where $\cos\theta_i = x_i/x$. The evaluation of the integral is then straightforward and turns out to be approximately ($kl_\nu \ll 1$)

$$p \approx -\frac{3\mu}{(2)^{\frac{1}{2}}\pi} U k^2 a_1 a_2 (l_\nu/x) \frac{e^{i(kx-\omega t+\pi/4)}}{x} \cos\theta_1 \cos\theta_3 \frac{\sin\alpha}{\alpha} \frac{\sin\beta}{\beta} \times \left(\cos\theta_3 - \frac{1}{3\cos\theta_3}\right) \quad (4)$$

$$\alpha = (ka_1/2)\cos\theta_1; \quad \beta = (ka_2/2)\cos\theta_2.$$

It is interesting to express the shear generated sound pressure in terms of the sound pressure $U\rho c$ that would be generated if the piston were oscillating in a direction normal to its plane, generating a plane wave with the same velocity amplitude U as before. The expression (4) can then be written

$$|p| \approx \frac{3\sqrt{2}}{\pi}(kl_\nu)(l_\nu/x)^2 \rho c U \sin\alpha \sin\beta(\cos^2\theta_3 - \tfrac{1}{3})/\cos\theta_2. \quad (5)$$

As an example, assuming a frequency of 10 000 cps, we get a shear generated sound pressure of the order of 180 db below $U\rho c$.

* Supported by Contract N5 ori-07861 with the Office of Naval Research.

[1] M. J. Lighthill, Proc. Roy. Soc. (London) A211, 564 (1952).

Note on the Calibration of Disk Recording by Interference Patterns

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BOTH the sets of interference fringes described by Mr. B. B. Bauer in his paper "Calibration of Test Records by Interference Patterns" [27, 586 (1955)] will be found to be situated in the plane in which the unmodulated disk groove, considered as a cylindrical mirror, forms an image of the light source. The improvement in definition which he observes when a camera, focused on the disk surface, is stopped down can thus equally well be achieved by focusing on this plane at full aperture. For observation purposes this has the advantage of using the maximum brightness of the pattern.

The origin and nature of the two sets of interference fringes was described by us in a paper[1] published in 1953, which has apparently not come to the notice of Mr. Bauer. We did not, as Mr. Bauer has done, use the distribution of these fringes as a measure of the modulation on the disk. However, the realization that the light patterns and fringes were situated in a focal plane not on the disk surface enabled us to calculate the effect of diffraction on the distribution of light intensity near the theoretical edge of the pattern. We then described[1,2] a measuring method which, like the fringe measuring method, can be shown to avoid diffraction errors, but unlike the latter, imposes no abnormal restrictions on the lowest recorded amplitude which can be measured. Our method employs unfiltered white light and, embodying the principle of the sextant, requires the observer to make an edge-to-edge coincidence of two images of the light pattern situated in the focal plane. This adjustment is independent of any pattern "swinging" which may occur when the disk rotates, since both patterns swing together and it is their relative position which is of interest and not their position with respect to any static measuring point, such as scale-mark in the optical system. It is of interest to note that this method is equally applicable to direct measurement of "B" lines (to use Mr. Bauer's terminology) since it enables the position of any part of the pattern, edge or B-line, to be measured independently of any pattern swinging which may be present.

The patterns from high-frequency tones with a recorded amplitude lower than those used in Mr. Bauer's illustrations will be found to be complicated by the presence of A-lines at the edge. This obscures observation of the B-lines and the use of optical filters to sharpen the latter only aggravates the situation by permitting the survival of A-lines (fringes) of a high order. All methods of observation of the patterns are, of course, susceptible to this effect, but any one which employs white light, when the A-fringes toward the pattern edges are rapidly obscured, is less affected than one employing filtered or monochromatic light.

[1] P. E. Axon, and W. K. E. Geddes, Proc. Inst. Elec. Engrs. 100, Part III, No. 66 (July, 1953).
[2] Method and Apparatus for Ascertaining the Amplitude of Signal Frequency Bands on Disk Records, British Patent Specification 2102/51, January, 1951.

Ultrasonic Irradiation of the Central Nervous System at High Sound Levels*

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High level ultrasound produces, under properly controlled dosage conditions, selective changes in the central nervous system. The physical mechanism of the action of the sound requires elucidation. Some of the problems associated with determining the physical mechanism are discussed and a preparation and procedure are described which are appropriate for accurately determining dosage relations for such a study. The quantitative results obtained with this preparation are presented.

THE high level ultrasonic method for producing selective, accurately localized lesions in brain tissue by focusing an ultrasonic beam in the region to be affected now constitutes a unique tool for neurological research and human neurosurgery.[1,2] Extensive histological studies,[3,4] on monkeys and cats, demonstrate that accurately localized selective changes can be made at a chosen region in the brain without destroying tissue between the chosen region and the area of entry of the sound into the brain. Both fibers and cell bodies can be destroyed without interrupting blood vessels traversing the lesion area, and nerve fiber tracts can be interrupted without destroying surrounding or neighboring gray matter.[1–4]

If the full potentialities of this new method of producing selective changes in brain are to be realized the physical mechanism of the action of the sound on the tissue must be understood. Previous publications[5,6] from this laboratory on the physical mechanism reported evidence demonstrating that damaging temperature levels and cavitation are not responsible for the action of the sound. This earlier work was accomplished using frogs as the biological test specimen. To further elucidate the physical mechanism, a comprehensive investigation involving the determination of the ultrasonic dosage relations, i.e., duration of exposure as a function of the acoustic variables (intensity, particle velocity, pressure, etc.), required to realize a given functional end point (paralysis of the hind legs following irradiation of the lumbar enlargement of the spinal cord) has been undertaken. The dosage relations will be determined at a variety of frequencies with the preparation under various hydrostatic pressures and at a number of base temperatures. This is essential in order to separate concomitant secondary effects from the primary action of the sound, for example, the temperature coefficient of the primary action as contrasted with the primary mechanism itself. Since mammals are the most important animal class to which this new method will be applied, it is desirable that a representative of this group be used for this dosage study. The young mouse (strain LaF1), 24 hours after birth (weight 1.2 to 1.4 g), is a convenient preparation for the following reasons:

(1) It is essentially poikilothermic,[7] that is, it possesses virtually no temperature control mechanism, so that it can be carried through reversible temperature cycles, with its temperature being reduced to nearly 0°C, without producing either physiological or morphological changes.

(2) Ossification is not complete. As determined by standard staining techniques, the tissue overlying the dorsal side of the cord is soft tissue, while that over the lateral and ventral sides shows a slight degree of ossification. Thus, acoustic absorption in the region surrounding the spinal cord is low, and no surgery need be performed in preparing the animal for irradiation.

(3) This animal is small in size so that it is possible to irradiate the desired region with a nearly uniform acoustic field with a single controlled ultrasonic pulse.

In order to realize a dosage study of the type envisioned, i.e., such that the experimental results can be interpreted with some facility to yield information concerning the fundamental physical mechanism, it is essential that the tissue of interest be exposed only once to the radiation. If multiple exposures (both temporal and overlapping spatial-temporal) are used, uncertainty arises regarding the magnitude of the residual effect[6] of the previous exposure. Data obtained with the use of multiple exposures are thus of limited value. However, the technique is useful in limiting the maximum temperature rise by the choice of an appropriate duty cycle and, therefore, may be used during the initial stage in a mechanism study in order to rule out the possibility of a damaging temperature level as the basic factor. For single exposures, the region to be affected by the sound must be irradiated with a beam which is uniform since experimental results obtained by the use of nonuniform beams are more difficult to interpret to elucidate the fundamental mechanism. Therefore, an unfocused quartz crystal is used to develop a traveling wave field. At 5% below the peak intensity, the beam width (along the length of the spinal cord) is 2.6 mm.

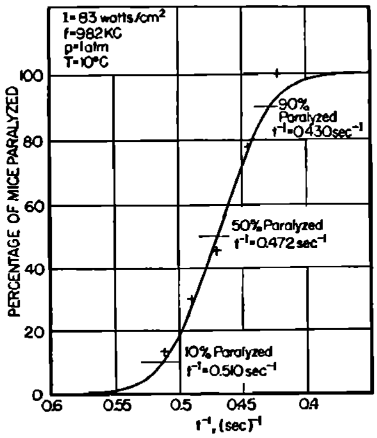

FIG. 1. Sigmoidal distribution of percentage of mice paralyzed as a function of the reciprocal of the duration of exposure at a constant sound intensity.

In the study undertaken at this laboratory, the mice are irradiated at the third lumbar vertebra. Since motor paralysis of the hind legs is the functional end point observed, the region of the spinal cord which must be altered is that containing the neurons and fibers associated with the femoral, sciatic, and obturator nerves. This region, at which the axis of the acoustic beam is centered, was determined by acoustic means. In the lumbar region, the vertebral segments are 0.67 mm long, measured from corresponding edges. Thus, nearly four vertebral segments are irradiated with an acoustic intensity variation of no more than 5%. The over-all uncertainty of the center of the third lumbar vertebra with respect to the axis of the sound field is 0.25 mm. Since the beam width at 95% of the peak intensity is 2.6 mm, it appears that the over-all accuracy of positioning the animal in the sound field is adequate.

The acoustic field is calibrated each day with a thermocouple probe which has previously been calibrated by a radiation pressure detector[8,9] utilizing a small steel sphere.

In preparing the animal for the irradiation procedure, the mouse is first cooled to render it dormant so that it can be properly positioned in the mouse holder and remain in that position until it is placed in the sound tank. The mouse holder is designed to prevent movement once the animal is properly positioned in the acoustic field. The positioning of the animal in the mouse holder is accomplished by an optical arrangement.

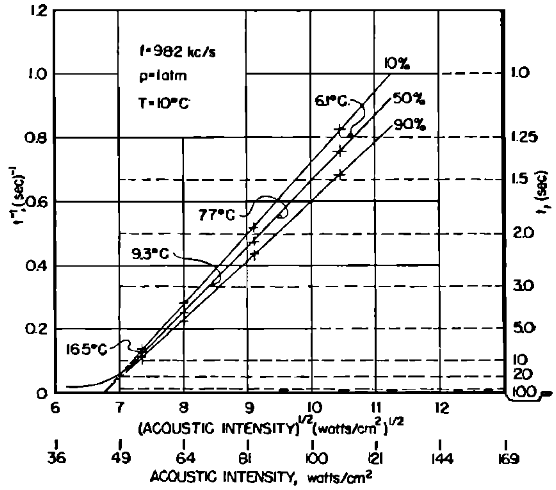

FIG. 2. Threshold region for paralysis of the hind legs of mice under ultrasonic irradiation. The reciprocal of the duration of exposure is shown as a function of the square root of the acoustic intensity for 3 percentages of animals paralyzed. The temperatures shown in the graph are the temperature increases measured by imbedded thermocouples in the spinal cords of the irradiated mice corresponding to the values of acoustic intensity and duration of exposure at the coordinate positions indicated by the arrows.

The holder containing the animal is then placed in the sound tank, which is filled with degassed 0.9% saline. Several minutes are permitted to elapse before irradiation in order that the animal can reach temperature equilibrium which is realized, as checked by measurement with imbedded thermocouples, in this period of time. When the mouse reaches equilibrium, a single acoustic pulse of rectangular envelope (having rise and decay times of several microseconds), predetermined acoustic intensity (plane wave case), and time duration is then initiated. After the cessation of the sound, the animal holder is removed from the tank and the mouse is rapidly warmed to room temperature. The animals are examined for paralysis or overt movements approximately 15 min after exposure and again after 6 hours.

TABLE I. Temperature rises measured by imbedded thermocouples in spinal cords of irradiated mice at various values of the sound intensity and duration of exposure.

t(sec)	I(w/cm²)	$I^{\frac{1}{2}}$	ΔT(°C)
7.70	54	7.4	16.5
2.88	71	8.5	9.3
1.80	90	9.5	7.7
1.25	112	10.6	6.1
0.965	140	11.8	6.0
0.865	154	12.4	5.7

Thus far, results have been obtained at a frequency of 982 kc, a hydrostatic pressure of one atmosphere, and base temperatures of 10°C and 20°C. These results show that a well-defined threshold region exists. This threshold region is defined as follows: If a large number of animals are irradiated with identical values for the acoustic field variables for various periods of time, and the percentage of animals paralyzed at each duration of exposure is plotted as a function of the reciprocal of the time duration of exposure, a sigmoid curve is obtained. A typical sigmoid curve obtained by standard statistical treatment of the data is shown in Fig. 1. Each point represents approximately 20 animals. The threshold range at the chosen values for the acoustic field variables is arbitrarily defined as the range of time durations of exposure from 10% of the animals paralyzed to 90% of the animals paralyzed. The collection of these threshold ranges for various values of a specific acoustic variable, for example, particle velocity amplitude, defines the threshold region for that variable.

Figure 2 exhibits the threshold region (with the square root of intensity as the acoustic field variable) at a frequency of 982 kc, a hydrostatic pressure of one atmosphere, and a base temperature of 10°C. The ordinate is the reciprocal of the exposure time, and the abscissa is the square root of the acoustic intensity. Time and intensities are also indicated on the coordinate axes for convenience. The plotted points are obtained from sigmoid curves similar to that shown in Fig. 1. From Fig. 2, it is seen that in the range of dosages between approximately 50 w/cm² (10-sec duration) and 120 w/cm² (1-sec duration), the relation between the values of the reciprocal of the exposure time and the square root of the acoustic intensity (at which 50% of the animals are paralyzed) appears to be linear. In this linear range, the boundary values of the threshold region, at constant intensity, differ by only 17%. At the extremities of this region, the threshold curves deviate from linearity.

In the course of this study, measurements were made of the temperature rise in the spinal cord of the mice as a function of ultrasonic dosage. This was accomplished by imbedding small thermocouples in the cord. Table I shows the results of these measurements for dosages within the threshold region. These temperature rise values are also indicated at the corresponding dosage coordinates in Fig. 2. Considering these temperature increases in the cord in conjunction with the value for the base temperature of the animal, 10°C, it can be concluded that temperature rise is not the primary factor for the observed alterations in the central nervous system. Pulsed sound with an appropriate duty cycle can be used to suppress the temperature rise resulting from acoustic absorption. The use of a pulse width of 0.4 sec and a duty cycle of 40% as reported by other investigators[10] does not, however, yield a practical advantage in this respect. Experiments were performed at this laboratory to compare single and multiple pulsing methods of irradiation. The results are shown in Table II.

TABLE II. Comparison of the temperature rises in spinal cords of irradiated mice under various pulsing procedures. Values are given for two sound intensities and three duty cycles.

I w/cm²	Sd. on (sec)	Sd. off (sec)	Duty cycle (%)	No. of pulses	ΔT (°C)	Diff. (%)
100	0.400	0.60	40	10	15.7	3.2
100	4.000	···	100	1	16.2	
100	0.100	0.90	10	10	4.3	19
100	1.000	···	100	1	5.2	
70	0.400	0.60	40	7	8.9	5.3
70	2.800	···	100	1	9.4	
70	0.100	0.90	10	10	2.5	49
70	1.000	···	100	1	3.8	

Two duty cycles were chosen for the multiple pulsing scheme (40% and 10%) to compare with a single pulse of equal total irradiation time. The experiments were carried out at two intensities. In Table II it is seen that the 40% duty factor provided a rather negligible decrease in the temperature rise compared with a single pulse of the same total exposure time, the difference being approximately 3%. At the same intensity, the 10% duty factor provides a greater advantage over the single exposure procedure, but the decrease is still only 20%. In any event, since it is possible by suitable choice of preparation to obtain the ultrasonically produced changes in the complete absence of a questionably damaging temperature increase and, since results obtained from multiple pulsing procedures are more complex to interpret, it is felt that the single pulse method constitutes the procedure of choice at our present stage of understanding of the physical mechanism.

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Historical Note on the Haas Effect

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THE writers' attention has been called to a tendency, particularly among persons more recently introduced to the problems of sound re-enforcing systems, to consider the phenomena now known as the Haas effect as something just recently discovered and understood. It may be of interest to members of the Society that one aspect of the phenomena was reported at the fourteenth meeting of the Society held at Harvard University, December 6–7, 1935. Abstracts of the pertinent papers, No. 21 by Fay and No. 22 by Hall, may be found on page 239, volume 7 of the Journal. The point which is stressed in these abstracts is that, in a sound re-enforcing system, a suitable time delay in the amplified sound produces a desirable illusion in that the re-enforced sound, as well as the direct, appears to originate at the mouth of the talker.

In a system set up for graduation exercises at Symphony Hall, Boston, time delay was introduced by installing the sound projectors 20-ft behind and 45-ft above the speaker's lectern. This arrangement gave a maximum delay corresponding to nearly 50 feet of sound travel. The directional illusion was found to be complete for this delay. By chance, the seats in the second balcony nearest the stage were substantially equidistant from the talker and from the nearer loudspeaker; a person in one of these seats found that when he moved his head a few inches, the apparent origin of the sound shifted abruptly from talker to loudspeaker. It was therefore possible with this setup to investigate the effect of time delays ranging from nearly zero to about 20 milliseconds. The illusion was perfect throughout this range, that is to say, it was impossible to get any aural indication of the direction of the loudspeakers.

At the December, 1935 meeting of the Acoustical Society a demonstration was made showing the effects on the illusion of varying the time difference and the relative intensities of the sound from two loudspeakers widely separated in the horizontal plane. The amount by which the level of the delayed source could exceed the level of the first source without destroying the illusion depended on the amount of the delay and the nature of the sound.

It was planned to find the limitations of the effect more precisely, but the reaction of the meeting to our presentation indicated that everyone who had any experience with sound re-enforcing systems knew all about the beneficial effects to be obtained by delaying the amplified sound heard by the audience. It was generally known at the time that a sound reaching an observer by two paths of slightly unequal lengths appeared to the observer as a single sound coming from a direction corresponding to the shorter path. We believed that it was not generally known that the effect is substantially unchanged when the