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Studies of the cavitational effects of clinical ultrasound by sonoluminescence: 3. Cavitation from pulses a few microseconds in length

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Abstract. Sonoluminescence can readily be seen when aerated water is insonated with continuous wave therapeutic ultrasound at room temperature but is not easily observed when short pulses of diagnostic ultrasound are used. In this work an ultrasound generator, operating in the region of 1 MHz and capable of producing pulses of different length and repetition rate, was used for insonation. The pulse repetition rate of the ultrasound was fixed at 1 kHz since this is characteristic of diagnostic machines, and a series of thresholds for sonoluminescence was obtained for two transducers, one therapeutic and one diagnostic, as the number of cycles in each pulse was varied. Sonoluminescence was observed for pulses of a few cycles, but the ultrasound intensity threshold for onset increased sharply with decreasing pulse length. Under all conditions tested, sonoluminescence was more readily sustained than initiated. At about 20 cycles per pulse, peak negative pressures of about 400 kPa initiated sonoluminescence. These conditions are well within the range of some regimens for Doppler ultrasound and not far removed from the diagnostic situation.

1. Introduction

Transient or stable cavitation of gas-filled bubbles may occur in a liquid that is subjected to high intensity ultrasound. During a transient collapse, the gas in the bubbles reaches temperatures at which free radicals are formed (Edmonds and Sancier 1983). On recombination, these free radicals produce sonoluminescence (Walton and Reynolds 1984) and thus the production of light from a medium, on insonation, may indicate a potential biological hazard.

Sonoluminescence is readily seen in our experimental system when a tank of water is insonated with continuous wave therapeutic ultrasound (Pickworth *et al* 1988) and is primarily associated with the establishment of a standing wave pattern (Leighton *et al* 1988). It is also observed with pulsed physiotherapeutic ultrasound, where the shortest pulses are typically 2 ms. These pulses are still long enough for a standing wave field to be set up in water whenever a reflection occurs. We wish to know whether cavitation can occur with the same experimental arrangement under diagnostic ultrasound conditions where the pulse length may be too short for a standing wave system to be set up but other cavitation mechanisms may be operating, e.g. non-linear distortion forming shocks which may excite cavities (Bacon 1984, Duck and Starritt 1984). Crum and Fowlkes (1986) have observed luminescence flashes characteristic of violent cavitation from ultrasonic pulses as short as one cycle at a frequency of 1 MHz, implying that there is a mechanism for cavitation when standing waves are not present. However they used duty cycles of between 1:3 and 1:20, i.e. pulse repetition frequencies of between 250 and 50 kHz, whereas in the diagnostic situation duty cycles are more typically 1:1000 (Duck *et al* 1985). As discussed in several earlier papers (Hill *et al* 1969, Ciaravino *et al* 1981, Pickworth *et al* 1988), pulsed enhancement of cavitation can occur if the length of the off-time is carefully chosen.

The present work involves an alternative approach to that of Crum and Fowlkes. The frequency of the ultrasound from the generator was set at about 1 MHz to provide comparisons with previous work, and the pulse repetition frequency was fixed at 1 kHz. The RF output voltage (V) to the transducer and the number of cycles in each pulse (N) were then varied and, for each value of N, the threshold value of V for sonoluminescence was found. Sets of threshold values for two transducers have been obtained and measurements with a needle hydrophone and a force balance were used to convert values of V into figures for the spatial peak negative pressure and the ultrasound intensity. Possible implications for the diagnostic use of ultrasound are discussed.

2. Materials and methods

2.1. The ultrasound generator

The ultrasound generator was built at the University of Surrey and comprises three separate modules: a signal oscillator and control module, a power supply providing stabilised HT and EHT voltages, and an ultrasonic power output unit with tuning and amplitude controls. Further details of the generator are given in the Appendix.

When coupled to an appropriate transducer the ultrasound generator can provide: (i) a variable intensity output, from zero to the maximum limit for the transducer; (ii) a sound wave of frequency approximately 1 MHz tunable over a narrow range; (iii) continuous wave or pulsed ultrasound; (iv) in pulsed mode, any number of complete cycles between 1 and 99; (v) a pulse repetition rate of between 100 Hz and 1 kHz.

2.2. The transducers

The ultrasound generator was used to drive two different transducers. One was a physiotherapeutic transducer of the type designed for use with a Therasonic 1030 generator (Electro-Medical Supplies). The manufacturer's figure for its effective radiating area was 440 mm^2. A needle hydrophone (see below) was used to check that the position of the last axial maximum was consistent with this figure. To drive this transducer the generator was tuned to give the maximum negative pressure. The measured frequency was 1.09 MHz, the frequency at which this transducer was designed to operate.

The second transducer was a diagnostic transducer NE 4161 (Nuclear Enterprises), with an effective radiating area of 299 mm^2 and designed to operate at 1.5 MHz. Since this frequency could not be obtained with our generator, a calibrated needle hydrophone (Dapco NP 10-3) and oscilloscope were used to find the maximum negative pressure. Within the frequency range of the generator, this was obtained with a driving frequency of 0.97 MHz.

The needle hydrophone was also used to determine the temporal shapes of the pulses produced by the two transducers. The appearance of the pulse was recorded on an oscilloscope so that build-up and decay times could be studied.

2.3. *Calibration of output*

Two methods were used to calibrate the ultrasound output. First, for each transducer the position of the spatial peak was found using the needle hydrophone. This was approximately 10 cm from each transducer. The value of the peak negative pressure was then found at this point as the peak RF power output was vari[illegible] Se[illegible]ond, the spatial average, temporal average intensity (I_{sata}) was found from [illegible]on pressure measurements using a calibrated force balance (Anson *et al* 1989). [illegible] these measurements a transducer–target distance of 10 cm, which corresponded to the position of the focus of the diagnostic transducer, was selected.

Since the pulse repetition frequency of the generator is known, a value for the spatial average pulse average intensity (I_{sapa}) can be found from the relation

$$I_{sapa} = I_{sata} \times 1000/N. \tag{1}$$

We shall equate I_{sapa} to I_{satp} (the spatial average temporal peak intensity). This is exact for a square pulse envelope. As a result of pulse build-up and decay times of a few microseconds, it is only an approximation which will be better at 99 cycles per pulse than at 10 cycles per pulse. I_{satp} is the intensity figure given on most therapeutic units.

2.4. *Experimental set-up*

The experimental arrangement is shown in figure 1 and has been described in detail elsewhere (Pickworth *et al* 1988). Essentially the transducer insonates a tank of water

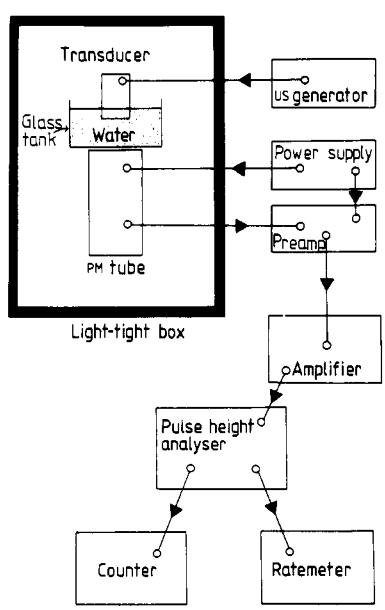

Figure 1. Schematic diagram of apparatus.

and sonoluminescence is detected by a photomultiplier tube (RCA 8575R) coupled to a pulse height analyser. For the present set of experiments a limited range of pulse heights was selected from the middle of the spectrum, i.e. large enough to be above the region of electronic noise and pulse pile-up but not so high that the background count has become insignificant.

The presence or absence of sonoluminescence was investigated for both transducers using a fixed pulse repetition frequency, but the number of cycles in each pulse varied between 1 and 99 and the peak output from the generator varied between 0 and 300 V. Observations were made as the pulse length was both increased and decreased to its final value at fixed intensity, and as the intensity was both increased and decreased to its final value at fixed pulse length.

Light pulses were counted for 30 s and sonoluminescence was assumed to have occurred if a series of counts was significantly greater than the background over the selected pulse height range.

3. Results

3.1. *Pulse shapes*

The temporal shapes of the pulses produced by the two transducers are shown in figure 2. N is defined as the number of complete cycles within the time that the generator is counting out the pulse duration. Thus N includes the pulse build-up time but not the decay time. Both pulses reached 95% of their maximum amplitude within a few microseconds (8-9 μs for the therapeutic transducer, 6-7 μs for the diagnostic transducer). From this point until the pulse from the generator is terminated and the hydrogen thyratron fired, there is only around 5% variation in the maximum and minimum pressure values. So far the two pulses are very similar. However, with the therapeutic transducer the decay time significantly lengthens the effective pulse duration. The acoustic pressure has only decreased to about 80% of its maximum value 10 μs after the end of the generator's pulse, and only after about 17 μs has there been

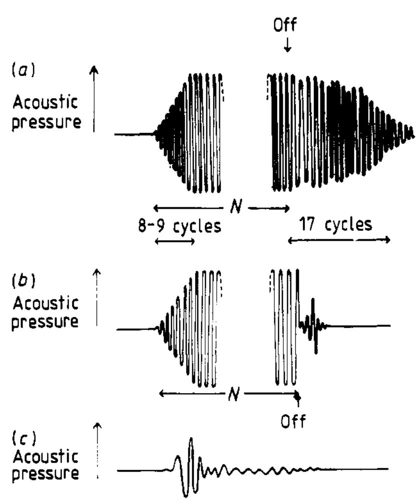

Figure 2. Temporal pulse shapes of (*a*) the therapeutic transducer, (*b*) the diagnostic transducer and (*c*) the diagnostic generator and transducer used by Crum and Fowlkes (1986) at their respective spatial peaks. Not to scale.

a significant reduction. Thus at short pulses the effective pulse length will be much greater than the measured pulse length with this transducer (figure 2(*a*)). In contrast, with the diagnostic transducer the pulse stops almost instantaneously (figure 2(*b*)).

3.2. Calibration

The hydrophone was used to relate scale readings on the RF power output meter to spatial peak temporal peak negative pressure amplitudes. A hydrophone calibration factor of 2.25 ± 0.05 kPa mV^{-1} had been obtained by cross calibration against a membrane hydrophone (F A Duck private communication) which had been calibrated at the National Physical Laboratory. Results are shown in figures 3 and 4. The maximum peak negative pressure attainable with the therapy transducer was 1.4 MPa. For the

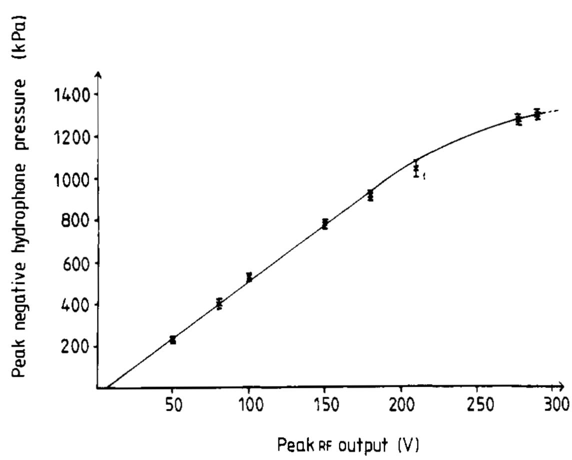

Figure 3. Peak negative hydrophone pressure against scale reading of RF voltage output for the therapeutic transducer. The highest pressure at which the hydrophone was calibrated was 850 kPa. Above 1200 kPa the hydrophone may be underestimating the peak negative pressure but the difference from linearity is 10% at most.

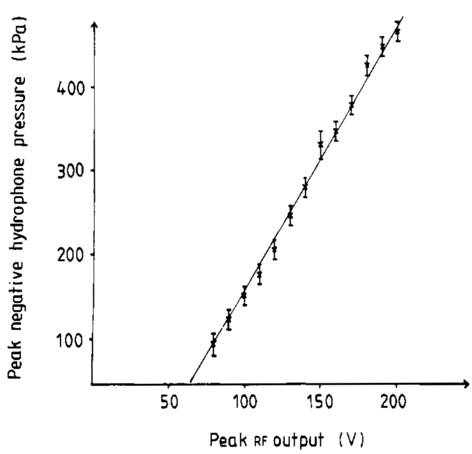

Figure 4. Peak negative hydrophone pressure against scale reading of RF voltage output for the diagnostic transducer.

diagnostic transducer, which was not being driven at its resonant frequency, the maximum peak negative pressure attainable was only 480 kPa.

Spatial average temporal average intensities were measured using the force balance for different numbers of cycles per pulse and results are shown in figures 5 and 6. From these figures and equation (1), values of I_{sapa} may be calculated. Table 1 shows results for both transducers. The errors quoted include the systematic error introduced by pulse build-up and decay.

3.3. Observations of sonoluminescence

A typical background count for the middle of the selected range of pulse heights was 950±200 in 30 s. The luminescent count rate was first monitored near the middle of the range of pulse heights. If the count rate was greater than the average background count plus three standard deviations at this pulse height (1550 for the quoted background), then sonoluminescence was assumed to be present. If the count was less

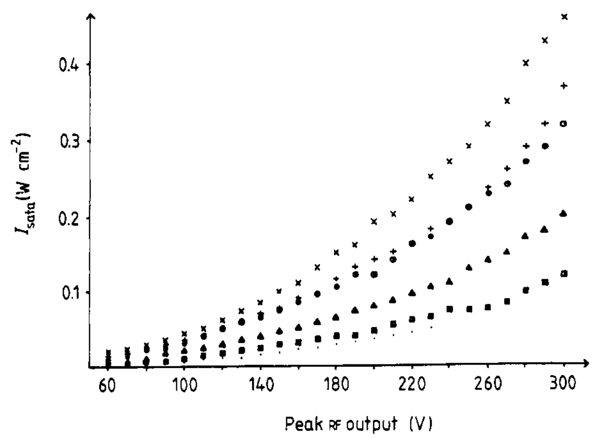

Figure 5. Spatial average temporal average intensity against scale reading of RF output for the therapeutic transducer for several pulse lengths: × × ×, 99 cycles per pulse; + + +, 80 cycles per pulse; ⊙ ⊙ ⊙, 60 cycles per pulse; △ △ △, 40 cycles per pulse; ⊡ ⊡ ⊡, 20 cycles per pulse, · · ·, 10 cycles per pulse.

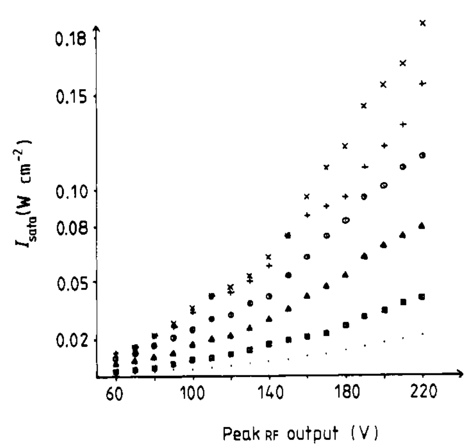

Figure 6. Spatial average temporal average intensity against scale reading of RF output for the diagnostic transducer for several pulse lengths. Symbols refer to the same pulse lengths as in figure 5.

Table 1. Average values of I_{sapa} over the range of pulse lengths investigated. For the diagnostic transducer, the pulse lengths used to obtain these averages were $N = 10$, 20, 40, 60, 80 and 99. For the therapeutic transducer, the average is based on $N = 40$, 60, 80, 99. For shorter pulses the systematic error due to pulse shape became appreciable.

Peak RF O/P (V)	Diagnostic transducer $I_{sapa} \pm$ SD (W cm^{-2})	Therapeutic transducer $I_{sapa} \pm$ SD (W cm^{-2})
60	0.17 ± 0.02	-
70	0.22 ± 0.05	0.23 ± 0.03
80	0.27 ± 0.03	0.31 ± 0.04
90	0.34 ± 0.04	0.40 ± 0.05
100	0.42 ± 0.03	0.49 ± 0.06
110	0.50 ± 0.04	0.58 ± 0.08
120	0.56 ± 0.04	0.71 ± 0.10
130	0.65 ± 0.05	0.84 ± 0.11
140	0.76 ± 0.07	0.95 ± 0.11
150	0.89 ± 0.07	1.09 ± 0.17
160	1.06 ± 0.05	1.22 ± 0.17
170	1.18 ± 0.05	1.38 ± 0.17
180	1.32 ± 0.08	1.59 ± 0.19
190	1.54 ± 0.09	1.77 ± 0.18
200	1.69 ± 0.11	1.92 ± 0.12
210	1.84 ± 0.14	2.10 ± 0.20
220	2.04 ± 0.12	2.32 ± 0.28
230	-	2.56 ± 0.24
240	-	2.76 ± 0.32
250	-	3.08 ± 0.38
260	-	3.36 ± 0.40
270	-	3.64 ± 0.32
280	-	4.11 ± 0.37
290	-	4.42 ± 0.35
300	-	4.90 ± 0.33

than this, the count was taken at other pulse heights. A count that was consistently between one and three standard deviations above background at three or more pulse heights was taken as a positive result. This method takes into account the fact that sonoluminescence can occur across a wide range of pulse heights.

The results obtained using the therapeutic transducer are summarised in figure 7. On a graph of RF voltage output from the generator against the number of cycles in each pulse, three regions can be seen. In the upper region, sonoluminescence could always be detected. In the lower region, sonoluminescence did not occur, or was too faint to be recorded as significant (detection limit about 5×10^5 photons per second). There is also a broad middle region where sonoluminescence occurred sometimes, while at other times it did not.

The principal feature of the graph is that as the number of cycles per pulse (N) decreases, the peak RF output required to generate cavitation increases. With the powers that could be generated with the present system, the smallest value of N for which sonoluminescence could be observed was $N = 7$. No sonoluminescence could be observed for $N = 1$. The results for the diagnostic transducer are shown in figure 8. This graph has the same form as figure 7, but there are some differences. The minimum value of N at which sonoluminescence can be observed is now 20, and the band of uncertainty is narrower.

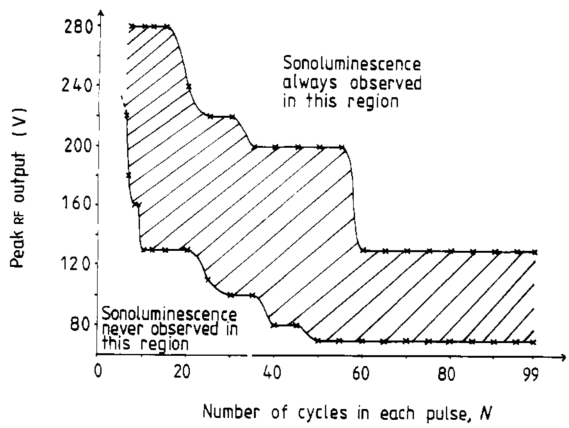

Figure 7. Peak RF output against the number of cycles per pulse for the therapeutic transducer, showing three distinct regions. The shaded area represents settings where sonoluminescence sometimes occurs.

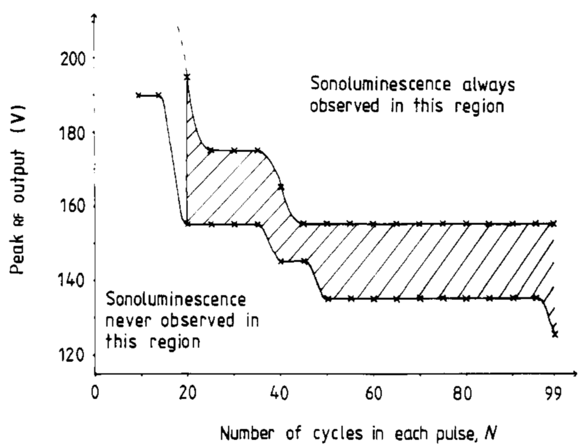

Figure 8. Peak RF output against the number of cycles per pulse for the diagnostic transducer, the shaded area again representing the region of uncertainty.

In both figures 7 and 8 the appearance or non-appearance of sonoluminescence in the middle region is in part random but is influenced by whether the output is being turned up or down to reach the value specified. As shown in figure 9, for the diagnostic transducer, if either the power or the number of cycles per pulse is being increased to its final value, sonoluminescence is less likely to be detected, whereas if the power is first turned up to its maximum value, then turned down, or the number of cycles per pulse is decreased from 99 to its final value, sonoluminescence, once initiated, is sustained at the lower values. Note that figures 7 and 8 show the boundaries between the three regions and not experimental points.

4. Discussion

This work shows that it is possible to record sonoluminescence from water on insonation with pulses of a few microseconds duration when relatively long time intervals between pulses are used. In general, the results with the two types of pulse are similar. The

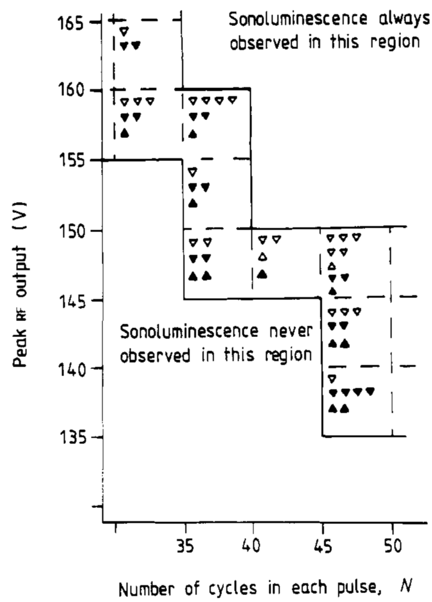

Figure 9. Expanded section of figure 8 showing how the appearance of sonoluminescence depends on whether I or N is being turned up or down: △, sonoluminescence present, I or N being increased; ▲, sonoluminescence absent, I or N being increased; ▽, sonoluminescence present, I or N being decreased; ▼, sonoluminescence absent, I or N being decreased. Note that nearly all the open triangles are pointing downwards.

threshold for sonoluminescence detection remains virtually unchanged between 60 and 99 cycles per pulse. For the therapeutic transducer the threshold power output is 70-130 V (figure 7), corresponding to an intensity (I_{sata}) at 99 cycles per pulse of between 0.03 and 0.07 W cm^{-2} (figure 5), while for the diagnostic transducer the threshold power output is 135-155 V (figure 8), corresponding to an intensity of 0.06-0.08 W cm^{-2} at 99 cycles per pulse (figure 6). The corresponding peak negative pressures are 330-660 kPa for the therapeutic transducer (figure 3) and 270-330 kPa for the diagnostic transducer (figure 4). If the threshold is expressed as a pulse average (table 1) the values of 0.23-0.84 W cm^{-2} and 0.70-0.97 W cm^{-2} for the therapeutic and diagnostic transducers respectively are of the same order of magnitude as that found for therapeutic ultrasound which utilises long pulses of 2000 cycles, or continuous wave ultrasound.

In the regions of uncertainty in figures 7 and 8, the appearance of sonoluminescence depends partly on whether N and/or I is being decreased or increased in order to reach the values at which measurement is to be made. If N or I is decreased towards its final value, sonoluminescence is more likely to be present, indicating that it is more easily sustained than initiated.

When the number of cycles in the pulse becomes very small the peak RF output required for sonoluminescence rises sharply. Using the data in figures 5 and 6 it may be shown that this rise occurs at ultrasound intensities (I_{sata}) of about 0.02-0.03 W cm^{-2} for each transducer.

For the diagnostic transducer this rise is at $N = 20$. For the therapeutic transducer the sharp rise appears to be for shorter pulses ($N = 10$). However, because of the long decay time for the therapeutic transducer (figure 2(a)) the effective pulse length is about 10-15 cycles longer than the recorded value of N. Crum and Fowlkes (1986) mention a ringing-down effect in their pulses. Their acoustic pressure waveform was not a single cycle (see figure 2(*c*)). However, their pulse closely resembled the scanning mode pulse of a diagnostic ultrasound system. A diagnostic scanner will produce a very short pulse but it is still not a single cycle. All work in which pulses of a few cycles are used is subject to practical limitations on pulse shape. For pulses of 1 or 2 cycles it may also be of importance whether the pulse is positive- or negative-going first.

It has been suggested that sonoluminescence is associated with standing waves and Leighton *et al* (1988) showed that strong sonoluminescence depends on the presence of a high standing wave content. If standing waves are a prerequisite for sonoluminescence, observation of sonoluminescence at low values of N would imply that any light must have come from the bottom of the water tank. For example, with a pulse of 20 cycles, standing waves only occur within 13.6 mm of the bottom of the tank ($\lambda = 1.36$ mm in water). We have examined the insonated tank with an image intensifier. As either N or I is decreased, bands of sonoluminescence (see Leighton *et al* 1988) gradually fade away, but they are never stronger near the reflecting surface. The implication is that there is some sonoluminescence associated with short pulses of travelling waves.

Flynn (1982) has calculated that microsecond pulses of ultrasound can generate transient cavitation in water, although the temporal peak intensities required are 10-30 W cm^{-2}. In our work, a practical limit to the lowest value of N at which sonoluminescence could be recorded was set by the power that could be achieved with the generator. Extrapolation of figures 7 and 8 to one or two cycles per pulse is not possible but the results do not contradict Flynn's calculation. Some diagnostic systems now in clinical use generate microsecond length pulses of ultrasound with temporal peak intensities in excess of 100 W cm^{-2} (Carstensen and Flynn 1982) and with peak negative pressures of 2 MPa (Duck *et al* 1985), whereas in our work the maximum values of peak negative pressure are 1.4 MPa for the therapeutic transducer and 480 kPa for the diagnostic. For Doppler equipment, pulse durations of 20 or 30 cycles per pulse are not uncommon and pulses of 90 cycles are possible (Duck *et al* 1987). Pulse repetition frequencies are between 1 and 10 kHz, peak negative acoustic pressures can be up to 3 MPa, and temporal average intensities may be as much as 0.4-0.8 W cm^{-2}. These figures are summarised in table 2 (*a*) and (*b*) and suggest that cavitation could occur in water under conditions created by diagnostic and pulsed Doppler ultrasound equipment at 1 MHz. It should also be noted that most commercial diagnostic and Doppler equipment generates ultrasound at frequencies between 2.25 and 7.5 MHz.

Table 2. (*a*) Operating conditions encountered with diagnostic and pulsed Doppler ultrasound systems.

	Pulse length (cycles per pulse)	Peak negative pressure (MPa)	I_{sata} (W cm^{-2})
Diagnostic equipment[a]	1-5	0.1-3.90	0.02-0.4
Doppler equipment[c]	2-48	0.2-2.60	0.04-0.8[b]

[a] From Duck *et al* (1985).
[b] Spatial peak temporal average values.
[c] From Duck *et al* (1987).

Table 2. (*b*) Conditions under which sonoluminescence was observed in water at 1 MHz.

	Shortest pulse length at which sonoluminescence is observed (cycles/pulse)	Peak negative pressure required (MPa)†	Corresponding I_{sata} ($W\ cm^{-2}$)
Diagnostic transducer	20	0.33	0.02
Therapeutic transducer	15-20 including ringing	1.0	0.03

† Averaged over the area of the hydrophone detector (0.6 mm diameter).

It is well established that the likelihood of cavitation decreases with increasing frequency (Esche 1952) so it seems likely that if the experiments reported in this paper were repeated at higher frequencies, for a given value of N the threshold intensities required to generate sonoluminescence would be higher. However, it is not clear how the threshold intensities for sonoluminescence would be affected if the frequency was varied while the actual duration of the pulse was kept constant.

In conclusion, we have demonstrated that sonoluminescence can occur when the time interval between pulses is relatively long, although at short pulse lengths the ultrasonic intensity required to initiate sonoluminescence is high. Hence the output characteristics of diagnostic imaging and Doppler equipment should be such that the peak intensity and the pulse duration are as low as practicable, thereby ensuring that the chance of sonoluminescence occurring is minimised.

Acknowledgments

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Appendix

Further details on the ultrasound generator are given below.

The high-frequency pulse generator provides a continuous train of pulses which feeds the power output stage via a 50 Ω line driver. An additional feed controls a countdown timer stage which in turn provides a gating signal to the mode control switch. Pulsed or continuous wave modes are provided. The output of the mode control switch feeds the control input of the power output stage.

In pulsed mode, the counter stage is initiated by a trigger pulse from a rate oscillator. When the counters reach zero another pulse is generated, thus the initiating trigger pulse and the 'count complete' pulse define the exact number of pulses within the pulse envelope. The two pulses toggle a bistable which controls the output power amplifier.

The output stage was complicated by the techniques used to generate the variable frequency drive and pulse counting and gating circuitry for the pulsed mode. The grid of the power output valve is driven by rectangular pulses which, due to the band pass characteristics of the tuned circuit loading the anode, produce a sine wave output signal. The quality of the sine waves produced will depend on the '*Q*' of the tuned circuit loading the output. A high '*Q*' tuned circuit gives good waveforms but produces a slow build-up and decay envelope in the pulsed mode.

To enhance the build-up of the pulse, the output valve is overdriven by modulating the cathode with a decaying pulse at the start of each pulse. The decay of the pulse is damped by applying a short circuit to the tuned circuit by way of a hydrogen thyratron which, when fired, absorbs the energy in the tuned circuit.

The mode control stage gates the ultrasonic oscillator to produce the required high-frequency pulse burst. This is amplified and buffered by a unity-gain push-pull stage before feeding the grid of the output valve. Amplitude control is achieved by varying the HT voltage of the amplifying stage. The signal across the transducer is capacitatively attenuated and rectified to provide a peak RF voltage detector.

Electrical tuning was achieved using plug-in ferrite-cored fixed inductors and an additional variable capacitor in parallel with the transducer for fine-tuning control. The design enables the generator to be robust enough to survive being driven at maximum output into a mismatched load.

Résumé

Etude des effets de cavitation par sonoluminescence avec les ultrasons utilisés en clinique.

La sonoluminescence peut être observée facilement lorsqu'une onde ultrasonore continue, du type de celles utilisées en thérapie, est émise vers de l'eau aérée, mais n'est pas aisément mise an évidence lorsque l'on s'adresse à un faisceau ultrasonore pulsé, du type de ceux utilisés en diagnostic. Dans le cadre de ce travail, les auteurs présentent un générateur à ultrasons opérant dans la gamme de fréquence 1 MHz et capable de produire des impulsions de longueur et de fréquence variables, utilisé pour l'étude. La fréquence de répétition des impulsions ultrasonores à été fixée à 1 KHz, ce qui correspond aux caractéristique des machines utilisées en diagnostic; une serie de seuils de sonoluminescence a été obtenue pour deux transducteurs, un à usage thérapeutique et un à usage diagnostique, en faisant varier le nombre d'oscillations dans chaque impulsion. La sonoluminescence a été observée pour des impulsions de quelques cycles, mais le seuil de puissance du faisceau ultrasonore permettant le déclenchement de la sonoluminescence augmente rapidement quand la longueur de l'impulsion diminue. Pour toutes les conditions testées, il a été plus facile d'entretenir la sonoluminescence que de la déclencher. Pour des impulsions comprenant environ 20 cycles, le pic de pression négative nécessaire pour déclencher la sonoluminescence est de l'ordre de 400 kPa. Ces conditions correspondent tout à fait à celles recrutées dans le cas des appareils 'Doppler' et ne sont pas très loin de celles des appareils de diagnostic.

Zusammenfassung

Untersuchung der Hohlraumeffekte von klinischem Ultraschall durch Sonolumineszenz: 3. Hohlraumbildung durch Pulse von einigen Mikrosekunden Länge.

Sonolumineszenz kann leicht beobachtet werden, wenn mit Luft durchsetztes Wasser mit kontinuierlichen Wellen therapeutischen Ultraschalls bei Zimmertemperatur beschallt wird, ist aber schwer zu sehen bei kurzen diagnostischen Ultraschallpulsen. In der vorliegenden Arbeit wurde ein Ultraschallgenerator mit einer Betriebsfrequenz von etwa 1 MHz und der Möglichkeit Pulse verschiedener Länge und Wiederholungsrate zu erzeugen, für die Beschallung verwendet. Die Pulswiederholungsrate des Ultraschalls wurde auf 1 kHz festgelegt, da dies charakteristisch ist für diagnostische Geräte. Man erhielt eine Reihe von Schwellenwerten für Sonolumineszenz für zwei Wandler, einen therapeutischen und einen diagnostischen, wenn die Anzahl der Zyklen in jedem Puls variiert wurde. Sonolumineszenz wurde beobachtet bei Pulsen mit wenigen Zyklen, wobei der Schwellenwert der Ultraschallintensität zur Auslösung der Sonolumineszenz stark ansteigt mit abfallender Pulslänge. Unter allen getesteten Bedingungen wurde die Sonolumineszenz eher aufrechterhalten also ausgelöst. Bei etwa 20 Zyklen pro Puls führen Spitzendrucke von 400 kPa zur Sonolumineszenz. Diese Bedingungen liegen innerhalb der Gesetzmäßigkeiten für Doppler-Ultraschall und nahe an Situationen, wie sie in der Diagnostik auftreten.

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