FIG. 2. Predicted overall sound-pressure-level change versus altitude (solid line—left ordinate) and observed A-scale data (symbols—right ordinate). Dotted line shows a linear regression of observed data.

Influence of subarachnoid structures on transmeningeal ultrasonic propagation*

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The previously observed frequency dependence of the ultrasonic threshold dose, for production of irreversible lesions in mammalian brain, is ascribed to the brain meninges. The collagenous trabeculae of the subarachnoid space, interposed between the arachnoid and the pia mater, are considered responsible by virtue of the increased elastic moduli associated with their structural supporting role. A plane three media model provides acoustical parameters of these anatomic structures. The method provides the frequency-independent lesion-threshold function \( H_{12} = 200 \text{ W/cm}^2 \text{ sec}^{-1/2} \).

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The recent observation\(^1\) of a weak frequency dependence of threshold ultrasonic dosages for irreversible structural changes in the mammalian central nervous system has raised questions of the acoustical inhomogeneity of organs, the importance of the latter in selecting dosages for specific purposes, and the range and distribution of values of the crucial parameters present. Thus, it was found\(^4\) that, in irradiating through the intact meningeal structures (though overlaying scap and skull bone were removed), the relationship between along with the changes in overall sound pressure level predicted by Eq. (1). Although there is scatter in the data, most are seen to fall very close to the slope of the curve. The dotted line shows the results of a linear regression analysis of the A-scale data. The equation for this line is

\[
L = 87 - 0.05 h \text{ dB, (2)}
\]

where \( h \) is the altitude in kilometers. The noise levels reported here are generally lower than those reported by Lane.\(^6\)

III. CONCLUSIONS

Experimental data taken on board several commercial aircraft operating at varying altitudes have shown that turbulent-boundary-layer noise received inside the aircraft varied with changes in the density and the local sound speed as predicted by existing theory.\(^2,3\)


the exposure time and the acoustic intensity delivered to
the site of interest in the organ necessary to produce
threshold lesions in the brains of adult female cats was
describable by $H^{1/2} = C(f)$, where $C$ is the “threshold
intercept function” and has a weak dependence on fre-
quency. Figure 1 shows the function $C$ versus fre-
quency with the original data, the data obtained to test the
hypothesis promoted below, and the resulting computa-
tions of the theory.

The three membranes enveloping the central nervous
system, viz., the dura mater, the arachnoid, and the
pia mater comprise the meninges. The outer mem-
brane, the dura mater, is a tough collagenous structure
offering insignificant acoustic attenuation, as shown by
in vitro measurements. 2 The dura mater closely over-
lies the thin arachnoid membrane—a delicate structure
enclosing the subarachnoid space containing the cerebro-
spinal fluid and a weblike architecture of connective
collagen fibers extending between the arachnoid and the
third membrane, viz., the pia mater. 3

It is proposed that the subarachnoid space, with its
network of collagen trabeculae, is responsible for the
observed frequency dependence of the threshold inter-
cept function. The very high bulk modulus of elasticity 4
of the collagen trabeculae is considered to yield a stra-
tum differing in acoustic impedance from that beyond
the two bounding surfaces. Further, the increased
sound velocity in these solid fibers, over that of the
liquid cerebrospinal fluid, is considered to produce a
progressively increasing phase difference as the ultra-
sonic waves traverse the subarachnoid space. These
views are supported by the observations that (1) surgical
removal of the dura mater, with the attending dis-
ruption of the subarachnoid integrity, results in in-
creased lesion size for equivalent radiation dosage,
i.e., greater intensity delivered to the site, and (2) at-
tenuation measurements made on the removed menin-
geal structures yield values too low to account for the
tenuation in intact structures.

The problem is treated as simple plane wave propa-
gation through three media of differing densities, sound
velocities, and acoustic impedances. The three-layer
configuration is considered to have plane, parallel
boundaries and the characteristic acoustic impedance
of the central layer differs from the two bounding con-
tiguous ones, which are taken to be equal to each other.
That is, the impedance of the physiological saline cou-
pling solution of the experimental arrangement is taken
to be equal to that of the parenchymal tissue of the
brain, while the impedance of the intermediate sub-
arachnoid space differs from these. The two bounding
layers are considered sufficiently long in extent, due to
the geometry of the acoustic path from transducer to
dura mater and due to the high absorption coefficient of
the brain tissue, to minimize reflected energy. The
ratio of the ultrasonic intensity incident on the saline-
meningeal boundary to that transmitted beyond the pla-
mater-parenchymal boundary can be found in any ele-
mentary text on acoustics 5 as

$$1 + \left[ \frac{1}{2} \left( \frac{Z_2}{Z_1} + \frac{Z_3}{Z_1} \right)^2 - 1 \right] \sin^2 k h,$$

where $h$ is the wave number, $l$ is the length of the in-
termediate layer, i.e., the subarachnoid space, and
$Z_1$ and $Z_2$ are, respectively, the acoustic impedances
of the equal bounding layers and the intermediate layer.
It is this function that is shown in Fig. 1. The require-
ments for a good fit are well satisfied as six data points
are available to evaluate three constants, i.e., six
equations in three unknowns. These constants provide
an average thickness of the subarachnoid space of 250μ,
a speed of sound through this region of 1800 m/sec, and
a frequency-independent value for the threshold inter-
cept function in the brain parenchyma of 200 W/cm²/
sec 1/2. It is seen that the theory predicts a successaon
of extrema, with a minimum value to occur near 7 MHz.
Experimental examination of this point was begun follow-
the theoretical prediction and the result is shown on
the figure.

The significance of these findings extends beyond
dosimetry refinements. For example, the ratio of
maxima to minima for the threshold intercept function
is approximately 4 dB. Thus, in the absence of the
skull, a round-trip ultrasonic signal may undergo as
much as an 8-dB intensity difference in those areas of
the brain where the path through the subarachnoid space
is not a multiple of a half wavelength, as may occur
near sulci. A more appropriate choice of transducer
center frequency may now be made over previous ones
determined by commercial availability, etc. It may be
considered that these findings may also contribute to
clinical diagnosis as, for example, in the detection of
subdural hematomas.

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FIG. 1. Threshold intercept function versus frequency for ir-
reversible structural changes in mammalian brain. (*) original-
data, (0) recent data obtained to test hypothesis, (solid
line) calculations from theory. The error bars are plus and
minus one standard deviation times a confidence factor in-
versely proportional to the number of data points.
Rayleigh disk in an aligned nematic liquid crystal

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If a Rayleigh disk were suspended in an aligned nematic liquid crystal there would be two torques acting on the disk: one due to the acoustic wave and the other an elastic torque due to the liquid crystal. For a disk of radius 50 μm an acoustic intensity typically of ~1 mW/cm² would orient the disk at 45° to the direction of the incident wave if the acoustic wave is directed perpendicular to the optic axis of the liquid crystal. The applicability to detection of acoustic fields is noted.

We would like to point out that if the disk were inserted in an ordered fluid such as a nematic liquid crystal the fluid itself would give a torque to counteract that of the acoustic wave. We have suspended platelets in p-methoxybenzilidene-p-n-butylaniline (MBBA), a nematic liquid crystal. The MBBA was sandwiched between two glass-plane surfaces with the optic axis of the MBBA parallel to the glass planes. This orientation was accomplished using the method of Chatelain. The elastic forces acting on the platelets suspended in the MBBA cause them to be perpendicular to the glass planes.

If the platelet is a disk of radius r we may place the origin of a coordinate system at the center of the disk with the z axis perpendicular to the plane of the disk. We then may easily calculate the torque the nematic exerts on the disk from a knowledge of \( F_r \), the elastic-free energy. According to de Gennes

\[ F = \frac{1}{2} K \int \frac{d\tau}{\alpha(\psi)} \left[ \nabla \alpha(\psi) \right]^2, \]

where \( K \) is the effective nematic elastic constant and \( \alpha \) is the angle the liquid crystal director makes with the z axis. The integration is over the volume of the liquid crystal which is assumed large compared to the disk volume. Assuming the disk axis makes an angle \( \phi \) with respect to the equilibrium director far from the disk we have the boundary condition \( \alpha(\infty) = \phi \). We take the director perpendicular to the disk at the surface of the disk and omit edge effects of the disk. For equilibrium, Eq. (2) becomes \( \nabla \alpha = 0 \). In analogy to electrostatic calculations there is a set of nonintersecting surfaces surrounding the disk over each of which \( \alpha \) is a constant. The set is a family of confocal ellipsoids

\[ x^2/(\rho^2 + \psi) + y^2/(\rho^2 + \psi) + z^2/\psi = 1, \]

where different values of \( \psi \) give different members of the family and a unique value of \( \alpha \). Solving for \( \alpha \) under these conditions we find

\[ \alpha = (2\phi/\pi)\tan^{-1}(\psi^{1/2}/\phi), \]

Using Eq. (2) we have, therefore,

\[ F = 4Kr \phi^2 \]

and hence, the elastic torque is

\[ \Gamma_r = 8Kr \phi. \]

If an acoustic wave is directed normal to the glass surface there will be two torques acting on the disk. The acoustic wave will tend to turn the disk parallel to the plane of the glass and the nematic fluid will tend to turn the disk perpendicular to the plane of the glass.

Letting \( r \sim 50 \mu m, K \sim 5 \times 10^4 \) dynes, \( \theta = \phi = \pi/4, \rho \sim 1 \) g/cm² we may set the elastic and acoustic torques equal and solve for \( r \). Knowing the speed of sound in MBBA (~1.5 x 10^3 cm/sec) we find the acoustic intensity required to turn the platelets by \( \pi/4 \) is ~1 mW/cm².