydrophone measurements were used for the source transducer. Lateral alignment was achieved by searching for the maximum temperature enhancement at equilibrium. A second reference temperature probe was used to simultaneously measure the water bath temperature during the acoustic measurements, and long-term drifts were compensated by evaluating the temperature difference between the two probes.

For each frequency f, the temperature-versus-time curve including the switch-on and switch-off process of the source transducer was recorded, and the temperature enhancement ΔT at equilibrium was determined. The temperature-to-intensity transfer function $H(f)$ was then calculated as the quotient of the temperature enhancement $\Delta T(f)$ and the ultrasound intensity $I(f)$ derived from the hydrophone measurements. The frequency responses of three sensor prototypes with different absorber sizes are depicted in Figure 2.

In general, the transfer function of the smaller diameter sensors is lower. This is expected due to the larger surface-to-volume ratio for smaller absorber diameters leading to a stronger impact of heat losses. The transfer functions show some variations, in particular at low frequencies, which seem to be caused by acoustic resonances within the absorber rod. Despite these variations, reasonable results can be expected for the measurement of broadband pulses as emitted from medical diagnostic ultrasound machines. Here, the pulse spectra will cover several of the absorber resonances, and an average transfer factor at the working frequency of the device under test as suggested by the second order polynomial fits (Figure 2) may be used for adequate temperature-to-intensity conversion for frequencies above 2.5 MHz.

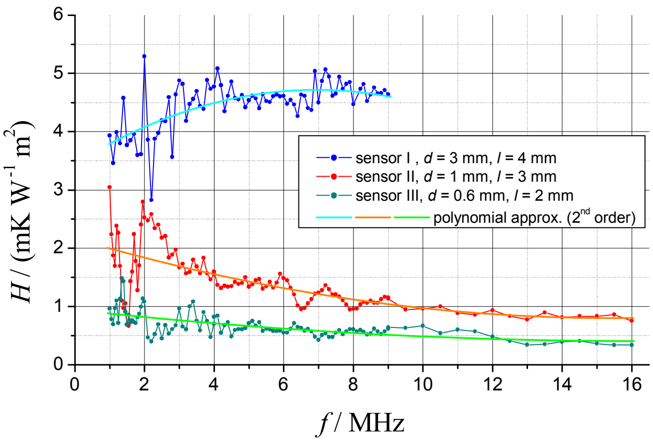

Figure 2: Frequency response of three different thermal intensity sensor prototypes with plexiglas absorbers of different sizes.

4. Application to Exposimetry

To investigate its capabilities in practice, the 0.6 mm diameter thermal sensor was utilized for extensive acoustic intensity measurements and output beam characterization on a commercial diagnostic ultrasound machine (Siemens Sonoline Sienna). Two different transducer heads were used: a 3.5 MHz convex array (C5-2) and a 7.5 MHz linear array (7.5L40). The setup for the intensity scans is depicted in Figure 3. The transducer is slightly immersed in the water contained in a measurement tank and adjusted to emit the ultrasound beam vertically downwards. The thermal sensor is mounted onto a stepper motor-driven *xyz*-positioning system which is controlled by a computer. The measurement software program controls the sensor movement for axial scans (*z*-direction) and for beam profile line scans in the azimuth and elevation directions (*x*- and *y*-directions, respectively) and records the data from the temperature probe of the ultrasound sensor and from the probe for the water bath reference temperature. The temperature-versus-time curves recorded are automatically evaluated regarding the equilibrium temperature enhancement in comparison to the switched-off condition of the transducer. Using the acoustic calibration data of the thermal sensor as given by the polynomial fit for sensor III (Figure 2), a temporal-average intensity value I_{TA} is determined for each measurement location. A mechanical stirrer is used to achieve a homogeneous temperature distribution in the water bath and to avoid clouds of warmth in front of the thermal sensor front face.

Figures 4 and 5, respectively, show the results of axial scans for pulse Doppler (pD) and for motion (M) mode operation of the diagnostic machine using different transducers, working frequencies, repetition rates, output power, and focal length settings. The overall maximum intensities occur when the azimuthal focal length is chosen to match the fixed focal length of the elevational lens. In addition to the thermal sensor measurements, hydrophone-based intensity measurements were performed for comparison using a 0.62 mm effective diameter needle-type hydrophone (MH28-5, Force Technology) and a 0.55 mm effective diameter coplanar membrane hydrophone (Ip038, Marconi). As is standard, plane wave assumptions were used to calculate the intensities from the ultrasound pressure data measured [2]. To compensate for variations of the frequency responses of the hydrophones determined by broadband calibration, the pulse deconvolution method was applied to obtain the pressure-time waveforms from the signal voltage data [2],[3]. The results obtained with the three sensors of comparable sensor diameter, e. g. comparable spatial resolution, show very good agreement and demonstrate the reliable applicability of the thermal sensor for different ultrasonic frequencies and waveforms in the wide range of intensities typically used in medical diagnostic ultrasound. Only in the near field, did the thermal sensor provide systematically larger intensity values. This is probably caused by intensity contributions due to ultrasound waves partly reflected at the sensor and then again at the transducer, impinging again on the sensor. In principle, such artificial contributions can also be observed in hydrophone measurements, but here they are usually excluded from the intensity summation due to the time gating when acquiring the waveform with an oscilloscope.

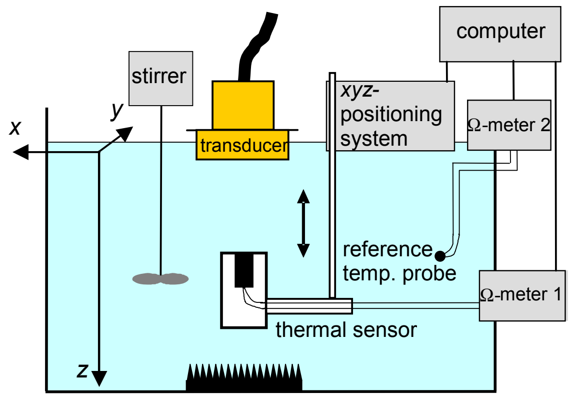

Figure 3: Setup for intensity scans using the thermal sensor technique.

Figure 6 shows the azimuthal and the elevational beam profile results at focus for the linear array transducer operated in M mode for the settings that lead to the overall intensity maximum of this operation mode according to Figure 5. The agreement with the results of the corresponding hydrophone measurements is again good and similar beam widths were obtained by the different measurement methods. From this, it can be deduced that the spatial resolution of the thermal sensor is similar to that of the hydrophones used and that it is basically given by the absorber diameter of 0.6 mm, as was expected.

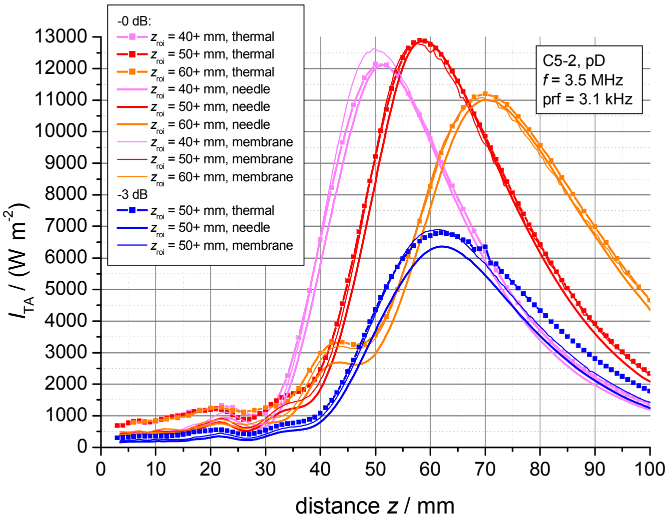

Figure 4: Axial intensity beam plot for the convex array transducer operated in pulse Doppler mode; working frequency setting of $f = 3.5$ MHz, pulse repetition frequency of prf = 3.1 kHz, maximum and -3 dB output power, different focal settings z_{roi}.

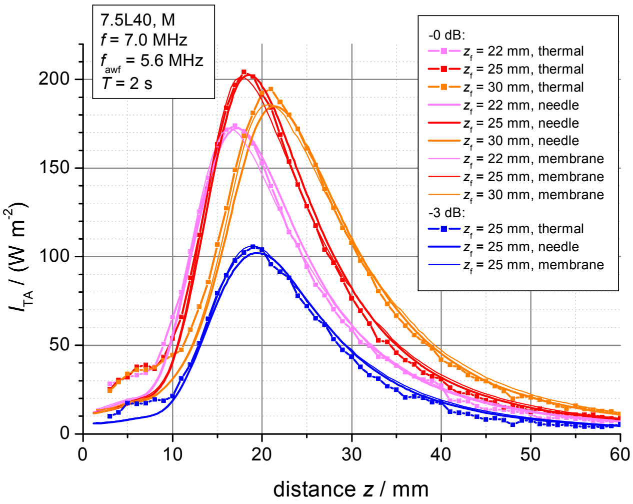

Figure 5: Axial intensity beam plot for the linear array transducer operated in motion mode; working frequency setting of $f = 7$ MHz, time base of $T = 2$ s (prf = 272 Hz), maximum and -3 dB output power setting, different focal settings z_{f}.

5. Discussion and Conclusions

The thermal sensor technique described is a simple, low-cost, and practical alternative to hydrophone-based methods for the determination of temporal-average intensities. A calibrated prototype sensor was applied to measure axial scans and beam profiles at the focus of transducers working at typical frequencies of diagnostic ultrasound equipment. Some measurement examples were shown and in general good agreement was found between the results of the thermal sensor and additional hydrophone measurement results. The maximum deviations of the spatial-peak temporal-average intensities I_{SPTA} obtained with the thermal sensor from the corresponding hydrophone-based results were below 12 % for the measurements performed. In view of typical uncertainties of intensity values derived from hydrophone measurements of ± 20 % to ± 30 %, this can be considered a rather good agreement.

The advantages of the thermal sensor technique are especially evident for intensity measurements in the case of scanning and combined modes of the diagnostic device, where the synchronization between hydrophone measurements and the complex pulse emission pattern can be difficult. Since the thermal sensor technique is inherently temporal-averaging, there is no need for the determination of the individual repetition rates of all the different pressure waveforms occurring at each measurement location. Even modern diagnostic systems which may support operation modes without any fixed pulse repetition or scan repetition rates, can easily be characterized with the method described.

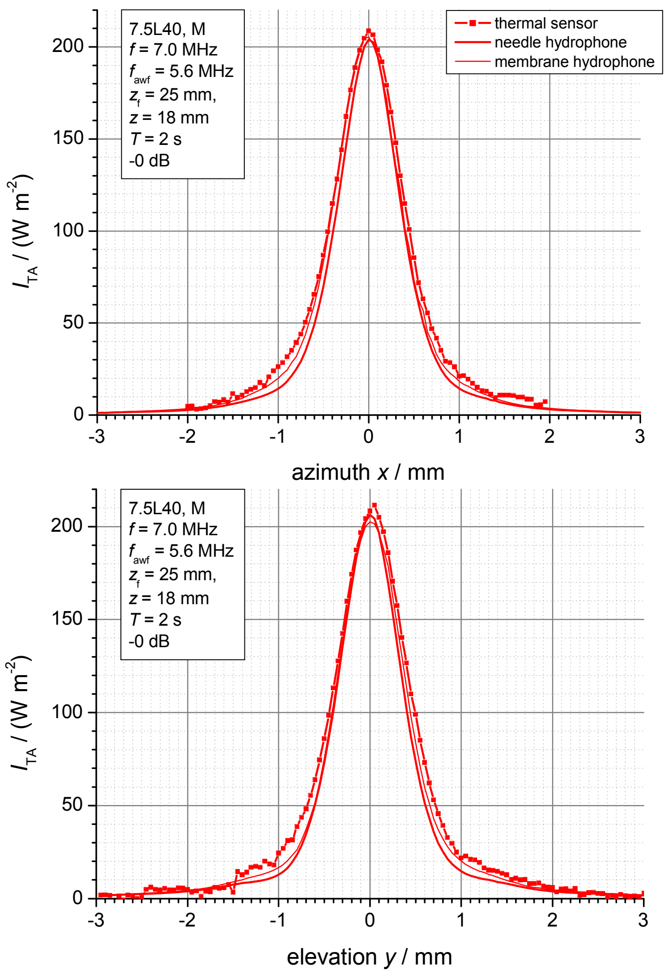

Figure 6: Profile scans in the *x*- and *y*-direction for the linear array transducer operated in motion mode; settings as given in Figure 5 that lead to the overall intensity maximum.

References

[1] V. Wilkens, Measurement of output intensities of multiple-mode diagnostic ultrasound systems using thermoacoustic sensors. Proc. 2005 IEEE Ultrason. Symp., Rotterdam, The Netherlands (2005), 1722-1725.

[2] IEC: Ultrasonics - Hydrophones - Part 1: Measurement and characterization of medical ultrasonic fields up to 40 MHz. International Electrotechnical Commission, International Standard IEC 62127-1 Ed.1 (2007).

[3] V. Wilkens, C. Koch, Amplitude and phase calibration of hydrophones up to 70 MHz using broadband pulse excitation and an optical reference hydrophone. J. Acoust. Soc. Am. **115** (2004), 2892-2903.