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Cutaneous Perception of Microwaves*

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ABSTRACT

The most obvious effect produced when microwaves are directed into an absorbing substance is the conversion of electromagnetic energy into heat. Awareness of microwave exposure is developed by several mechanisms among which are cutaneous thermal sensation or pain. Although the subjective awareness of warmth is only a rough indicator of microwave exposure, nevertheless, several investigators have established the thresholds for microwave induced thermal sensation and pain in man. The threshold for warmth perception is reached at a warming of the skin at a rate of about .001°C per second. Threshold and intensity of temperature sensation depend to a large extent on the size of the skin area changing temperature. This paper is a review of the available information on cutaneous sensation of microwave energy which indicates that when a 40 cm² area of the face is exposed to microwaves, thermal sensation can be elicited within 1 second at power densities of 21 mW/cm² for 10,000 MHz and 58.6 mW/cm² for 3,000 MHz. Within 4 seconds the threshold is lowered by approximately 50%, i.e. 12.6 mW/cm² (10,000 MHz) and 33.5 mW/cm² (3000 MHz). On this basis, if the entire face were to be exposed, the threshold for thermal sensation to 10,000 MHz would be 4-6 mW/cm² within 5 seconds or approximately 10 mW/cm² for a 0.5 second exposure. Threshold for pain reaction to 3000 MHz exposure of a 9.5 cm² area of the forearm ranges from 830 mW/cm² for approximately 3 minutes to 3.1 W/cm² for a 20 second exposure period. If a larger area (53 cm²) is exposed, the pain threshold for a 3 minute exposure is 560 mW/cm². These data and other information on microwave sensation suggest that cutaneous perception of microwaves may provide a protection factor with sufficient margin of safety constituting a warning mechanism to prevent exposure to microwaves at levels that could be injurious.

Introduction

The extensive investigations into microwave bioeffects in the Tri-Service Program[18, 19, 21, 22, 26] and recent reviews[2, 17, 20] conclusively showed that for frequencies between 1200 MHz and 24,500 MHz, power density of 100 mW/cm² or more could have pathophysiologic manifestations. At power densities below 100 mW/cm², evidence of pathologic change is equivocal. It is, therefore, important to assess the possible biologic effects of power densities below 100 mW/cm². Of the various biologic effects, perception of microwave energy, especially cutaneous sensation, is not only of academic interest but also of practical significance from the point of view of hazards evaluation and standard setting.

The most obvious effect produced when microwaves are directed into an absorbing substance is the conversion of the energy into heat. Microwaves

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entering an absorbing substance cause increased rotation of permanent dipoles of molecules, with a consequent increase in the temperature of the medium[10].

The question is often asked as to whether one can sense the presence of microwaves. Awareness of microwave exposure is developed by several mechanisms including cutaneous thermal sensation or pain. Although the subjective awareness of warmth is only a rough indicator of microwave exposure, nevertheless, several investigators have established the thresholds for microwave induced thermal sensation and pain in man. This paper is a review of the available information on cutaneous sensation of microwave energy.

Cutaneous Thermal Sensation

Awareness of microwave exposure is developed by several mechanisms including cutaneous thermal sensation or pain. The physiology of thermal sensation and pain which is essentially the basis for cutaneous perception of microwave energy has been the subject of several studies. The subjective awareness of warmth could be an indicator of microwave exposure, and, several investigators have established the thresholds for microwave induced thermal sensation and pain in man.

Sensations of warmth and cold are evoked by radiation exchanges between the skin and the environment[9]. There seems to be no specific morphological substrate of thermoreceptors; the thermosensitive structures are a network of free nerve endings[1, 25, 28]. Thermosensitive nerve endings can be defined in two different ways: (a) by the specific temperature sensation aroused by stimulation of a receptor and (b) by the response of a receptor —as indicated by action potentials—to temperature changes[15].

At certain constant temperatures, the thermoreceptors show a steady discharge, the frequency of which is dependent on the absolute temperature. The steady discharge of a single fiber has a maximum frequency of 2 to 15 impulses/sec. The temperature of the maximum discharge is between 38 and 43°C for so called warm fibers[15].

The threshold for warmth perception is reached at a warming of the skin at a rate of about 0.001°-0.002°C per second in the skin temperature range of 32°-37°C. Threshold and intensity of temperature sensation depend to a large extent on the size of the skin area changing temperature. Similarly, the minimal time of warming the skin before a temperature sensation is elicited depends on the size of the area affected and on the density of the specific temperature receptors in that area.

The main experimental evidence indicates that temperature sensation is little influenced by the absolute temperature of the skin and is governed by the rate of change of the skin temperature[6, 14]. These sensations, which are so important to the body economy as thermal detectors for regulating body temperature, are evoked when even the slightest change in skin temperature occurs[7]. Subthreshold changes in skin temperature do occur, however, without evoking temperature sensations. Whether or not these subthreshold changes play a role in thermoregulation is unknown. On the other hand, marked alteration in rate of change and magnitude of change in skin temperature can occur without evoking the temperature sensations usually reported. Thus, precooled skin can be rapidly heated without evoking sensations of warmth[11]. Results of Cook[3], however, indicate that skin temperature is the vital factor in determining pain, though only in so far as this is a measure of the temperature of the thermal pain receptors below the skin surface.

Although spatial summation of warmth sense occurs, some investigators suggest summation is absent in the case of pain sensation; this appears to be based on experiments with irradiated areas of 10 cm^2 and less, in which the pain-producing intensity was independent of area[7]. Cook[3], on the other hand, showed that the intensities provoking pain, like those producing sensation of warmth, decrease with increasing exposed area. A physical explanation of both these phenomena, not involving spatial summation, is that the rate of heat transfer from the superficial tissues decreases with increasing exposed area. Thus radiation intensities to produce either warmth or pain decrease with increasing area if it is assumed that sensations of warmth and pain depend only on the temperature of end-organs[3].

It should be pointed out in this context that the temperature of the skin (and presumably that of the temperature receptors) can be changed and then maintained at some level, higher or lower than the initial level. Temperature sensation, which initially may be quite marked, gradually subsides, and the subject reports feeling thermally neutral. Since adaptation is such a prominent phenomenon in the study of temperature sensation, the absolute temperature of the sensory endings cannot be the sole determinant of temperature sensation. There are many other easily observable phenomena which also indicate that temperature sensations do not depend only on the absolute temperature of the cutaneous thermal receptors[11].

Energy Absorption

The absorption of microwave energy is directly dependent upon the electrical properties of the absorbing medium, specifically, its dielectric constant and electrical conductivity. These properties change as the frequency of the applied electrical field changes. Values of dielectric constant and electrical conductivity have been determined for many tissues as functions of frequency. The absorption coefficient of a medium into which electromagnetic radiations are directed describes how the energy is absorbed with depth of penetration[23].

Knowledge of the electrical properties of a medium permits direct calculation of the absorption coefficient. Absorption coefficients of 5 cm^{-1} and 1.2 cm^{-1} for 10,000 MHz and 3,000 MHz, respectively, have been obtained. The reciprocals of these coefficients define the depths at which the incident intensity is reduced to $1/e$, or about 37 percent of its initial power. For 10,000 MHz microwaves, this is about 2 mm, while for 3,000 MHz microwaves, it is approximately 8 mm[10].

Presumably, as exposure duration exceeds 10 sec, heat transfer processes become important enough to significantly reduce tissue temperature. Local increase in blood flow is primarily responsible for heat transfer[10].

During irradiation of the arm, using 10-cm microwaves, Cook[4] found that tissue thermal conductivity tripled after 30 sec because of increased local blood flow. On the other hand, Hendler *et al*[13] found that when the forehead skin was irradiated with far infrared the thermal inertia of these tissues (thermal inertia is the product ($k\rho c$), where k = thermal conductivity, ρ = density, and c = specific heat) remained constant for periods lasting up to 140 secs, with surface temperatures rising over 1°C.

Microwaves—Cutaneous Perception

Vendrik and Vos[27] and Eijkman and Vendrik[5] studied warmth sensation induced by infrared and microwave heating of the forearm skin. Vendrik and Vos[27], using 3,000 MHz (pulsed) showed that irradiating an area of the inner forearm of 13 cm^2 with microwaves resulted in a threshold temperature rise of 0.4-1.0° C, depending on the subject, which is in agreement with the threshold temperature rise obtained with infrared at a depth of about 0.3-0.5 mm. For stimulus duration longer than 3-5 seconds a pronounced influence of the rate of change of temperature was found. The change in the temperature gradient caused by irradiation with microwaves is so small that, during exposure times of not more than about 10 seconds, heat conduction is almost negligible. With a constant intensity of irradiation, therefore, temperature in the skin increases linearly with time. These authors suggest that a threshold sensation is obtained, when the temperature of the warmth receptors is increased by a certain amount, ΔT. For durations of the stimulus longer than 3-5 seconds, the rate of change of temperature has a very pronounced influence. This is an adaptation phenomenon. These authors also described effects of "peripheral" and "central" adaptation, and related these to the electrophysiological findings in cats, which had been reported by Hensel and Zotterman[16].

Schwan *et al*[24] found that if a person's forehead is exposed to 74 mW/cm^2 of 3000 MHz microwaves, the reaction time (the time which elapses before the person is aware of the sensation of warmth) varied between 15 and 73 seconds. Warmth perception of 56 mW/cm^2 ranged between 50 seconds and 3 minutes of exposure[11]. The forehead was selected for a study of warmth sensation, since previous studies had shown that the temperature receptors in the skin of the forehead are relatively numerous and evenly distributed, so that it constitutes a low-threshold region of uniform temperature sensitivity[8].

Hendler and his co-workers[10, 14] made detailed studies of the cutaneous receptor response of man to 10,000 MHz and 3,000 MHz microwaves and for infrared. Two pulsed microwave sources were used. The first consisted of a generator producing 2500 pulses per sec with a pulse width of 0.4 μsec and 3 cm wavelength in air. The second produced 300 pulses per sec with a pulse width of 2 μsec. The forehead was exposed through an aperture in a shield which blocked all radiation except that striking a central, circular area of approximately 37 cm^2. Irradiance levels of 10,000 MHz and 3,000 MHz microwaves as well as for infrared stimuli producing a threshold sensation of warmth are summarized in Table I.

Very brief exposures to near infrared, over a range of from 39 to about 570 msec, resulted in the same sort of response, although the energy level required for the shortest exposure was 125 mW/cm^2. Analysis of the infrared data indicated that the threshold of warmth sensation could be correlated with a temperature rise of about

TABLE I
STIMULUS INTENSITY AND TEMPERATURE INCREASE TO PRODUCE A THRESHOLD WARMTH SENSATION*

	3000 MHz	10,000 MHz		Far Infrared	
Exposure Time (sec)	Power Density (mW/cm^2)	Power Density (mW/cm^2)	Increase in Skin Temp. (°C)	Power Density (mW/cm^2)	Increase in Skin Temp. (°C)
1	58.6	21.0	0.025	4.2-8.4	.035
2	46.0	16.7	0.040	4.2	.025
4	33.5	12.6	0.060	4.2	—

* 37 cm^2 forehead surface area—data from Hendler, *et al* [10,14].

old for pain sensation as a function of exposure time is shown in Table II. The pain threshold was lower (560 mW/cm^2) for an exposed area of 53 cm^2 in contrast to 830 mW/cm^2 for a 9.5 cm^2 area.

TABLE II
THRESHOLD FOR PAIN SENSATION AS A FUNCTION OF EXPOSURE DURATION (3000 MHz; 9.5 cm^2 area)*

Power Density (W/cm^2)	Exposure Time (sec)
3.1	20
2.5	30
1.8	60
1.0	120
0.83	>180

* Cook, H. F.(3).

This study by Cook[3] indicated that the tolerated microwave power (560-830 mW/cm^2) for a given exposed area during long exposures (>3 min) suffers relatively small variations between individuals and anatomic sites. The maximum tolerated intensity is higher (830 mW/cm^2) for a smaller exposed area (9.5 cm^2) than for a larger area (53 cm^2, 560 mW/cm^2). The skin temperature corresponding to burning pain is independent of the area of exposure, radiation intensity, exposure time and anatomical site. Pain results when a critical skin temperature is achieved rather than from a critical temperature rise. With high intensities, the time of exposure to produce pain is an inverse function of radiation intensity.

Conclusion

The results of these studies indicate that when a 40 cm^2 area of the face is exposed to microwaves, thermal sensation can be elicited within 1 second at power densities of 21 mW/cm^2 for 10,000 MHz and 58.6 mW/cm^2 for 3000 MHz. Within 4 seconds the threshold is lowered by approximately 50%, i.e. 12.6 mW/cm^2 (10,000 MHz) and 33.5 mW/cm^2 (3000 MHz). On this basis, if the entire face were to be exposed, the threshold for thermal sensation to 10,000 MHz would be 4-6 mW/cm^2 within 5 seconds or approximately 10 mW/cm^2 for a 0.5 second exposure.

Threshold for pain reaction to 3000 MHz exposure of a 9.5 cm^2 area of the inner forearm ranges from 830 mW/cm^2 for long exposure (>3 min) to 3.1 W/cm^2 for a 20 second exposure period. If a larger area (53 cm^2) is exposed, the pain threshold for long exposures is 560 mW/cm^2.

These data and other information on microwave sensation suggest that cutaneous perception of microwaves may provide a protection factor with sufficient margin of safety constituting a warning mechanism to prevent exposure to microwaves at levels that could be injurious.

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0.02°C occurring about 200μ below the surface of the skin (Table I). Calculations of the temperature gradient (dT/dx) occurring within the cutaneous layers for the infrared and microwave stimuli producing theshold sensation revealed no consistent gradient in these layers for both the infrared and microwave cases. For the range of exposure times used, it was found that for both infrared and microwave stimuli which are capable of evoking threshold sensations, a threshold of warmth is elicited when the temperature of a more superficial layer of subcutaneous tissue approximately 200μ below the skin surface is increased about 0.01-0.02°C over the temperature of a deeper layer in the skin lying about 1000μ below the surface[10, 14]. In these studies it was also noted that there was a persistence of warmth after cessation of the exposure which is taken to indicate continued existence of an effective subcutaneous temperature difference between the subcutaneous tissue layers[14].

A comparison of the heating effects induced by infrared and microwave irradiation of skin leads to the postulation that establishment of a temperature difference between more superficial and deeper cutaneous layers is necessary to produce temperature sensation. The fact that this difference must be established between layers lying about 800μ apart is differentiated from the usual concept of a spatial temperature gradient[10]. The region of the skin in which the described temperature difference is considered to be established when warmth is experienced, is very well innervated by a profuse arborization of fine, naked axoplasmic filaments.

In the study by Hendler[10] it is apparent that for a 5 second exposure to 10,000 MHz over a 40 cm^2 area of the forehead, the threshold for thermal sensation is 12.6 mW/cm^2. The threshold for thermal sensation is 25 mW/cm^2 for exposures lasting 0.5 second. For the entire face, assuming uniform temperature sensitivity of the facial skin, the thermal sensation threshold would be 4-6 mW/cm^2 for a 5-second exposure or approximately 10 mW/cm^2 for a 0.5-second exposure. It should be pointed out, however, that due to shape factors and non-uniform sensitivity, it is likely that the figures may be somewhat low, although the practical significance of corrections to these figures is probably small. In this context it should be noted that the subjects used for threshold sensation experiments were well trained, and were particularly attentive to stimuli they expected. All extraneous sensory stimuli were removed or kept at some low, constant level. Consequently, these conditions are appreciably different from those to be expected in most practical situations, where naive personnel may be exposed to microwaves under very distracting circumstances[11].

Cook[3] investigated the pain threshold for 3,000 MHz microwaves. All experiments were carried out at a room temperature of 20 ± 1°C, and with minimal air circulation. As far as could be judged, the sensations of warmth and pain with microwave heating differed little from those felt when heating was produced by infrared radiation. The initial skin temperatures in these experiments were in the range 31.5-33.5°C, and the average skin temperature rise required to achieve pain was 15.0°C. Apparently a thermal pain sensation is evoked when end-organs located at approximately 1.5 mm below the skin surface reach a temperature of about 46°C.

Power density levels for pain threshold for an exposed area of 9.5 cm^2 were 3.1 W/cm^2 for a 20 second exposure to 830 mW/cm^2 for exposures longer than 3 minutes[3]. The thresh-

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