Absorption of Millimeter Waves by Human Beings and Its Biological Implications

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Abstract—**With recent advances in millimeter-wave technology, including the availability of high-power sources in this band, it has become necessary to understand the biological implications of this energy for human beings. This paper gives the millimeter-wave absorption efficiency for the human body with and without clothing. Ninety to ninety-five percent of the incident energy may be absorbed in the skin with dry clothing, with or without an intervening air gap, acting as an impedance transformer. On account of the submillimeter depths of penetration in the skin, superficial SAR's as high as 65–357 W/Kg have been calculated for power density of incident radiation corresponding to the ANSI guideline of 5 mW/cm^2. Because most of the millimeter-wave absorption is in the region of the cutaneous thermal receptors (0.1 – 1.0 mm), the sensations of absorbed energy are likely to be similar to those of IR. For the latter, threshold of heat perception is near 0.67 mW/cm^2, with power densities on the order of 8.7 mW/cm^2 likely to cause sensations of "very warm to hot" with a latency of 1.0 ± 0.6 s.**

Calculations are made for thresholds of hearing of pulsed millimeter waves. Pulsed energy densities of 143–579 μJ/cm^2 are obtained for the frequency band 30–300 GHz. These are 8–28 times larger than the threshold for microwaves below 3 GHz. The paper also points to the need for evaluation of ocular effects of millimeter-wave irradiation because of high SAR's in the cornea.

I. INTRODUCTION

WITH THE RECENT and projected advances in millimeter-wave technology, including the availability of high-power transmitters (hundreds of kilowatts of power) in this band, it has become necessary to understand the biological implications of this radiation for human beings. This paper discusses the following issues:

A. Power densities likely to be encountered close to the radiators in the frequency band 30–300 GHz.
B. Millimeter-wave absorption efficiency of the human body with and without clothing; the possibility of 90–95-percent coupling efficiency with clothing acting as an impedance matching transformer.
C. The possibility of very high rates of energy deposition in the skin because of the submillimeter depths of penetration.
D. Biological implications of millimeter-wave absorption. Under this heading, the following aspects are discussed:
    1. Potential effects on the human eyes with particular concern for the effects on the cornea in which high rates of energy deposition are encountered.
    2. Hearing sensations produced by millimeter waves.
    3. Thermal sensations produced by millimeter-wave irradiation.

Since most millimeter-wave energy is absorbed by the skin in the region occupied by the thermal receptors, it is suggested that the perception of millimeter waves may be similar to that of infrared (IR) irradiation, for which considerable data exists in the literature [1], [2]. For IR radiation, the threshold of detection of warmth is near a CW power density of 0.67 mW/cm^2 for whole-body irradiation with the threshold power density progressively increasing as the irradiated area is decreased [1]. In these experiments, the subjects were nude at normal room temperature. At a power density of 0.84 mW/cm^2, there was a reported "marked sense of warmth" [1]. These power densities are considerably lower than the 5 mW/cm^2 safety guideline suggested by the American National Standards Institute (ANSI) for the frequency band 1.5–100 GHz [3] and the 10 mW/cm^2 threshold limit value (TLV) suggested for this band [4] by the American Conference of Governmental Industrial Hygienists (ACGIH).

II. PRESENT AND PROJECTED HIGH-POWER SOURCES

Fig. 1 gives some of the capabilities of power output for various microwave power sources [5]. It is presently possible to generate power levels on the order of 100 kW at 100 GHz with projections in the future for power outputs on the order of 1 MW at this frequency. Recognizing that the gain of an aperture antenna such as a horn or a circular or rectangular aperture is given by $K(4\pi A_p)/\lambda^2$, where A_p is the physical area of the aperture and λ is the free-space wavelength of radiation, substantial antenna gains on the order of 30–55 dB can be obtained for moderate-sized radiators of diameters less than 60 cm. The factor K in the gain expression is dependent upon illumination of the aperture and it varies from about 0.5 to 0.75. The maximum power density $p_{\max}$ at a distance R_0 along the axis of the aperture antenna can be written as

$$p_{\max} = \frac{GP_T}{4\pi R_0^2}. \tag{1}$$

Power densities on the order of several watts/cm^2 can be

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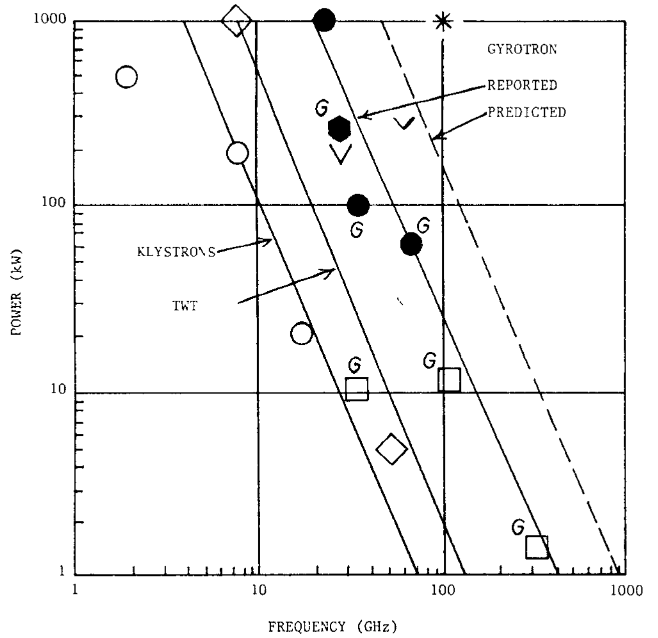

Fig. 1. Microwave tube power: (□) published Russian CW gyrotron data; (●) Russian millisecond pulsed gyrotrons; (○) klystrons; (◇) TWT's and extended interaction klystrons; (◆) millisecond pulsed gyrotron; (∨) CW gyrotron; (∗) Russian 100-μs pulsed gyrotron (from [5]).

TABLE I
THE REFLECTION COEFFICIENT, DEPTH OF PENETRATION, AND SURFACE SAR FOR THE HUMAN SKIN

FREQUENCY GHz	COMPLEX PERMITTIVITY	REFLECTION[a] COEFFICIENT $\lvert\rho\rvert^2$	SKIN DEPTH δ_{mm}	for p_{inc} = 5 mW/cm^2 SAR(O) W/kg
30	18.12 - j19.20	0.488	0.782	65.5
60	8.89 - j13.15	0.411	0.426	138.3
100	5.92 - j8.57	0.333	0.318	209.7
150	4.88 - j5.88	0.266	0.271	270.8
200	4.49 - j4.45	0.223	0.249	312.0
250	4.32 - j3.58	0.195	0.238	338.2
300	4.22 - j2.99	0.175	0.231	357.1

[a] Power absorption coefficient $=1-|\rho|^2$.

calculated at distances of tens of meters. For an antenna gain of, say, 50 dB, and a transmitted power P_T of 100 kW, $p_{\max} \simeq 8$ W/cm^2 at $R_0 = 100$ m. This points to a significant problem of back radiation, as well, from these antennas. For personnel working behind these apertures, the distance R_0 is generally no more than a few meters. It would, therefore, be necessary to ensure that back radiation is 65–75 dB lower than frontal radiation to obtain exposure power densities of less than or equal to 5 mW/cm^2, which is the present ANSI guideline for the millimeter-wave band. Back irradiation from aperture antennas is typically 45–55 dB below that of axial direction. Extra shielding would, therefore, be needed to ensure personnel-safe power densities behind the aperture antennas.

III. ABSORPTION OF MILLIMETER WAVES BY HUMAN BEINGS

Because of the high loss tangent of water (even deionized water) in the millimeter-wave band on account of the Debye relaxation of the water molecule, the millimeter-wave penetration into the biological bodies is likely to be less than one to two millimeters [6], i.e., predominately in the skin. The data are fairly sparse for the complex permittivity of the skin, as well as for the other biological tissues in the millimeter-wave region of the electromagnetic spectrum. At 23 GHz, measurements have been made with rabbit skin *in-vitro* [7], which has led to a formulation [8] of the complex dielectric constant of the skin being given by the Debye equation

$$\epsilon^*(\omega) = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 + j\omega\tau} + \frac{\sigma}{j\omega\epsilon_0} \tag{2}$$

where $\epsilon_\infty = 4.0$, $\epsilon_s = 42.0$, $\tau = 6.9 \times 10^{-12}$ s, $\epsilon_0 = 8.85 \times 10^{-12}$ F/m, and $\sigma = 1.4$ S/m. It should be noted that the corresponding values for pure water are considerably higher: $\epsilon_\infty = 5.0$, $\epsilon_s = 78.0$, $\tau = 7.5 \times 10^{-12}$ s, and $\sigma = 0$ [9].

We have used (2) to calculate the power-reflection coefficient $|\rho|^2$ and the depth δ of penetration (corresponding to the power density of $1/e^2$ or 13.5 percent of that at the surface) assuming normally incident plane waves. The calculated values of the reflection coefficient, the depth δ, and the specific absorption rate (SAR) at the surface are given in Table I. The SAR at a depth x within the skin is given by $\mathrm{SAR}(0)e^{-2x/\delta}$, where the SAR(0) at the surface is given by

$$\mathrm{SAR}(0) = \frac{2p_{\mathrm{inc}}(1 - |\rho|^2)}{\delta}. \tag{3}$$

Note that the SAR(0) increases rapidly with frequency on account of the decreasing δ and the increasing power-coupling coefficient $1 - |\rho|^2$. SAR's that are considerably in excess of the ANSI guideline of 8 W/kg for the peak value are therefore calculated for the millimeter-wave band 30 to 300 GHz. These SAR's are also given in Table I. For the ACGIH TLV of 10 mW/cm^2, SAR's twice those of the last column of Table I will be encountered.

It is a characteristic of the high permittivity media (such as the skin) that the internal energy propagates nearly normal to the interface with air for fairly wide angles of incidence. This can be seen from Snell's law, according to which the transmission angle θ_t relative to the normal is given by $\sin\theta_t = \sin\theta_i/\epsilon^*$. For large values of ϵ^*, $\theta_t \ll \theta_i$, leading to a near-normal propagation of the waves launched in such media. Idealized spherical or cylindrical shapes of skin-equivalent media may be used to estimate the power-transmission coefficients in terms of the angles θ and ϕ of incident plane waves relative to the body normal (see inserts of Figs. 2 and 3). The power-transmission coefficients are given by:

$$T_E = \left[\frac{2\cos\theta\cos\phi}{\cos\theta\cos\phi + (\epsilon^* - \sin^2\theta\cos^2\phi)^{1/2}}\right]^2 \tag{4}$$

$$T_H = \left[\frac{2(\epsilon^*)^{1/2}\cos\theta\cos\phi}{\epsilon^*\cos\theta\cos\phi + (\epsilon^* - \sin^2\theta\cos^2\phi)^{1/2}}\right]^2 \tag{5}$$

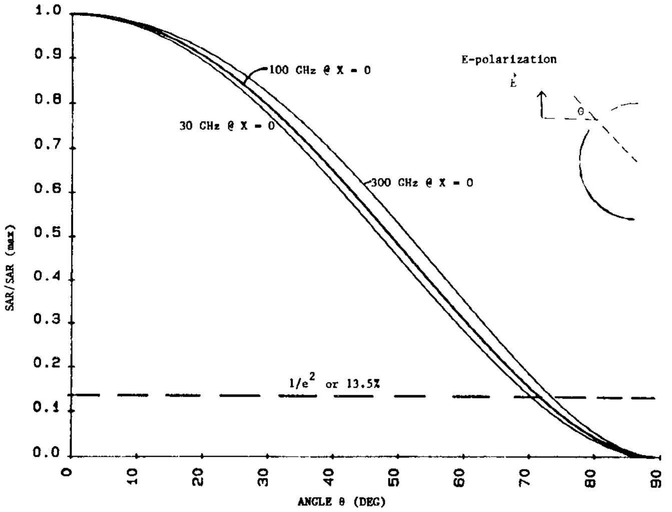

Fig 2. The variation of the superficial SAR with the angle θ of incidence ($\vec{E}$ in the plane of incidence).

where T_E and T_H refer to waves with incident $\vec{E}$-field in the plane of incidence (E-polarization, see insert of Fig. 2) or normal to the plane of incidence (H-polarization, see insert of Fig. 3), respectively. For a cylindrical body $\phi = 0$, the SAR variations as a function of angle θ have been calculated using the ϵ^* corresponding to that of the skin (eq. (2)). The results plotted in Figs. 2 and 3 for E- and H-polarizations, respectively, are interesting and they indicate nearly similar coupling and, hence, superficial SAR's regardless of the angle of incidence for fairly large angles of incidence. Here, $\text{SAR}|_{\max}$ is the SAR at the surface for $\theta = 0$ or normal incidence (given in Table I). Estimates of the angles θ for which $\text{SAR}/\text{SAR}|_{\max} = 1/e^2$ (or 13.5 percent) may be obtained from (4) and (5). Since $\epsilon^* \gg 1$, T_E and T_H for $\phi = 0°$ may be approximated to $T \simeq 4\cos^2\theta/|\epsilon^*|$, $T_H \simeq 4\cos^2\theta/|\epsilon^{*1/2}\cos\theta + 1|^2$. The angles of incidence for which $\text{SAR}/\text{SAR}|_{\max} \simeq 1/e^2$ are: $\theta_E \simeq \cos^{-1}(1/e) = 68.4°$ and $\theta_H \simeq 87.0°$ at 100 GHz. The corresponding angles for $1/e^2$ reduction in SAR are illustrated for the exact calculations shown in Figs. 2 and 3, respectively. These are in good agreement with the estimated angles.

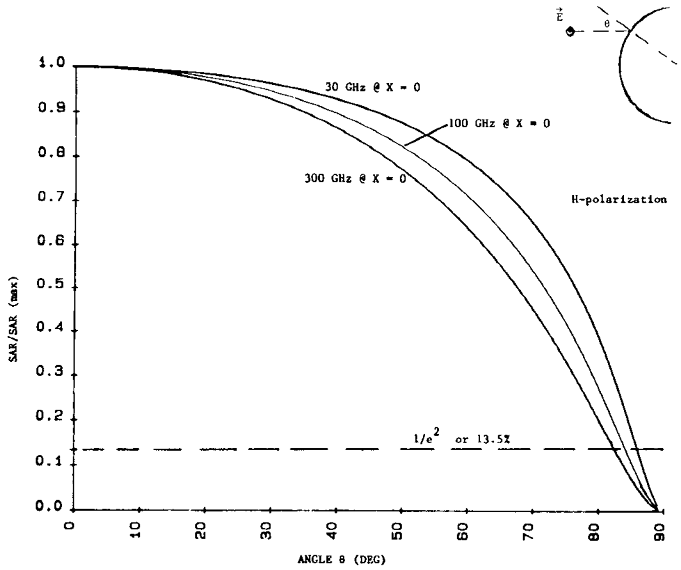

Fig. 3. The variation of the superficial SAR with the angle θ of incidence ($\vec{E}$ perpendicular to the plane of incidence).

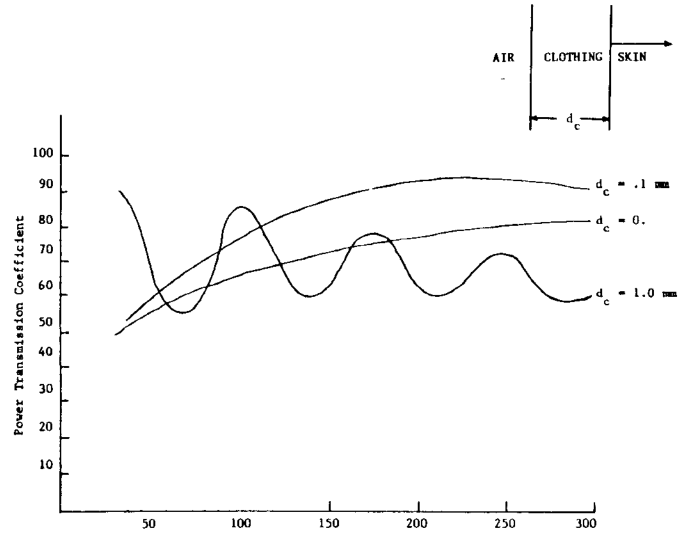

Fig. 4. Comparison of transmission coefficient with and without clothing ($d_a = 0$).

IV. Effect of Clothing on Millimeter-Wave Absorption

Thickness of human clothing is highly variable, from about 0.5 mm to 2.0 mm or more. Being a significant fraction of the incident wavelength, clothing may act as an impedance transformer resulting in an enhanced coupling of millimeter-wave energy to the body. Similar to a transmission-line analog previously developed for multilayered calculations [10], we have used an equivalent circuit where equivalent transmission lines ($Z_0 = 377/\sqrt{\epsilon_r}$) are used to represent layers of clothing, intervening air, and skin. The dielectric constant of clothing ϵ_c is known only at lower frequencies [11]. We have taken the same value in the millimeter-wave region and for dry clothing have assumed a dielectric constant of $4 - j\,0.1$ for the calculations. The calculated transmission coefficient as a function of frequency is shown in Fig. 4 for no clothing ($d_c = 0$) and for a couple of representative thicknesses ($d_c = 0.1$ and 1.0 mm). For frequencies such that $d_c \simeq \lambda_\epsilon/4$, where λ_ϵ is the wavelength within the clothing, clothing acts as an impedance transformer, resulting in an increased coupling of electromagnetic energy. Similar results are obtained when $d_c \simeq 3\lambda_\epsilon/4$, $5\lambda_\epsilon/4$, etc. Since $\epsilon_c \simeq 4.0$, these conditions are met for frequencies such that $f \simeq nc/(8d_c)$, where c is the velocity of light and $n = 1, 3, 5, \cdots$. For $d_c = 1$ mm, for example, peak coupling frequencies are therefore anticipated for $f \simeq 37.5$, 112.5, 187.5, and 262.5 GHz, with a decreasing peak of coupling because of the increasing loss at higher millimeter-wave frequencies due to the $-j\,0.1$ in the dielectric constant of clothing. These frequencies are in good agreement with those based on exact calculations shown in Fig. 4. We have calculated the peak absorption

TABLE II
FREQUENCIES IN GHz OF PEAK ABSORPTION FOR VARIOUS ASSUMED THICKNESSES OF CLOTH (d_c) AND AIRGAPS (d_a)

d_c mm	d_a = 0.0 mm	d_a = 1 mm	d_a = 2 mm
0.2	131.2 (96.4)	34.5 (67.1), 147.8 (95.6), 277.1 (92.9)	81.1 (92.6), 148.8 (95.5) 218.3 (92.2), 287.5 (92.8)
0.5	60.9 (95.2), 197.8 (87.4)	120.3 (87.7), 169.7 (83.8) 270.9 (83.3)	72.2 (95.2), 131.3 (81.1), 162.9 (78.9), 221.3 (84.7) 281.9 (79.3)
1.0	32.9 (92.7), 102.6 (87.5) 174.6 (80.0), 247.5 (72.9)	73.8 (54.4), 128.3 (84.1), 163.8 (78.4), 223.3 (55.8), 279.3 (70.7)	60.5 (79.9), 85.7 (77.2), 135.2 (79.9), 159.7 (75.0), 210.6 (74.9), 286.1 (68.9)
2.0	52.9 (85.5), 89.1 (79.3) 125.6 (72.9), 162.4 (66.9) 199.2 (61.5), 236.1 (56.5), 273.1 (51.9)	40.8 (57.1), 74.2 (48.1), 107.4 (61.2), 135.3 (71.4), 158.5 (66.0), 189.7 (48.1), 223.9 (40.4), 257.8 (46.6), 285.9 (50.4)	36.9 (46.6), 64.4 (79.6), 82.4 (73.7), 111.7 (47.5), 139.3 (69.7), 156.6 (64.2), 186.6 (43.1), 214.5 (59.0) 230.9 (54.9), 261.6 (37.4), 289.9 (49.9)

The corresponding coupling efficiencies in percent are given in parentheses.

frequencies in the frequency band 30–300 GHz for a number of assumed thicknesses of clothing and air gap. Some representative values are given in Table II together with the corresponding coupling efficiencies as percentages, which are given in parentheses. Coupling efficiencies of 90 to 95 percent are shown possible at various frequencies as a result of impedance matching to air with a proper combination of d_c and/or d_a.

It should, of course, be pointed out that such high coupling efficiencies are possible only with dry clothing. The presence of moisture will result in significant attenuation due to the high loss tangent of water at millimeter wavelengths.

V. BIOLOGICAL IMPLICATIONS OF THE ABSORBED ENERGY

A. Potential Effects on the Eyes

Epithelial and stromal injuries have been observed in the rabbit's eyes [12] after 30–60-min exposures to millimeter waves at 35 and 107 GHz in which the total absorption in the eye was on the order of 15–50 mW. Based on the exposed section of the human eye, we estimate a power absorption on the order of 15–25 mW for an incident power density of 10 mW/cm^2. This may imply a potential problem for the ocular apparatus as a consequence of millimeter-wave irradiation. Even though the injuries observed in [12] we found to be reversible and vanished 24–48 h after the exposure, the effects may be more serious and nonreversible in the case of longer term exposures. Ocular effects of millimeter waves should therefore be studied to understand the effects of longer term exposures.

B. Thermal Sensations of Millimeter-Wave Irradiation

Owing to the highly superficial nature of its absorption ($\delta \sim 0.23$–0.78 mm) and the fact that heat-sensing nerve endings are distributed in the skin at depths from 0.1 to 1.0 mm, perception of millimeter-wave absorption is likely to be very similar to that of far-infrared ($\lambda > 3\ \mu$) irradiation.

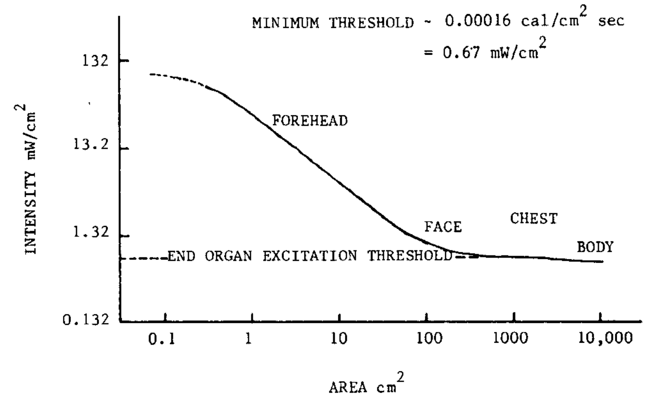

Fig. 5. Threshold of IR perception—Absorbed CW intensity versus exposed area [1].

Hardy and Oppel [1] have written an important paper on the threshold of IR perception and its variation with the exposed area of the body. Their data drawn in the form of a curve is reproduced in Fig. 5 in terms of mW/cm^2 as the unit of intensity rather than in calories/cm^2 s, in which the curve was originally drawn. This curve was obtained on the basis of a number of experiments with two Caucasian subjects. For exposures involving the largest areas, the subjects stood nude in a room at normal temperature. The minimum power density at the threshold of detection was 1.6×10^{-4} cal/cm^2 s, or 0.67 mW/cm^2, when the stimulus was applied to the chest, and was not much smaller when the radiation was incident on the whole body. Some pertinent points from the Hardy and Oppel [1] paper are given in the following.

A. Thermal sensors distributed at depths between about 0.1 and 1 mm responded to IR stimulus as if depth of penetration were of no consequence.
B. Sensation was perceived within 3 s of irradiation.
C. When the threshold stimulus for the face (~ 0.84 mW/cm^2) as applied to the whole-body, the subjects perceived a "marked sense of warmth."

D. On account of spatial summation, the intensity of the thermal sensation was stronger when larger areas of skin were irradiated.

It should be recognized that the more penetrating the radiation, the higher its threshold for warming sensation. Justesen *et al.* [13], for example, have measured an incident power density of 26.7 mW/cm^2 (absorbed power density $\simeq 8.9$ mW/cm^2) as the threshold of perception of warmth for irradiation of the ventral surface of the arm (exposed area of 177 cm^2) for microwaves at 2.45 GHz; yet for far IR radiation, the corresponding threshold measured by these authors is 1.7 mW/cm^2, which is considerably lower. Because of the similarity of the millimeter-wave radiation to far IR, we expect the lower number to be valid for the millimeter-wave bond for the ventral surface of the arm.

Because of a higher density of the thermal receptors in the skin of the forehead, somewhat lower thresholds have been measured for this region of the body. For an exposed forehead area of only 37 cm^2, the power densities for threshold warmth sensation at 3 and 10 GHz and for far IR have been reported to be 29.9 12.5, and 1.7 mW/cm^2, respectively [14]. The difference in the thresholds of perception at various frequencies (17.6 : 7.4 : 1 from the preceding numbers) may be ascribed to the lower efficiency of reception by the thermal receptors for the more deeply penetrating microwave radiation at 3 and 10 GHz. An estimate of the aggregate absorbed power per unit exposed area for the region of the thermal receptors may be made by integrating the SAR from depth $x = 0$ to $x = 1$ mm. Using (3) gives, for an assumed planar surface

$$\int_0^1 \mathrm{SAR}(x)\,dx = 2p_{\mathrm{inc}}(1-|\rho|^2)[1-e^{-2/\delta}]. \tag{6}$$

From the values of $|\rho|^2$ and δ from Table I, we can estimate the ratios of the integrated SAR's from (6). The integrated SAR's at 3, 10, and 300 GHz are proportional to 0.068 : 0.24 : 1. Since the threshold of perception may occur for roughly comparable absorbed power densities or integrated SAR, power densities that are inversely proportional to these numbers will therefore be needed at the three frequencies. The ratios of the incident power densities needed for perception are therefore 14.7 : 4.2 : 1. Recognizing that we have used an assumption of planewave irradiation of a planar surface, these ratios are not far from the values quoted earlier from [14].

Experiments have been performed [2] to determine the threshold power densities for various sensations; faint warm, warm, and very warm or hot, as a function of the area exposed to far IR on the dorsum of the right hand. A sensation of "very warm or hot" was experienced for an average power density of 21.7 ± 4.0 mW/cm^2 for an exposure area of 40.6 cm^2, while a similar sensation occurred for a lower exposure area of 9.6 cm^2 for a larger power density of 55.9 ± 4.9 mW/cm^2. The ratio $21.7/55.9 \simeq 0.4$ in the power densities is similar to that for thresholds of perception for similar surface areas from Fig. 5. Reaction time for the sensation "very warm or hot" was typically on the order of 1.0 ± 0.6 s. Recognizing that there is a further reduction by a factor of 2.5 in the threshold of perception for irradiation of areas that are larger than 40.6 cm^2 (Fig. 5[1]), it is not inconceivable that the sensation "very warm or hot" for larger millimeter-wave irradiation areas may well occur for 21.7/2.5 or 8.7 mW/cm^2. Experiments on human perception of millimeter-wave irradiation are unfortunately lacking in the literature. We have, therefore, relied on the data of human sensations to far IR to project the power densities for millimeter-wave irradiation. This has resulted in our pointing out a potential problem with the ACGIH TLV of 10 mW/cm^2 [4] for the millimeter-wave band 30–300 GHz. There is obviously a need for confirmation of these projections by experimentation with human volunteers. It should be mentioned that the IR threshold data cited are based on nude skin. As pointed out earlier, millimeter-wave absorption can occur through the dry clothing over the whole body, whereas IR irradiation is nearly masked by clothing except for uncovered areas such as the face, arms, and hands. A greenhouse-type effect may therefore occur for millimeter-wave irradiation resulting in thresholds of perception of warmth or of the senation "very warm or hot" for power densities that are smaller than those obtained for IR where nude subjects were used.

C. Hearing Sensations of Pulsed Millimeter Waves

Many investigators have reported on the audibility of pulsed microwave irradiation by human subjects [15]–[17]. The sound appearing to originate from within or near the head has been described as a click, buzz, or chirp depending on such factors as pulse width and repetition rate. Previous work has been limited to the frequency range 0.2–3 GHz. There are several distinctions in the nature of millimeter-wave absorption vis-à-vis than at lower microwave frequencies.

A. The absorption of millimeter waves is highly superficial with a depth that is on the order of a millimeter. Because of the spatial narrowness of the deposited energy (the depth of penetration at lower microwave frequencies is a few centimeters), the Fourier spectrum of the sonic components extends to higher frequencies, on the order of several hundred kilohertz. Much of this sonic energy is therefore beyond the human audible range even for the mechanism of bone conduction [18], which has been proposed for microwave hearing.

B. Because of the shallow deposition, the resulting SAR's are, however, considerably higher than those for comparable incident power densities at microwave frequencies below 3 GHz, where the auditory phenomenon has previously been studied.

We have used an analysis similar to that of Borth and Cain [17] to calculate the pressures that are caused in the

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[1] In Fig. 5, the threshold of perception for larger areas such as the face and the chest is 0.67 mW/cm^2 which is a factor of 2.5 smaller than 1.67 mW/cm^2 for an exposure area of 40.6 cm^2.

skin layer due to millimeter-wave irradiation. The corresponding pressures have also been obtained at the lower microwave frequencies of 0.915, 2.45, and 3.0 GHz for comparison with the experimental data on the threshold of human hearing at these frequencies. Our calculations assume a plane electromagnetic wave incident normally on a semi-infinite body possessing a complex dielectric constant equivalent to that of the skin [Table I] for millimeter wavelengths and two-thirds that of the muscle [19] at frequencies < 3 GHz. Assuming that the surface of the body is free, the expressions for the pressure per unit acoustic bandwidth ($F \equiv dp/df_a$) are given by the following [17].

1) Pressure Due to Thermal Expansion:

$$F_{th} = \frac{6\sqrt{2}\alpha v^2 I_0}{S\delta} \frac{[1-\cos(\Omega T)]^{1/2}}{\left(\Omega^2 + \frac{4v^2}{\delta^2}\right)} \frac{\text{dynes}}{\text{cm}^2\text{Hz}} \tag{7}$$

where

α coefficient of linear expansion ($\simeq 10^{-4}(°\text{C})^{-1}$),
v speed of sound ($\simeq 1.5 \times 10^5$ cm/s in high water-content tissues),
I_0 internal power density $= p_{\text{inc}}\,(1-|\rho|^2)$ in ergs/cm^2,
S specific heat (4.19×10^7 ergs/g°C),
δ microwave frequency-dependent skin depth in cm (fromTable I),
T pulse duration in s,
Ω acoustic frequency in rad/s $\equiv 2\pi f_a$.

It has been suggested that microwave hearing is caused by bone conduction of the induced pressure [18]. The threshold of hearing by bone conduction increases dramatically for acoustic frequencies f_a above about 14 KHz. The total induced pressure P due to thermal expansion has therefore been obtained by integrating (7) for $0 \leqslant f_a \leqslant 14 \times 10^3$. For the "audible" region $0 \leqslant f_a \leqslant 14$ KHz, for microsecond pulses, $\Omega T \ll 1$. Equation (7) can therefore be simplified to

$$F_{th} = \frac{6\alpha v^2}{S\delta} I_0 \frac{\Omega T}{\Omega^2 + \frac{4v^2}{\delta^2}}. \tag{8}$$

Upon integrating (8) for $0 \leqslant f_a \leqslant 14$ KHz, the total induced pressure P_{th} due to thermal expansion is obtained

$$P_{th} = 2.56 \times 10^5 I_0|_{\text{W/cm}^2} \cdot \frac{T}{\delta} \log\left(f_a^2 + \frac{v^2}{\pi^2\delta^2}\right)\Bigg|_{f_a=0}^{f_a=14\times10^3} \frac{\text{dynes}}{\text{cm}^2} \tag{9}$$

where T is in seconds and δ is in centimeters. The numerical values calculated for 30, 100, and 300 GHz, as well as for comparison frequencies of 0.915, 2.45, and 3.0 GHz, are given in Table III.

TABLE III
CALCULATED PRESSURES AND THRESHOLD OF HEARING

F_{GHz}	$\frac{P_{th}}{I_0T}\Big\vert$ μJ/cm^2	$\frac{P_{es}}{I_0T}\Big\vert$ μJ/cm^2	$\frac{P_{rp}}{I_0T}\Big\vert$ μJ/cm^2	Threshold[a] $I_0T\vert$ μJ/cm^2
.915[b]	2.14×10^{-2}	3.81×10^{-3}	1.10×10^{-5}	7.94
2.45[b]	1.67×10^{-2}	2.97×10^{-3}	0.93×10^{-5}	10.15
3.0[b]	1.63×10^{-2}	2.83×10^{-3}	0.91×10^{-5}	10.45
30.0	7.48×10^{-4}	1.97×10^{-3}	8.89×10^{-6}	71.25
100.0	3.05×10^{-4}	4.87×10^{-4}	4.65×10^{-6}	251.2
300.0	2.21×10^{-4}	1.95×10^{-4}	1.97×10^{-6}	477.8

[a] For $P_{th} + P_{es} + P_{rp} = 0.2$ dyne/cm^2 [16], [18].
[b] Calculated for comparison.

2) Pressure Due to Electrostriction:

$$F_{es} \simeq \frac{4\sqrt{2}\rho_m v^2 \operatorname{Re}\{\eta\}\epsilon_0(\epsilon^*-1)(\epsilon^*+2)}{3\delta^2} I_0 \cdot \frac{[1-\cos(\Omega T)]^{1/2}}{\Omega\left(\Omega^2 + \frac{4v^2}{\delta^2}\right)} \frac{\text{dynes}}{\text{cm}^2\text{ Hz}} \tag{10}$$

where

ρ_m mass density (1.0 g/cm^3),
η intrinsic impedance $= 377/\sqrt{\epsilon^*}$,
ϵ^* complex dielectric constant of the skin in the millimeter-wave range and 2/3 that of muscle at lower frequencies,

and the other quantities have the same meanings and magnitudes as in the expression for pressure due to thermal expansion. For T on the order of microseconds and $0 \leqslant f_a \leqslant 14$ KHz, the acoustic frequency-dependent term in the parentheses of (12) may be simplified to $T/4\sqrt{2}\pi^2(f_a^2 + v^2/\pi^2\delta^2)$ and the total induced pressure P_{es} due to electrostriction may be written as

$$P_{es} = \int F_{es}\,df_a$$
$$= 6.6405 \times 10^3 I_0|_{\text{W/cm}^2}\delta^{-2}\operatorname{Re}[\eta]|\Delta\epsilon|\frac{T}{f_1} \cdot \tan^{-1}\left(\frac{f_a}{f_1}\right)\Bigg|_{f_a=0}^{f_a=14\times10^3} \frac{\text{dynes}}{\text{cm}^2} \tag{11}$$

where

$$f_1 \equiv \frac{v}{\pi\delta}$$
$$\Delta\epsilon = |(\epsilon^*-1)(\epsilon^*+2)|.$$

The numerical values of the total induced pressure due to electrostriction have been calculated for the various irradiation frequencies and are also given in Table III.

TABLE IV
INCIDENT ENERGY DENSITY FOR THRESHOLD OF HEARING AND ITS COMPARISON WITH RELATIVE PENETRATION DEPTHS

F_{GHz}	δ cm	I_0T $\mu J/cm^2$	$P_{inc}T$ $\mu J/cm^2$	$\left.\frac{\delta_{0.915}}{\delta}\right\|_f$	$\frac{P_{inc}T}{P_{inc}T_{0.915}}$
.915	3.03	7.94	17.3	1.0	1.0
2.45	2.05	10.15	20.9	1.48	1.21
3.0	1.97	10.45	20.6	1.54	1.19
30.0	0.078	73.40	143.3	31.4	8.28
100.0	0.032	251.2	376.4	76.6	21.76
300.0	0.023	477.8	579.1	106.5	33.47

3) *Pressure Due to Surface Radiation Pressure:*

$$F_{rp} = \frac{2\sqrt{2}\,I_r}{c}\,\frac{[1-\cos(\Omega T)]^{1/2}}{\Omega}\,\frac{\text{dynes}}{\text{cm}^2\ \text{Hz}} \tag{12}$$

where I_r is the power density of reflected waves, $P_{inc}|\rho|^2$ is in ergs/cm^2 s, and c is the speed of EM waves in air (3×10^{10} cm/s).

Assuming $\Omega T \ll 1$ (for T on the order of microseconds), the total induced pressure P_{rp} can be written as

$$P_{rp} = \int F_{rp}\,df_a = 6.667\times10^{-11}T \cdot \frac{|\rho|^2}{1-|\rho|^2} I_0|_{\text{W/cm}^2} f_a|_0^{14\times10^3} \frac{\text{dynes}}{\text{cm}^2}. \tag{13}$$

The values calculated for the various irradiation frequencies are also given Table III.

The threshold of hearing for bone conduction is 60 dB relative to 0.0002 dynes/cm^2 or 0.2 dynes/cm^2 for pulse widths between 1 and 50 μs [18], [20]. The threshold values of I_0T for hearing can therefore be calculated by requiring that $P_{th} + P_{es} + P_{rp} = 0.2$ dynes/cm^2. The values of I_0T in μJ/cm^2 thus calculated are given in Table III. Since I_0 is the internal or coupled power density, it is not a quantity that is available directly. I_0 is, however, related to the incident power density in terms of the relationship $I_0 = p_{inc}\cdot(1-|\rho|^2)$. The results are reexpressed in Table IV in terms of $p_{inc}T$, or the incident energy density per pulse for threshold of hearing at the various millimeter wavelengths. The results are shown graphically in Fig. 6 as a function of the irradiation frequency. Also shown for comparison are the limited experimental data of Chou *et al.*, on one human subject [14] and that of Rissman and Cain [21] on five subjects. The experimental data are within a factor of 2 of the calculated values.

From these results, the following points may be made.

A. Although the pressure due to thermal expansion is the highest at the lower microwave frequencies, the same cannot be said for millimeter-wave irradiation. Here the pressure arising from electrostriction is comparable or even somewhat higher.

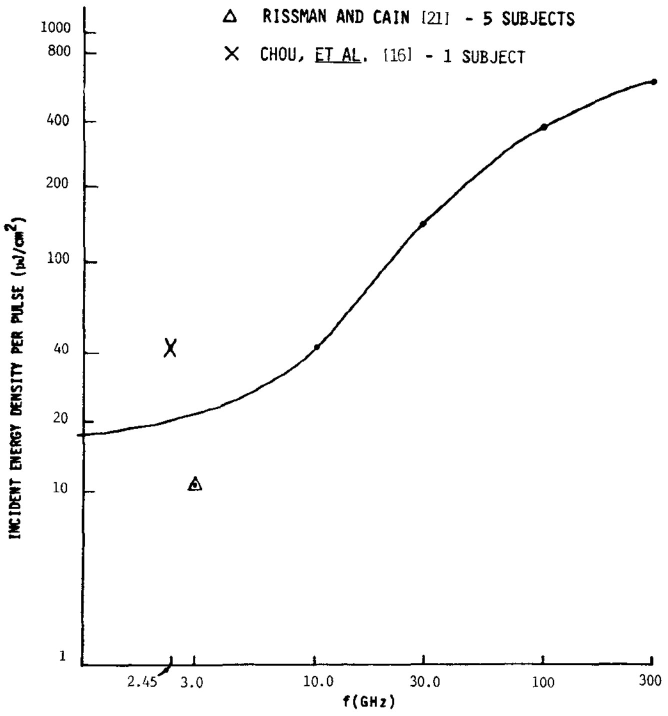

Fig. 6. Incident energy density per pulse as a function of frequency when threshold pressure (for bone conduction) is 60 dB Re 0.0002 dyne/cm^2.

B. The energy densities per pulse needed to cause hearing at millimeter wavelengths are a factor of 8–28 times larger than those at lower microwave frequencies (Table IV). The increase in the threshold energy density is considerably smaller than the decrease in the relative depth of penetration in the millimeter wave band.

VI. CONCLUDING REMARKS

Several potential problems have been pointed out for irradiation in the millimeter-wave band. These include extremely high superficial SAR's even for incident power densities of 5–10 mW/cm^2 that have been recommended as safety guidelines [3], [4]. Because of the high SAR's in the cornea of the eye, there is a need to study ocular effects of millimeter-wave irradiation for exposure durations longer than 30–60 min that have previously been used. We have quantified the effects of clothing on absorbed energy and have shown the possibility of enhanced millimeter-wave coupling ($\gtrsim 90$ percent) to human beings with clothing acting as an impedance-matching transformer. Because of the submillimeter depths of penetration of the millimeter waves, the sensations of the absorbed energy are likely to be similar to those of IR. For the latter, the minimum power density at the threshold of perception is near 0.67 mW/cm^2 when the stimulus is applied to the chest and not much smaller for irradiation of the whole body. The sensation of "very warm to hot" has been reported for an irradiation of an area of 40.6 cm^2 (dorsum of the hand) for an absorbed power density of 21.7 mW/cm^2 with a latency of 1 ± 0.6 s [2]. Because of spatial summation of thermal sensation, we have in this paper projected the sensation of "very warm or hot" for whole-body exposures for IR absorbed power densities on the order of 8.7 mW/cm^2. The IR data used for comparison are available only for unclothed body surfaces because the IR would be masked or attenuated by clothing. Millimeter-wave absorption, on the other hand, can occur through the clothing over the whole body. A greenhouse effect may therefore occur for millimeter-wave irradiation resulting in thresholds of perception of warmth and of the sensation of "very warm to hot" at power densities that are lower than those quoted above. There is definitely a need for psychophysical experiments to establish thresholds of perception of millimeter waves with and without clothing.

This paper also gives the calculated numbers of the energy densities of incident radiation for the threshold of hearing of pulsed millimeter-wave irradiation. These are shown to be about 8–28 times larger for the 30–300-GHz band than those for microwave frequencies below 3.0 GHz.

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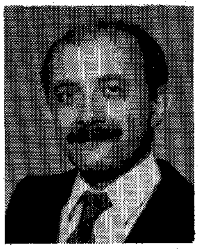

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