LETTERS TO THE EDITOR

Temporal peak intensity

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Two methods for measurement of the maximum intensity I_m as defined by the National Council for Radiation Protection are compared. One uses a calibrated broadband hydrophone; the other uses a spherical radiometer. A suggestion is made for measurement of a spatial average, temporal maximum intensity to be used in the nearfield of a transducer.

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INTRODUCTION

Recent observations indicate that, for pulsed ultrasound as used in medical diagnosis, temporal peak intensity is a better predictor of certain biological effects than temporal average intensity. In exposures of *Drosophila* larvae to low-temporal-average-intensity, microsecond-length pulses of 2-MHz ultrasound, an increase in the peak intensity by a factor of 3 above the threshold for effects, resulted in 70% killing. On the other hand, when the peak intensity was held constant and the temporal average intensity was varied through the pulse repetition rate, an increase in the temporal average intensity by a factor of 100 resulted in an increase in killing only from 60% to 80% (Child *et al.*, 1981).

Until recently, standards groups have been reluctant to provide definitions of peak intensities. The need was not apparent in the absence of clear cut biological effects of low-temporal-average-intensity, pulsed ultrasound; and furthermore, the techniques for measuring peak intensities were not readily available.

There still may be reason to avoid the use of the peak intensity concept. It is very likely that cavitation-related mechanisms are responsible for the above mentioned effects. If that is the case, the only completely adequate description of the physical cause of the biological effect may be the time dependent pressure in the acoustic pulse (Carstensen and Flynn, 1982). However, the biomedical community has become accustomed to specifying magnitude of ultrasonic exposures in terms of intensity rather than pressure. Hence, the peak intensity may serve a useful purpose, at least until specific mechanisms for potential biological effects of pulsed ultrasound have been established.

The National Council on Radiation Protection and Measurements, through its Committee No. 66 on Biological Effects and Exposure Criteria for Ultrasound (1983) has recently defined two peak intensities: The maximum intensity

$$I_m = p_m{}^2/2\rho c, \tag{1}$$

and the instantaneous maximum intensity

$$i_m = p_m{}^2/\rho c, \tag{2}$$

where p_m is the maximum absolute value of the pressure in the pulse, ρ is the density of the medium, and c is the speed of sound in the medium. This relationship between pressure and intensity is valid as long as a reasonable approximation to a plane, traveling wave is maintained (Beissner, 1982). Since these quantities are the same except for a factor of 2 and since the former maintains the relationship between pressure amplitude and intensity which applies for continuous waves and long pulses, we will confine our remarks to I_m.

Two methods for the measurement of I_m suggest themselves. The most obvious uses a calibrated miniature hydrophone to measure the pressure directly. Fortunately, devices which are adequate for this purpose are now available commercially. The second method uses the time averaged radiation pressure of the pulsed ultrasound. We conducted a brief test to assure ourselves that the two methods give substantially the same results.

I. CALIBRATED HYDROPHONE

A Medicoteknisk Institut, miniature, PVDF film hydrophone was used in our tests. We checked its calibration by comparison with a series of spherical steel radiometers ranging in size from 0.16 to 0.32 cm in diameter (Dunn *et al.*, 1977) and found the combined response of the hydrophone and its associated preamplifier to be -125 ± 1 dB vs 1 V/Pa over the frequency range from 1–7 MHz. This was in substantial agreement with the calibration supplied by the manufacturer.

II. RADIATION FORCE

The temporal average radiation pressure is proportional to the temporal average intensity which is just the energy per unit area per pulse multiplied by the pulse repetition frequency. After being assured that the pulse is not affected by the repetition rate in a given experimental arrangement, one can simply increase the repetition frequency until the radiation force is great enough to produce a suitable deflection of the spherical radiometer which is to be used as a detector.

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The average intensity measured by a radiometer is

$$I_{av} = f_p \int p(t)^2/\rho c \, dt, \tag{3}$$

where f_p is the pulse repetition frequency and the integration of instantaneous pressure $p(t)$ is over a single pulse. In terms of the maximum intensity I_m, Eq. (3) becomes

$$I_{av} = 2I_m f_p \int \left(\frac{p(t)}{p_m}\right)^2 dt. \tag{4a}$$

By writing the integral in terms of the envelope of the pressure pulse $p_{env}(t)$, we have

$$I_{av} = I_m f_p \int \left(\frac{p_{env}(t)}{p_m}\right)^2 dt. \tag{4b}$$

The last step relies on the fact that the average value of $(p_m \cos t)^2$ over a half period is $p_m{}^2/2$. Thus, Eq. (4b) is useful only if the amplitude of the signal changes slowly enough that an envelope of the pulse can be defined clearly. This was the case in all of our tests. For "pathologically" short pulses, Eq. (4a) may be required. In those cases, I_m serves mainly as a translation of a measured p_m from pressure to intensity terminology.

Since pressure has been normalized, one requires only relative measurements. For this purpose, any reasonably broadbanded, uncalibrated transducer would suffice. Since the receiver output voltage is directly proportional to pressure, the corresponding voltages can be substituted for pressures in the equations above. The integrals become constants which characterize the pulse of the source. If the received pulse is digitized, the integration of Eq. (4a) may be carried out numerically. Fortunately, only simplified equipment is required in most cases to use Eq. (4b); for, if the rf carrier and pulse repetition frequency are not synchronized, an oscilloscope screen will display the envelope of the pulse quite clearly.

For illustration, one of our tests used a ½-in.-diam, damped piezoceramic disk, resonant at 2.3 MHz as a source transducer. The PVDF, miniature hydrophone described above was placed in the farfield and the received pulse was recorded. When driven by a 1 μs burst of 2.3 MHz, the acoustic pulse rose to a maximum within 1 μs and decayed to $1/e$ of the maximum by 2 μs. The peak voltage was used for the calibrated hydrophone determination of I_m. The pulse envelope, ignoring the calibration, was used to evaluate the integral in Eq. (4b). The hydrophone was replaced by a 0.25-cm-diam steel sphere and the displacement caused by the radiation force of the ultrasound field was used to determine the temporal average intensity. Sample calculations are summarized in Table I.

In a series of approximately 20 tests at 1, 2, and 5 MHz, the two methods agreed on the average to within 10%. The choice of methods is arbitrary. As long as one can rely upon the calibration of a hydrophone, that technique has the advantages of simplicity.

Many biological and medical exposures to ultrasound are in the nearfield of the sources. Even the pulse shape varies from place to place in this region of the field. Since the sound distribution in the nearfield is very complex, it is frequently useful to describe the exposure in terms of the spatial average intensity. For pulsed sources which are used in the nearfield, we suggest a modification of the radiation pressure technique above to determine an effective spatial-average, temporal-peak intensity. Let the temporal-average, total acoustic power be determined with a large absorbing radiation force target. Then, let the spatial-average, temporal-average intensity be the total power divided by the area of the radiating surface. To determine the integral in Eq. (4b), use a pulse recorded with the hydrophone in the farfield. The use of the farfield pulse shape is completely arbitrary, but is probably justified in light of the complexity of the nearfield. Finally, let the spatial-average, temporal-peak intensity be the temporal average intensity divided by this integral.

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TABLE I. Sample calculations of the maximum intensity for a 2.3 MHz, 1-μs pulse.

(1) Calibrated hydrophone	
Maximum voltage v_m	0.3 V
Hydrophone calibration	− 125 dB vs 1 V/Pa
Maximum pressure p_m	6×10^5 Pa
Temporal maximum intensity I_m	10 W/cm^2
(2) Radiation pressure	
Pulse repetition frequency f_p	83 000 Hz
$\int \left(\frac{V_{env}(t)}{v_m}\right)^2 dt$	1.1×10^{-6} s
Temporal average intensity I_{av}	0.9 mW/cm^2
Temporal maximum intensity $I_m = I_{av/Kf_p}$	10 W/cm^2

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