Metrology of HITU fields

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Introduction

High Intensity Therapeutic Ultrasound (HITU) is a non-invasive technique for the treatment of various types of cancer, as well as non-malignant pathologies, by inducing localized necrosis of the tissue (Fig. 1). Even though HITU is already in clinical use, this technique is still an emerging therapeutic procedure, with a lack of knowledge on reliable and stable treatment planning and monitoring procedures [1].

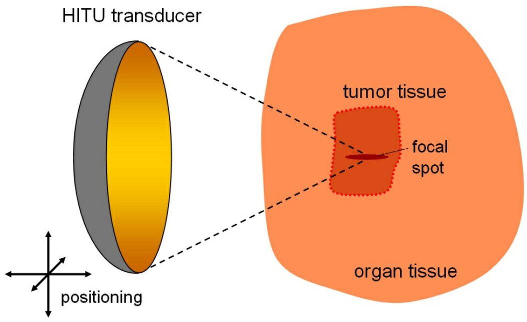

Figure 1: Principle of clinical HITU application. High intensity focused ultrasound beams achieve temperature rises of more than 50 K/s in the focal spot, which leads to a selective destruction of tissue (e.g. tumors).

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. Additionally, the evaluation of tissue thermometry methods, using MR or ultrasound itself, is important for treatment monitoring and quality assurance, as well as for choosing the appropriate ultrasound power for a desired local intensity and temperature rise, respectively.

Till now, standard measurement devices have not been applicable for measurements under these conditions. Ultrasound fields are well-investigated for output powers smaller than 20 W. This paper describes the first results of measurements in much stronger, highly focused fields (> 400 W ultrasound power at 1.5 MHz) using an absorbing target arranged close to the transducer. For this purpose, a radiation force balance setup was adapted for the determination of large acoustic output power quantities, completed with an estimation of the uncertainty budget.

Procedures for measurement of the ultrasound output power

The ultrasonic power *P* emitted by a transducer is the ultrasonic energy leaving the transducer per unit of time. Its value is usually considered as the time average. Due to the fact that the acoustical impedance of water is near to that of tissue, the measurements are regularly performed in water.

The most accepted measurement method providing a high level of metrological quality is the radiation force method. The acoustic radiation force *F* is the time-average force acting on a target placed in the acoustic field. This force is due to the radiation stress tensor - a local field quantity [2] - and is measured by means of a precision balance. The target, which should be either perfectly reflecting or perfectly absorbing and large enough to cover the ultrasonic beam completely, is inserted in the field and the radiation force acting on it is measured (Fig. 2).

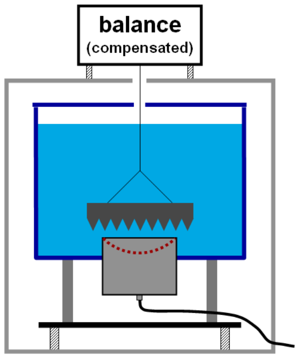

Figure 2: Scheme of radiation force balance setup with absorbing target. The transducer under investigation is placed at the bottom of the water vessel and emits the ultrasound waves upwards. The target is suspended from a compensated precision balance (required resolution: 10 µg or at least 100 µg).

Under the assumption of plane wave conditions, the ultrasound power *P* is proportional to the upwardly directed component of the radiation force *F*. Both quantities are linked by the speed of sound *c* in the medium

$$P = cF \,. \tag{1}$$

For non-plane fields the relation between power and radiation force depends on the field structure. Diffraction and focussing lead to deviations from equation (1).

The radiation force on an absorbing target in the field of a circular, spherically-focussed transducer was calculated numerically including diffraction [3]. A straightforward approximation formula can be obtained in the limit of vanishing diffraction, namely

$$P = cF \frac{2}{1+\cos\gamma} \tag{2}$$

where γ is the half focus-angle. The power *P* in (2) is that of a plane wave (1), if the focus-angle becomes zero.

Up to now no exact theoretical solutions have been available for conical reflecting targets. Hence, the use of this target type in strong focused fields like in HITU applications is less recommendable [4]. Other approaches to the determination of total acoustic output power are calorimetric procedures [5] or measurements by means of thermal expansion in combination with changes in buoyancy [6]. Both procedures take advantage of the absorption of the ultrasound wave in a target medium and monitor changes either of the temperature or the buoyancy.

In comparison to the radiation force balance technique, target heating and expansion do not depend on the sound field distribution, hence, fields of strong focused HITU transducers cause no additional problems during measurements. On the other hand, measurements by means of the radiation force balance are well established in the metrology of ultrasound fields, promising high precision and reliability and, therefore, they provide a safe basis for the expansion of the measurement range up to high power fields.

Measurement setup

The radiation force balance measurements were performed in arrangement "A" (Fig. 2, in accordance with IEC 61161 (2006) [7]), with an absorbing target (Ø 136 mm) placed above the HITU transducer (Imasonic, frequency 1.5 MHz, radius of curvature 100 mm, aperture 105 mm). A variable distance between the transducer and the target could be set by a translation stage. The transducer was driven with a sinusoidal waveform (R&S Signal Generator SMX), amplified by a 500 W power amplifier (Amplifier Research, 500A100A). The net electrical power feed into the transducer input was measured by means of a power meter (R&S Power Reflection Meter - NRT plus sensor head Z8) and the applied voltage with an rms level meter (Racal Dana 9393). The temperature of the water bath and the transducer was monitored during the whole measurement procedure.

Results

In a first attempt, the dependence of the measured electro-acoustic radiation conductance *G* on the distance to the transducer was investigated. Assuming a half focus-angle of γ=32.5°, the total acoustic output power was calculated in accordance with Eq. 2 and the electro-acoustic radiation conductance *G* was determined using

$$G = \frac{P}{U_{in}^2}, \qquad (3)$$

where U_{in} is the rms voltage applied to the transducer. To protect the target from damage the output power was limited to 200 mW for these measurements.

Fig. 3 shows a decline of *G* with increasing distance, which is typical of radiation force measurements. Possible reasons are a combined action of absorption losses and acoustic streaming in water and the finite target size. The slope is roughly independent of the target position, in front of the focus, in the focal region and behind focus.

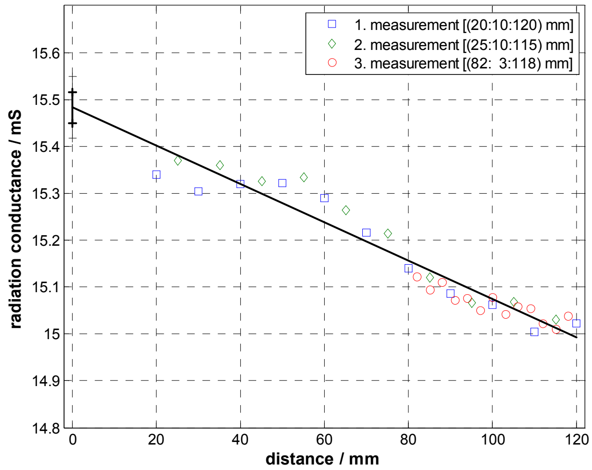

Figure 3: Dependency of radiation conductance *G* on the distance between transducer and target (nominal focus at 100 mm).

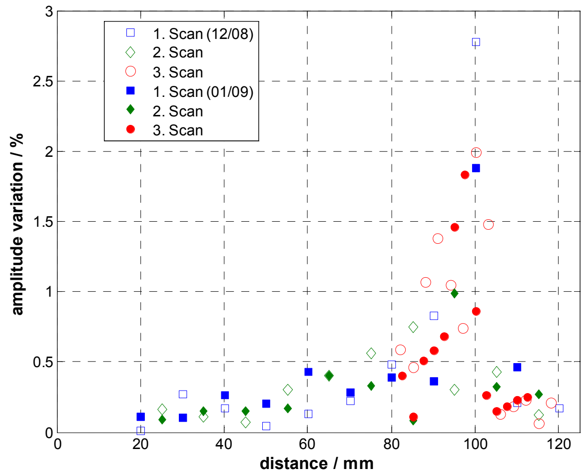

Figure 4: Dependency of amplitude variations of the radiation force, acquired by sub wave-length changes of the target position, on the distance between transducer and target (nominal focus at 100 mm).

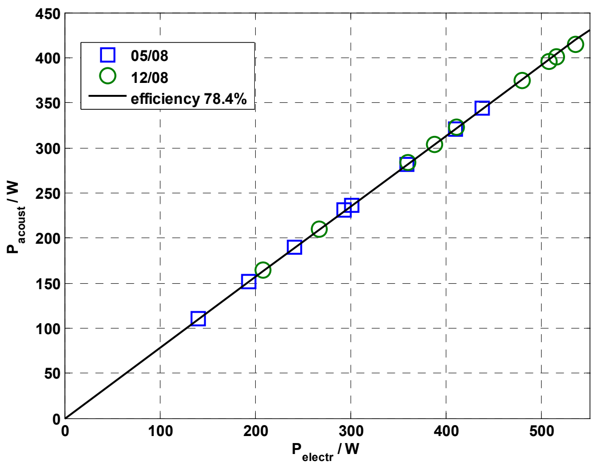

Figure 5: Total acoustical output power vs. electrical net input power.

In order to compensate for a possible standing-wave field due to target reflectivity, each measurement result in Fig. 3 has been averaged from measurements with sub wave-length changes of the target distance. The sub wave-length variations of the radiation force themselves are shown in Fig. 4. There is a pronounced effect in the focus. The reason is obviously that the wave reflected (or scattered back) by the absorbing target, which is to be regarded as a small unwanted target imperfection, arrives over the entire transducer surface in a coherent way if, and only if, the target is in the focal plane. In conclusion, there is an increased variability of radiation force results obtained close to the focus (see Fig. 4) but upon averaging over sub wave-length distance changes, there is no longer a focal anomaly (see Fig. 3) and formula (2) is applicable irrespective of the target position.

In further experiments the relationship between the total acoustic output power and the applied net electrical power was measured (Fig. 5). Up to an acoustic power of 420 W the transducer showed a stable efficiency of 78.4 %.

	Effect	Uncertainty (Type B)	
		Half-width of rect. prob. distribution	Standard uncertainty %
1	Sound field geometry	± 0.8 %	0.46
2	Speed of sound (small signal)	± 0.2 %	0.12
3	Gravity constant	0.0 %	0.0
4	Balance measurement	± 0.7 %	0.40
5	Distance correction	app. ± 0.5 %	0.29
6	Non-ideal target behaviour	± 1.9 %	1.10
7	Target heating	$\pm \frac{1}{3} \frac{P_{on} - P_{off}}{P_{on}}$	0.81
8	Focussing corr. factor (± 5°)	± 2.6 %	1.47
9	Reproducibility	± 0.5 %	0.29
		Pythagorean sum:	**2.14**
		* k (k=2)	**4.3**

Table 1: Contributions to the uncertainty of power measurements in HITU fields (f=1.5 MHz, P=400 W).

The estimation of the uncertainty budget for the performed high power measurements is mainly based on the established data for regular power measurements below 20 W. Additional contributions are due to target heating and the unknown field distribution (no. 7 and 8 in Tab. 1). The uncertainty contribution of target heating is assessed to be one third of the difference between the acquired "sound on" and "sound off" results, which takes into account the fact that the heat from the previous measurement cycles partly remains in the target. A further, major contribution is caused by the unknown amplitude distribution of the sound field, which leads to an uncertainty of the effective opening angle and, hence, of the correction factor for focused sound fields (no. 8 in Tab. 1). Future measurements of the sound field distribution may reduce this contribution to the uncertainty budget.

Summary

A radiation force balance arrangement for the investigation of an HITU transducer was developed and validated. The maximum power achieved with this setup was more than 400 W total acoustic output power. Considering all contributions, the estimation of the uncertainty budget yields 4.3 % (k=2) for measurements in the high power range.

Future steps are the extension of the measurement range up to a power of 500 W and a reliable determination of the opening angle. This requires further efforts in the development of measurement devices withstanding high intensity ultrasound fields.

Acknowledgements

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