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Studies of the cavitational effects of clinical ultrasound by sonoluminescence: 1. Correlation of sonoluminescence with the standing wave pattern in an acoustic field produced by a therapeutic unit

T G Leighton†, M J W Pickworth‡, A J Walton† and P P Dendy‡

† Cavendish Laboratory, University of Cambridge, Cambridge, UK
‡ Department of Medical Physics, Addenbrooke's Hospital, Cambridge, UK

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Abstract. A Therasonic 1030 (Electro-Medical Supplies) therapeutic ultrasound generator operating at 1 MHz continuous wave was used to insonate aerated water at two temperatures, 22 °C and 37 °C. Using various acoustically reflecting materials, sound fields were set up with different standing wave components. Measurements of the acoustic pressure variations on the axis of the sound fields were made using a needle hydrophone and the results were compared with photographs of the spatial distributions of the image intensified sonoluminescent light output. The near field region was used, thereby simulating the clinical situation.

Sustained sonoluminescence was observed for nominal intensities of 3 W cm^{-2}, and acoustic reflections of greater than 40%. Under these conditions, if sonoluminescence did not appear spontaneously it could always be induced by rotating the transducer. Whenever bands of maximum light output formed they correlated closely with the pressure antinodes in the standing wave pattern. Very little light was produced by travelling wave fields.

1. Introduction

When gas bubbles of a suitable size in a liquid are subjected to high intensity acoustic pressure fields, they grow isothermally during the expansion phase of the sound cycle and collapse adiabatically. As the bubble radius reaches a minimum value, the gas contained within the bubble may reach temperatures of several thousand degrees; high enough to produce electronically excited molecules and free radicals, which can either radiate back to the ground state, or recombine radiatively to produce sonoluminescence (Walton and Reynolds 1984). Spectral measurements, and experiments that employ radical scavengers, show that sonoluminescence originates mainly from the recombination of free radicals (Sehgal *et al* 1980). Since the production of light indicates the presence of free radicals, sonoluminescence would indicate at least the potential for biological damage.

Therapeutic ultrasound is currently used in continuous wave or pulsed modes, with frequencies of 1 or 3 MHz, and nominal output intensities of a few W cm^{-2} (Allen and Battye 1978). Sound directed into the human body may undergo partial reflection by discontinuities (e.g. bone, tissue variations, fluid sacs), thereby setting up standing waves. This study simulates such conditions using a physiotherapeutic unit with 1 MHz continuous wave ultrasound at an intensity of about 3 W cm^{-2} (spatial average), and high gain image intensification to observe any sonoluminescence.

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Wagner (1958) suggested that sonoluminescence originates at the pressure antinodes of a standing wave field but did not check the positions of these pressure antinodes. Conversely Graham *et al* (1980) reported the presence of considerable sonoluminescence from travelling waves, but they too did not quantitate the nature of the sound field, so it is possible that there was a standing wave component. The sound field set up by a Therasonic transducer, in laboratory simulations, can contain a range of standing wave components as a result of reflections off the liquid surface, container walls and absorbers (Tyszka, personal communication). To obtain meaningful results, it is necessary to measure the sound field with a hydrophone in the region where sonoluminescence is being recorded. Therefore this study aims to correlate the spatial distribution of sonoluminescence with the standing wave component of the sound field.

2. Methods

The apparatus was arranged as in figure 1 and the ultrasound generator was a Therasonic 1030 (Electro-Medical Supplies). The water temperature in the large bath was thermostatically controlled to within 1 °C of 22 °C or 37 °C. A sample cell, measuring 10.1 cm by 2.6 cm and 4.2 cm deep, containing aerated water was used for two of the three experiments. The end of the cell nearest the transducer was an acoustically transparent acetate window and the whole cell was painted black to prevent sonoluminescence originating inside the large water bath being scattered up into the optical system. An acoustic reflector was positioned at the back of the cell—either a thick brass block (27.5 mm) of high acoustic reflectivity, or a thin brass plate (0.75 mm) of intermediate reflectivity. To obtain the lowest acoustic reflectivities, i.e. most similar to a travelling wave system, the sample cell was removed and the experiment was performed in the large water bath, which was lined with several layers of wire wool to act as an acoustic absorber.

The acoustic pressure on the axis of the transducer in the region of interest was determined using a needle hydrophone (Dapco NP10-3). This had been calibrated against a membrane hydrophone (Duck, personal communication) which had been calibrated at the National Physical Laboratory. The position of the hydrophone relative to the transducer was determined, to within 0.1 mm, using an adapted micropositioner.

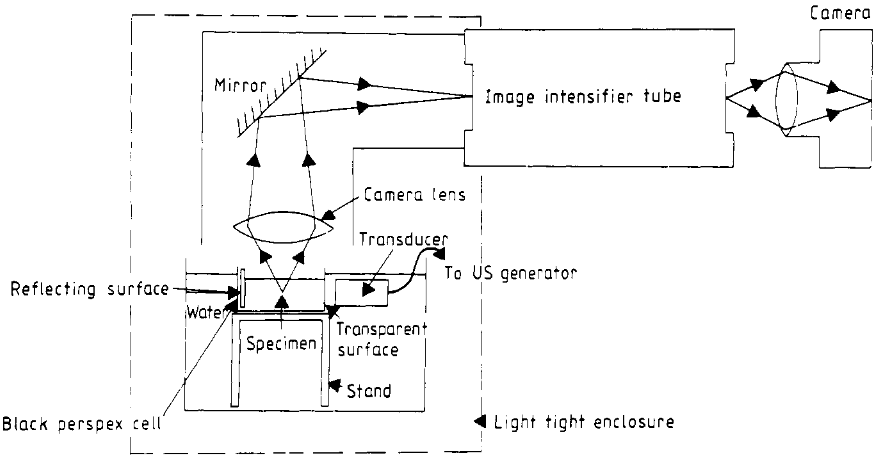

Figure 1. Schematic diagram of apparatus.

The output characteristics of the Therasonic were measured using a UWII Biotec force balance. Further details are given in the paper by Pickworth *et al* (1988). For the majority of these experiments the acoustic intensity was 3.3 W cm^{-2}, although in the final experiment a spontaneous malfunction in the Therasonic 1030 produced an output of 10 W cm^{-2}. For a travelling wave, a Therasonic intensity of about 3.3 W cm^{-2} corresponded to a reading of between 0.3 and 0.4 MPa on the hydrophone.

The hydrophone was removed while sonoluminescence was recorded. This was done by photographing the output phosphor of the image intensifier (EMI type 9912, with a bialkali photocathode) with a Nikon F2 camera. Each point of light recorded

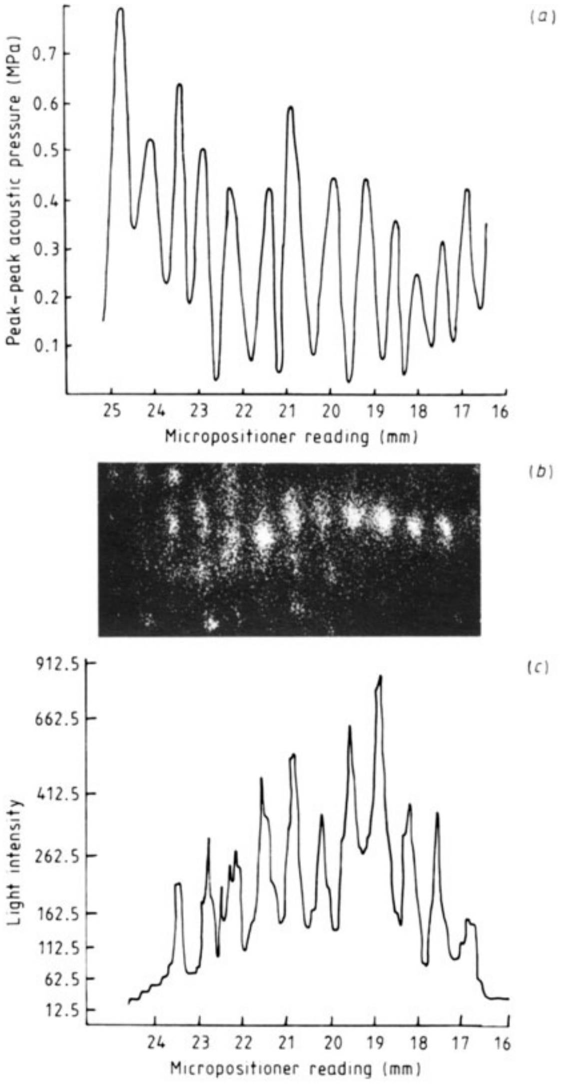

Figure 2. Results obtained with the brass block reflector at 22 °C, showing (*a*) Peak-to-peak acoustic pressure as measured with the needle hydrophone; (*b*) Photograph of the appearance of the corresponding sonoluminescence as seen through the intensifier; (*c*) Light intensity (as measured in relative units). (*a*), (*b*) and (*c*) have a common abscissa.

on the negative represents a single photon which entered the microscope objective, and released a single photoelectron from the input photocathode of the image intensifier. Walton and Debenham (1980) describe the image intensifier system and its associated optics in more detail. The film (Kodak Tri-X) was developed in a standardised manner, and the densities across each negative measured by a microdensitometer (Joyce, Loebl and Co. Ltd MkIIIB), using the known H-D curve for the film-developer combination. Thus the relative light intensities could be measured in arbitrary units and compared. With the ultrasound off, the light intensity noise was 0.08 units.

All measurements were taken in the near field (i.e. within 10 cm of the transducer) as in clinical practice, and the transducer insonated the region of interest from the right as seen in figures 2-5.

The proportion of a given sound field which is standing wave, expressed as a percentage, is calculated from the peak-to-peak acoustic pressure maximum at an

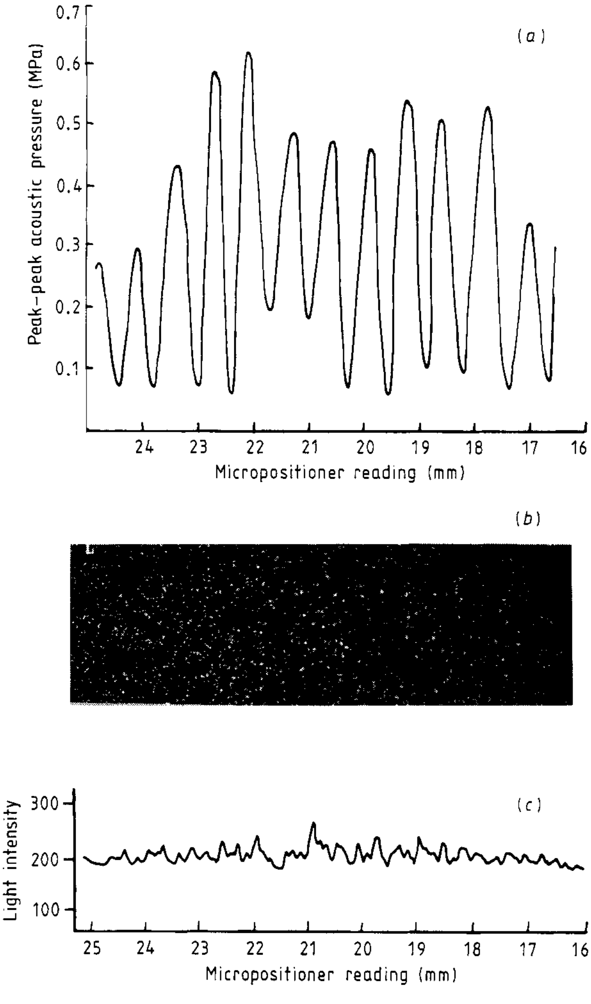

Figure 3. Results obtained for the brass block at 37 °C. (*a*), (*b*) and (*c*) are as in figure 2.

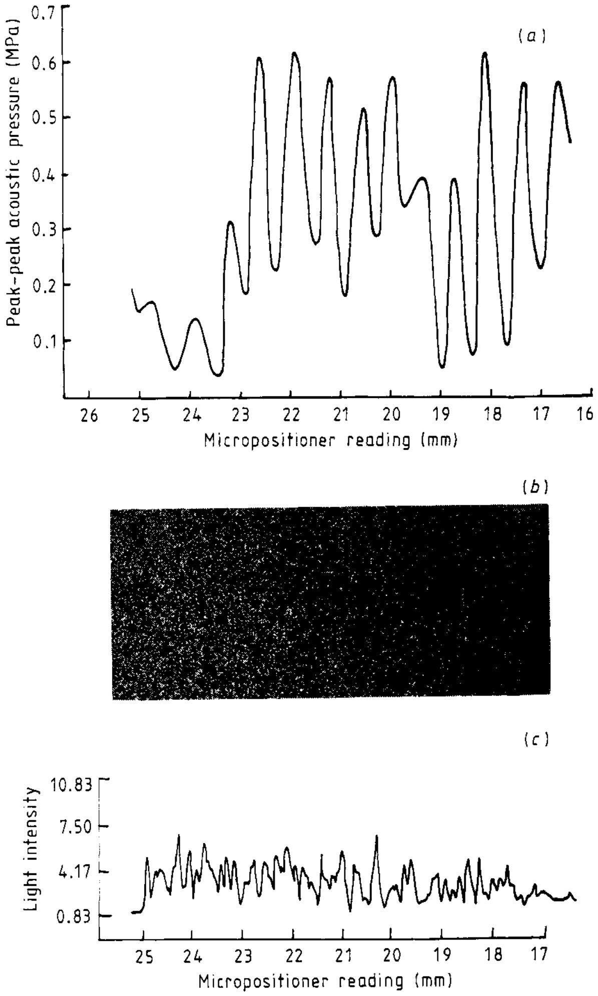

Figure 4. Results obtained for the thin brass plate at 22 °C. (*a*), (*b*) and (*c*) are as in figure 2.

antinode $P_{\max}$, and the pressure minimum at the adjacent node $P_{\min}$, from the relation

$$(P_{\max}-P_{\min})/(P_{\max}+P_{\min})\times 100\%.$$

Where bands of light are seen, average values are quoted across this region of the sound field.

Rocking the transducer often encouraged sonoluminescence. This was not due to the removal of bubbles from the face of the transducer, as the transducer was regularly cleaned of bubbles.

3. Results

3.1. *Thick brass block*

When the 27.5 mm thick brass block was placed at the end of the cell (figure 1) and the water bath was maintained at 22 °C, the sound field was found to be 79% standing

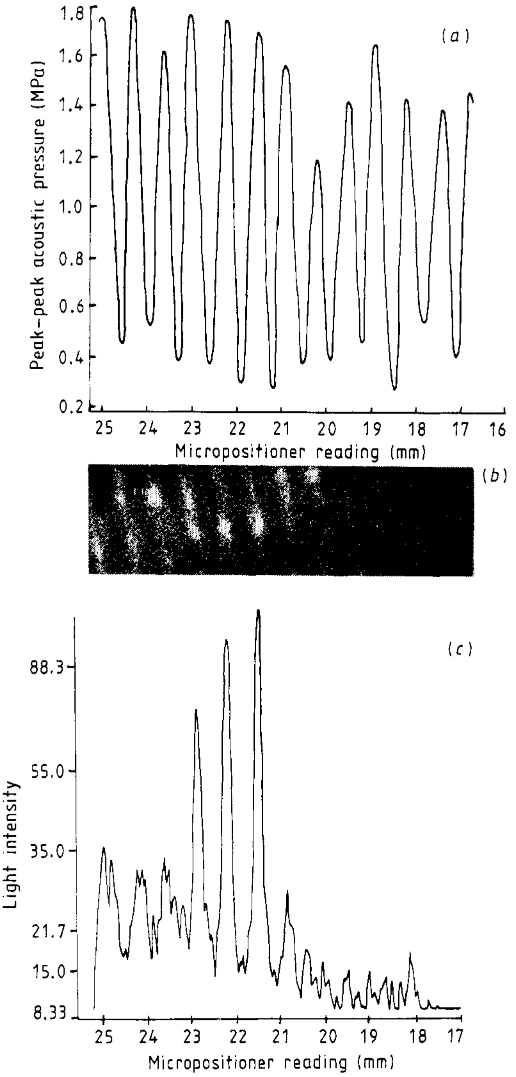

Figure 5. Results obtained for the thin brass plate at 37 °C. (*a*), (*b*) and (*c*) are as in figure 2. In figure 5(*a*) the mean pressure amplitude is about 1 MPa. This is consistent with the spontaneously high output of 10 W cm^{-2} from the generator noted in the methods section. The occurrence of bands is not solely due to these augmented pressures, because bands were also seen from this geometry with mean acoustic pressures of about 0.4 MPa.

wave on average (figure 2(*a*)). Clear bands of light were seen (figure 2(*b*)), with maxima of intensity of up to about 1000 units (figure 2(*c*)). The bands appeared approximately 10 s after switching on the ultrasound although unbanded sonoluminescence was observed sooner. The light bands coincide closely with the positions of the pressure antinodes as calculated from the complete hydrophone trace. Occasional apparent mismatches are due to errors in precise measurement of the position of individual pressure antinodes with the hydrophone.

At 37 °C, the acoustic field was on average 59% standing wave (figure 3(*a*)), and the sonoluminescence was roughly uniform over the field of view with an intensity of around 200 units (figures 3(*b*) and 3(*c*)).

3.2. Thin brass plate

When the 0.75 mm brass plate was placed at the end of the cell, the acoustic field was 40% standing wave at 22 °C (figure 4(*a*)). No bands of light were seen (figure 4(*b*)): the average intensity of sonoluminescence was around 5 units (figure 4(*c*)).

At 37 °C, the sound field was 61% standing wave (figure 5(*a*)), and clear bands of light were seen (figure 5(*b*)) peaking at intensities of 100 units (figure 5(c)). As with the thick brass block, light bands were positioned at regions of the sound field where the standing wave component was greatest. Good correlation between the position of the light bands and the pressure antinodes is again observed.

3.3. Absorber

From the hydrophone measurements, the standing wave component was estimated to be less than 2%, at either 22 °C or 37 °C. No bands of light were seen in either case. At both temperatures, when the ultrasound was first switched on, sonoluminescence was seen to flash evenly over the screen (but at very low intensities) for 1-2 s. Because our comparative measurements of intensity require a long time exposure (typically 20 s), no difference could be measured between exposures with the ultrasound on and those with it off. However, the subjective estimate was that light intensities during the flash were below one unit of intensity.

Regardless of the reflector used, sonoluminescence sometimes did not appear until a minute or so after first switching on the ultrasound. An oscillatory rotation (rocking) of the transducer about a vertical axis passing through its centre, of order ±20°, and with a period of 1-2 s, always helped to initiate sonoluminescence. Rocking is not an arbitrary motion introduced into this experiment, but an attempt to simulate the motion an ultrasonic transducer makes over a patient's body in physiotherapy. If clear light bands formed, they did not fade when rocking stopped. In experiments where bands did not occur, the sonoluminescence always faded once rocking ceased. Provided that the transducer was rocked if necessary, the presence or absence of bands of light in any given sound field showed 100% reproducibility.

4. Discussion

These results show conclusively that bands of sonoluminescence appear at the pressure antinodes in a standing wave field. The standing wave field is complex (for example, with the brass block at 22 °C the proportion of standing wave in the region of the bands varied between 68% and 92%), but the intensity of the light in the bands correlated well with the magnitude of the standing wave ratio at different points in the field. The acoustic reflectivity of the brass block was higher than that of the brass plate and since the appearance of sonoluminescence is associated with the standing wave pattern, it would be expected that bands of light would appear when the average standing wave proportion was highest. Bands were indeed seen when the brass block was used at 22 °C (79% standing wave) and when the brass plate was used at 37 °C (61%), but not with the block at 37 °C, nor with the plate at 22 °C.

Pickworth *et al* (1988) found that the sonoluminescence produced by a Therasonic unit increased with temperature between 22 °C and 45 °C. The most likely explanation for the absence of light bands when the brass block was used at 37 °C is that cavitation had been confined to the region close to the transducer (Walton and Reynolds 1984). The presence of bubbles close to the transducer could also contribute to the apparently anomalous behaviour of the standing wave ratio.

Experimental arrangements in which there was little or no standing wave component failed to produce any persistent sonoluminescence and any sonoluminescence associated with travelling waves was very small. Furthermore, the banding pattern suggests that strong sonoluminescence is associated with standing waves.

Two factors contribute to the time delay before bands appear. First, bubbles may need to grow to resonant size by rectified diffusion before unstable cavitation can occur. However, theoretical calculations suggest that this process should take no longer than a few milliseconds. Second, bubbles will have to migrate to pressure antinodes.

Two other observations merit discussion:

(1) On switching on the ultrasound there was an immediate light flash that was quickly extinguished. This applies to all reflecting surfaces.

(2) Rocking the transducer caused similar flashes of light.

The most likely explanation is that when sound is switched on, or when the beam scans across the bubble field, previously non-oscillating bubbles start to oscillate. Initially, the radial motion of the bubble wall contains transients which decay to leave the steady-state oscillation. One of the authors (TGL) has produced numerical solutions of the equations describing bubble wall motion (Neppiras 1980), which take account of these transients. Results show that the transients enhance some compressions, with the temperature of some bubbles reaching more than 2000 K. High-speed photography of bubbles in a 10 kHz acoustic field has recently confirmed the action of these transients.

Sacks *et al* (1982) noted that if a test-tube filled with biological material was insonated, bioeffects were greatly increased by slowly rotating the test-tube. Church *et al* (1982) postulated that, in stasis, the acoustically active gas bubbles and the biological material would be well separated. The former, being below resonant size, gather at pressure antinodes, whilst the single cells collect at the pressure nodes as they are greater than resonant size. Church *et al* then suggested that motion of the test-tube disturbs the acoustic field, resulting in the possibility of cells coming into close proximity with violently oscillating bubbles, leading to increasing damage. Our observations suggest that this mixing process may not be the whole explanation and that any disturbance of the sound field resulting from relative motion of the transducer and specimen may increase the bubble activity itself.

The acoustic reflectivities encountered biologically range from a few per cent (e.g. 3% between muscle and kidney) to values comparable with those in the above experiments. The higher acoustic reflectivities are found for interfaces between lung and any adjacent biological material (of order 70%) and for interfaces involving bone (of order 60% reflectivity) (Wells 1977). Reflectivities of nearly 100% will be present at the tissue-air interface diametrically opposite the transducer in a body, although a 1 MHz beam will have been attenuated by about 60% (pressure amplitude) after passing through 10 cm of tissue. In conclusion, the intensity of sonoluminescence is related to the standing wave ratio and when the standing wave component is high, strong banding effects at the pressure antinodes are frequently observed.

Sonoluminescence can be produced in water at the power levels, and with the transducer movements, employed in physiotherapy, and with the acoustic reflectivities occasionally encountered in practice.

Acknowledgments

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Résumé

Etude par sonoluminescence des effets de cavitation des ultrasons utilisés en clinique: 1. Corrélation de la sonoluminescence et du système d'ondes stationnaires produit par un générateur à usage thérapeutique.

Les auteurs ont utilisé un générateur d'ultrasons à usage thérapeutique Therasonic 1030 (Electro-Medical Supplies), fonctionnant en onde entretenue à 1 MHz, pour irradier de l'eau aérée à deux températures, 22 °C et 37 °C. A l'aide de matériaux présentant des réflections acoustiques différentes, ils ont établi des champs sonores comportant des ondes stationnaires de caractéristiques diverses. Ils ont effectué des mesures de variations de pression acoustique sur l'axe des faisceaux sonores à l'aide d'un hydrophone de type aiguille et ils ont comparé les résultats aux données de photographies des distributions spatiales révélées par la lumière sonoluminescente amplifiée. Ils ont considéré la région de champ proximal, simulant ainsi les conditions cliniques. Une sonoluminescence soutenue a été observée pour une intensité nominale de 3 W cm^{-2}, et des réflectances acoustiques supérieures à 40%. Dans ces conditions, si la sonoluminescence n'apparaissait pas spontanément, elle a toujours pu être induite par rotation du transducteur. Quelles que soient les structures de bandes de luminescence maximale produites, elles ont toujours été corrélées aux ventres de pression du système d'ondes stationnaires. Les champs d'ondes progressives n'ont produit que peu de lumière.

Zusammenfassung

Untersuchungen der Kavitationsoffekte von klinischem Ultraschall durch Sonolumineszenz: 1. Korrelation zwischen Sonolumineszenz und Stehwellenmuster in einem akustischen Feld das von einem therapeutischen Ultraschallgerät erzeugt wurde.

Ein Therasonic 1030 therapeutischer Ultraschallgenerator, betrieben bei 1 MHz kontinuierliche Wellen, wurde benutzt zur Beschallung von kohlensaurem Wasser bei zwei Temperaturen, 22 °C und 37 °C. Unter Verwendung verschiedener akustisch reflektierender Materialien wurden Schallfelder mit verschiedenen Stehwellenkomponenten hergestellt. Messungen der Schwankungen des akustischen Druckes entlang der Achse des Schallfeldes wurden wurden mit Hilfe eines nadelförmigen Unterwasserempfängers durchgeführt. Die Ergebnisse wurden verglichen mit Photographien der räumlichen Verteilungen der bildverstärkten Sonolumineszenz-Lichtausbeute. Dabei wurde das Nahfeld verwendet, um die klinische Situation zu simulieren. Dauersonolumineszenz wurde beobachtet für nominale Intensitäten von 3 W cm^{-2} und akustischem Sättigungsreflexionsgrad größer als 40%. Unter diesen Bedingungen konnte die Sonolumineszenz, wenn sie nicht spontan auftrat, durch Rotation des Wandlers induziert werden. Wenn immer sich Bänder maximaler Lichtausbeute bildeten, waren sie eng korreliert mit den Druckbäuchen in den Stehwellenmustern. Sie wenig Licht wurde erzeugt durch Wanderfelder.

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