Glaser

A Review of Selected Biological Effects and Dosimetric Data Useful for Development of Radiofrequency Safety Standards for Human Exposure*

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ABSTRACT

This report examines the bases for developing radiofrequency exposure standards which can be related to the thermogenic properties of electromagnetic fields. A review of selected biological effects, including dosimetric data and simulation of human thermodynamic characteristics that are pertinent to standards development, is presented. Based on the analogy of thermal-stress standards that have been developed for hot industrial environments, limits on increases of body temperature are proposed as criteria for limiting exposure to radiofrequency fields, i.e., occupational exposures involving deep heating of the whole body should not increase core temperature in excess of 1°C. Since energy deposition from exposure to some RF fields is likely to be non-uniform and may be high in tissues that are not adapted to high rates of absorption or dissipation of thermalizing energy, means are needed to adjust focal thermal loading against the whole-body averages. A limit on core temperature is inadequate when focal elevations of temperature are close to the limits for protein denaturation, as may well occur even though the core temperature may rise less than 1°C. Safety limits for the general population are also discussed and here the permissible thermal load should be low enough to cause no more than an insignificant increase in core temperature. Areas needing further research to reduce the uncertainties in developing safe exposure limits for man are delineated. Even in highly adverse environmental conditions the gross thermal load and consequential heat stress from exposure to radiofrequency fields at the 10 mW/cm² level will be small compared with that generated by any physical effort. On the basis of available data, it is concluded that the safe value for continuous exposure to 10 mW/cm², widely used in Western countries, appears to provide an adequate margin of safety for both occupational and environmental exposure for frequencies above about 1 GHz. This limit may well be too high (perhaps by an order of magnitude) for some frequencies below 1 GHz where body resonances cause a significant increase in energy deposition and where local temperature rises occur. At the same time the present averaging period of 0.1 h seems unjustifiably short.

INTRODUCTION

Our communication is addressed to examining the adequacy of the 10 mW/cm² level, widely accepted in many Western countries, as a "safe" limit for exposure of individuals to radiofrequency (RF) electromagnetic (EM) fields. This examination has been prompted by several factors. The existence of the much more stringent safety limits promulgated in the USSR (GOST, 1976; Shandala, 1978) is a source of continuing controversy. The rationales underlying these stringent standards have been argued at length but without resolving the issues because Western methodology has produced no substantial corroborative evidence giving sustained support for the more restrictive approaches. Insofar as the standards in the USSR are based in part

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on effects in small laboratory animals due to RF exposure in the frequency range 1–10 GHz, it is highly pertinent that recent research shows that the energy absorbed in these animals may be as much as 30 times greater than that for man in a field of a given strength. On the other hand, this research also suggests that the "safe" level of radiofrequency exposure, 10 mW/cm², used in the United States, United Kingdom and other Western nations, may be too high at lower RF frequencies. Although the American National Standards Institute (ANSI, 1974) voluntary standard for industry and the very similar standards of the UK have been widely upheld as applicable in the work place and even for non-occupational exposures, doubts have been expressed about their applicability to the general population. In view of the absence of any safety standard specifically designated for the population as a whole, several organizations, including the US Environmental Protection Agency and the UK National Radiological Protection Board, have been looking into this situation for some time. These various factors, when taken together, have been effective in creating a sense of uncertainty in the general population and are reflected in the public attitude that where there is no standard, a need for regulation exists (Justesen, 1978). A standard that is 20 years old is seen by many, not as one that has stood the test of time but as one that is obviously out of date (cf Glaser and Dodge, 1975).

Our thesis can be summarized as follows: (1) absorption of RF energy at high field strengths can be dangerously thermogenic to man and animals; (2) Western safety standards were initially established on a thermal basis; (3) we have sufficient new data to warrant re- examination of the adequacy of these thermally based standards; (4) the overwhelming thrust of the biological evidence we have is that thermal reasoning is a sound basis for a safety standard; (5) in terms of hazard the only "specific" effect of RF energy that need be considered is the unique way that the energy may be deposited internally in man, leading to temperature gradients and thermal loads which are difficult, if not impossible, to mimic by other methods.

This communication approaches the problem by viewing man as a biological entity in which various thermoregulatory mechanisms function to maintain a constant body temperature. Over 20 years ago similar arguments were introduced by Schwan and his colleagues (see for example Schwan and Li, 1956; Schwan, 1957) with respect to the development of RF safety standards. In many environmental conditions heat conservation will be more important than heat dissipation, but in viewing absorption of RF energy as a hazard we need to consider only the factor of dissipation. The homeostatic process has to cope with and is stressed by internal heat production via the metabolic functions of the body and external sources of thermal energy, be they high ambient temperature, sunlight or other sources of radiant energy, such as RF waves. The thermal load placed on man by RF fields is considered as only one of many thermal factors present in the environment, and it is proposed that the development of safety standards for man's exposure to such fields should follow a similar path to that proved in developing the thermal stress limits for work in hot environments.

In arriving at our thermally based position, we acknowledge the claims that weak (as averaged) pulsed and sinusoidally modulated fields may have potentially adverse effects. Reference is to reports of alterations of blood-brain barrier or neurocirculatory function, of augmented effux of calcium ions in *in vitro* brain materials, and of altered behavioral response to psychoactive drugs (cf Frey, et al., 1975; Oscar and Hawkins, 1977; Merrit, et al., 1978; Blackman et al., 1979; Bawin, et al., 1975, 1978; Thomas, et al., 1979). Though, in our opinion, the 20- to 30-min exposures that have resulted in the cited weak-field changes of biological function are not implicative of adverse effects, we agree that chronic studies are indicated and must continually be monitored to ensure that any safety guide developed now can be modified to properly reflect new results as they become available. We suggest that a valid scientific and realistic approach to a review of the Western standards is thorough study of the thermogenic properties of RF energy and their physiological effects.

THERMAL SUSCEPTIBILITY OF MAN

The susceptibility of man to thermally stressing environments has been studied extensively for many years. In 1944 Robinson et al. (1945) defined an "index of physiological effect" based on a subject's heart rate, skin temperature, rectal temperature, and rate of sweating during exposure to the environment being evaluated. They developed data that define physiologically equivalent effects associated with a wide range of environmental conditions. Their work suggested that for a given level of work activity, there are combinations of environmental conditions that elicit the same physiological stress; that is, if the environmental conditions are changed and the level of work activity is maintained, a different physiological stress reaction could become evident.

With increased understanding, various limits have been developed, aimed at protecting people who must work in a hot environment. These limits have made use of a number of different parameters that affect man's ability to tolerate thermal loads, the more important of these being air temperature, relative humidity (RH), air velocity, duration of exposure to the hot environment and the work rate during exposure. In developing its own criteria document for a recommended standard for occupational exposure to hot environments (NIOSH 1972), the US National Institute of Occupational Safety and Health reviewed the available proposals for controlling thermal stress in hot environments. NIOSH found that some of the proposals (Yaglou and Minard, 1957; Brief, 1970; Wyndham, 1962) could not be recommended to industrial workers because the margin of safety was too small. The NIOSH recommendations correlate permissible work rate with environmental factors to ensure that any increase in rectal temperature in man should be less than 1°C — they provided evidence that a 1°C rise in rectal temperature should be allowed as a reasonable upper limit for man's thermoregulatory response to heat stress. This view is also endorsed by WHO, but should be recognized as being conservative. Regular diurnal temperature excursions of 1.5°C in any individual are normal, and in directly equivalent circumstances the range of core temperatures of individuals may well exceed 1.0°C. Even after acclimatization there is a difference of 0.5°C ascribable to a tropical as opposed to a temperate climate. In Samson Wright's *Applied Physiology* (1971) it is stated that, after a 3 mile race, rectal temperatures as high as 40–41°C have been recorded in athletes, and that emotional stimuli can induce transitory body temperature excursions in mammals by as much as 2°C (Justesen, et al., 1974).

Figure 1, taken from Lind (1963) and reproduced in the NIOSH report, illustrates the levels of rectal equilibrium temperature of one subject operating at three different work rates in a wide range of climatic conditions. Effective temperature, used in Fig. 1, is an empirical sensory index, combining into a single value the subjective sensation of the thermal effect of

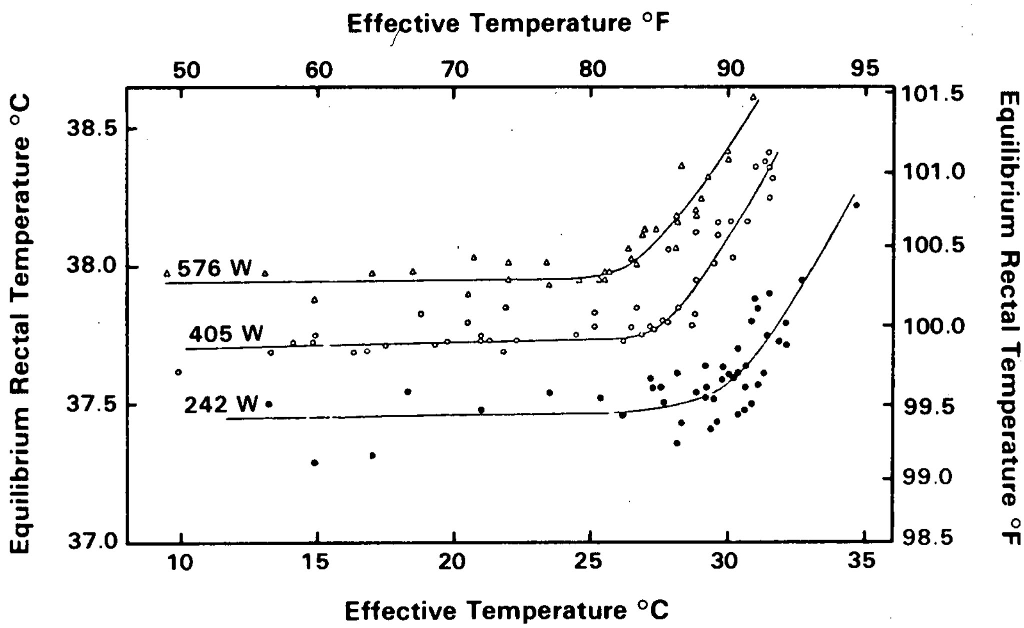

Figure 1 The levels of equilibrium rectal temperature of one subject working at 242, 405, and 567 W in a wide range of climatic conditions. From Lind (1963).

temperature, humidity, and air speed upon the human body. In still air at 100% RH, the effective temperature is the same as the dry bulb temperature, otherwise it is always lower. Lind's results show that the equilibrium rectal temperature in man is essentially independent of the environmental conditions up to a maximum effective temperature; below this temperature it is determined solely by the work rate. The higher the work rate, the higher the equilibrium rectal temperature and the lower the maximum allowable effective temperature.

Each data point in Fig. 1 was developed by an experiment that was continued until the equilibrium rectal temperature was reached, this being a period of 30 to 60 min depending on the combination of heat and work. The original work leading to this finding is credited to Nielson (1938) and subsequently was confirmed to hold only below critical air temperatures by Wyndham (1954). Wyndham and his associates showed that the sweat rate in men was a function of rectal temperature. They found that at rectal temperatures higher than about 38 to 39°C, sweat rate (the principle thermoregulatory process operating at high thermal loads) becomes insensitive to further increases in rectal temperature. At higher rectal temperatures, the thermoregulatory process becomes saturated.

According to Wyndham et al . . . "although the individual may experience difficulty in completing a task when his rectal temperature exceeds 101°F (38.3°C), he is not at the point at which excessive or intolerable conditions occur, with a danger of rectal temperature rising to hyperpyrexial levels, until the thermoregulatory processes are saturated or reach their maximum values. This does not happen until rectal temperatures reach 102–103°F (38.9–39.4°C) . . . It is equally clear that no industrially advanced nation can allow an industry to expose its employees to conditions which would saturate their thermoregulatory, processes, i.e., produce rectal temperatures in excess of 102–103°F (38.9–39.4°C), with a consequent risk of heat stroke."

Subsequent work by Stolwijk et al. (1968) added further data on how rectal temperature varies as a function of heat load and how, within limits, it is essentially independent of ambient air temperature. Figure 2 adapted from their paper demonstrates a linear relationship between rectal temperature and heat produced during exercise for three different ambient air temperatures. The correlation coefficient for the relationship between these two variables was found to be 0.91. When Lind's results are plotted in this way they yield a parallel line displaced to rectal temperatures higher by about 0.3°C.

In the NIOSH guidelines the environmental conditions are expressed in terms of the wet bulb globe temperature (WBGT).[1] Ramsey (1978) has summarized these WBGT guidelines in Table 1 which were arrived at by OSHA's Standard Advisory Committee on Heat Stress (Ramsey, 1975). The values of WBGT shown are intended not as upper limits or tolerance levels, but as levels that indicate the need for instigation of work practices to reduce adverse thermal effects. The values shown in Table 1 assume adult males, normally clothed, acclimatized, physically fit, in good health and nutrition.

It is important to note that in studies of young females (Lofstedt, 1966), it was found that females had higher body temperatures and lower sweat production than did young males for the same heat exposure. In accordance with these findings Dukes-Dubos (1976) has suggested lowering the WBGT threshold limits shown in Table 1 by 0.5°C to compensate for lower heat tolerance and 1°C for lower aerobic capacity in women. In a similar approach,modifications to the threshold values have been suggested for the obese and elderly as supported by the work of Minard (1973) and Henschel (1976). A lowering of the thresholds by 1-2°C is suggested due to these two factors. Minard (1973) and Webb (1964) have pointed out the higher heat storage and physiological stress associated with the unacclimatized state. Wyndham (1973) has discussed similar factors for workers not conditioned to a physical work task; In view of these data yet another modification of the WBGT values in Table 1 are suggested of about 2°C. Other modifications due to higher air velocities and different clothing have been suggested and Table 2 taken from Ramsey (1978) summarizes all of these modifications.

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[1]The WBGT is a method of quantifying the thermal characteristics of environmental conditions in a single parameter. WBGT is equal to 0.7 wet bulb temperature + 0.3 globe temperature where the globe temperature is obtained via a measurement of air temperature inside a 6 inch diameter black copper sphere (see Walters, 1968; Minard et al., 1964; Taylor et al., 1968). As with "effective temperature," WBGT is always lower than dry bulb temperature unless the measurements are made in still air at 100% RH.

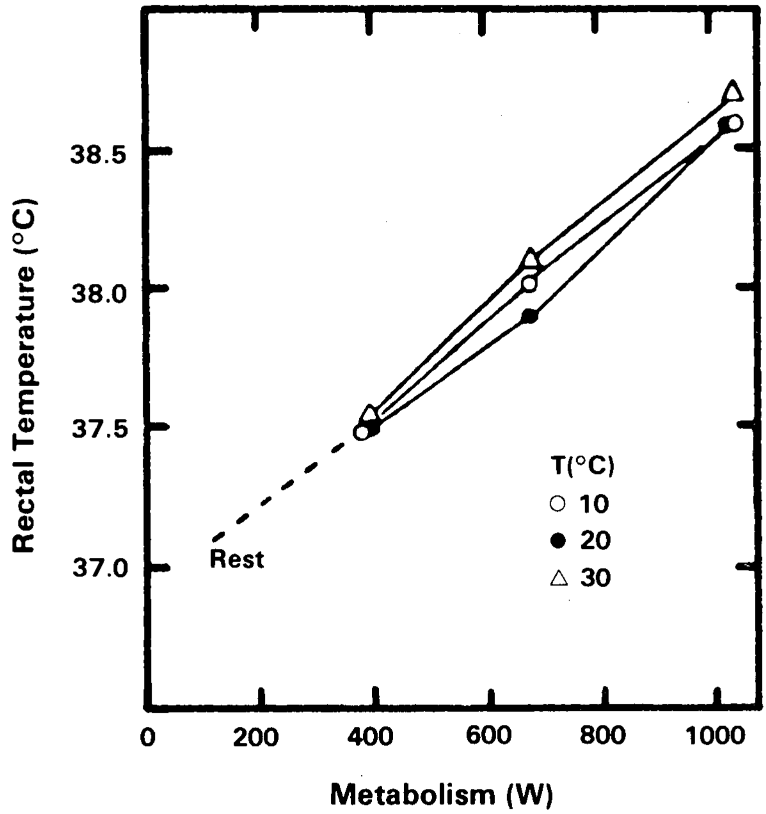

Figure 2 Variation of rectal temperature with metabolic rate at three different environmental temperatures. Adapted from Stolwijk et al. (1968).

Table 1 THRESHOLD WBGT LEVELS (Two hour time weighted average values) (taken from Ramsey, 1978)

Activity Level	Threshold °C	WBGT °F
Light work (less than 233W)	30	86
Moderate work (234–349W)	28	82
Heavy work (350–465W)	26	79
Very heavy work (greater than 465W)	25	77

Table 2 Suggested modifications to threshold WBGT values shown in table 1 (taken from Ramsey, 1978)

Factors	Modification	
	WBGT °C	WBGT °F
1. Unacclimatized, not physically fit	-2	-4
2. Air velocity:		
1.5 m/s (300 fpm) and air temperature 35°C (95°F)	+2	+4
3. Clothing:		
Shorts; semi-nude	+2	+4
Impermeable jacket or body armor	-2	-4
Rain coats, fireman's coat	-4	-7
Completely enclosed suits	-5	-9
4. Obese, elderly	-1 to -2	-2 to -4
5. Female	-1	-2

Givoni and Goldman (1972) developed a series of formulae useful for predicting rectal temperature response to work, environment, and clothing. For our purposes the most interesting aspects of their work are illustrated by Fig. 3. This figure includes predicted and measured rectal temperatures at two work rates, two wind speeds, and three clothing types. The data were obtained at a dry bulb temperature of 35°C and about 50 percent RH. Givoni and Goldman also conclude, "It seems that, from the point of view of the response of rectal temperature to ambient temperature, there are two zones. Below about 30°C and down to the 15°C examined in the present study, rectal temperature at rest or work is independent of the ambient air temperature per se, while above this zone it rises with it."

These findings are relevant to considerations of the thermal load which can be safely imposed on an individual by the absorption of radiofrequency energy. It seems clear that on the basis of classical heat stress concepts, safe work practices dictate maintaining the rectal temperature elevation in man to no more than about 1°C over his normal value. If exposure to radiofrequency fields is added as another component of the environment then corresponding adjustments may be required in work rate or other environmental conditions to maintain the rectal temperature rise within the prescribed limit but this is only likely to be necessary under extreme ambient conditions where heat rejection is difficult. The selection of a 1°C rise included consideration of the obvious fact that strenuous exercise in man results in an increase in average body temperature and that for all activity there is an associated physiologic strain. Maintaining physiologic conditions of heat stress within reasonable limits, according to sound dosimetric and biological research data, should also be acceptable in considering exposure to radiofrequency energy.

On the basis of the foregoing information the following general conclusion is reached. Under most environmental conditions up to about 30°C, the rectal temperature is determined

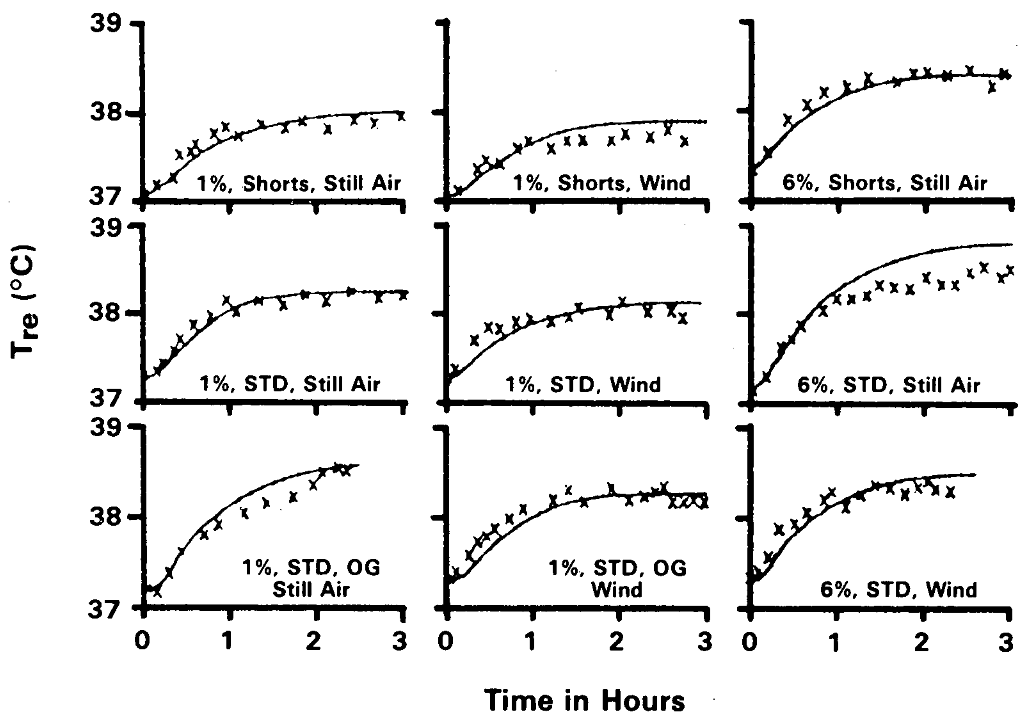

Figure 3 Comparison of predicted (lines) and measured (points) patterns of rectal temperature with two work levels (M = 310W and 470W attained by walking on an inclined treadmill at 1 and 6% grades), two wind speeds (still air = 0.5 m/s, and 5 m/s), and three clothing types (shorts, fatigues, and fatigues and overgarment). Air temperature was 35°C and vapor pressure 21 mm Hg in all experiments. From Givoni and Goldman (1972).

only by the work intensity for heat acclimated, young, physically fit males. In view of the observation by Kraning et al. (1966) that a heat load induced by physical activity is twice as strenuous on the cardiovascular system as an equal load caused by a hot environment, it seems conservative to assume that the heat stress induced by the absorption of RF energy will not produce higher rectal temperatures than an equivalent metabolic rate caused by exercise. In this case, the rectal temperature is used as a measure of the whole-body thermal stress level caused by the RF exposure and is most appropriately used for exposures at frequencies that ensure deep penetration into the body by the electromagnetic fields. An additional consideration, which may become most important under certain conditions of exposure, is the possibility of highly non-uniform deposition of energy within the body of man and subsequent non-uniform increases in localized tissue temperatures, the biological consequences of which may not be properly reflected by deep body average (rectal) temperature. With the proviso that for some conditions it may also be necessary to control local hot spots, it would seem reasonable to define intensity of radiofrequency irradiation as a function of frequencies that could potentially elevate man's rectal temperature by 1°C. Extensive theoretical calculations of body absorption by man have been performed by Durney et al. (1978) and an inversion of these specific absorption rate (SAR) curves from the viewpoint of thermal loads of RF energy in man (Tell, 1978) can be used to outline the limits of the RF fields to which man may reasonably be exposed.

THERMOGENIC BIOEFFECTS OF RADIOFREQUENCY ENERGY

The thermogenic properties of radiofrequency energy have been extensively documented in the literature on biological effects. A significant problem in making use of many of these data, however, is that it is very difficult, if not impossible, to obtain meaningful relationships among the observed effects, the parameters of environment and EM fields, and the potential impact of such exposures on human health. Upon examining the literature we found a surprisingly small number of reports that are directly quantitatively useful for the development of thermally based RF exposure standards. Few of the available reports provide sufficient technical detail to permit other than a purely qualitative insight. Table 3 summarizes a selection of what we perceive to be some of the more useful biological data. In this table, observed biological endpoints have been tabulated against the SAR. When not provided directly from the reports, values of SAR have been derived from the given exposure parameters and reference to Durney et al. (1978) with the assumption of electric field polarization with the body axis.

On the basis of the available bioeffects data the following conclusions seem reasonably supportable: 1. When an animal is thermally loaded to approximately its Basal Metabolic Rate (BMR) value, noticeable signs of heat stress become evident; 2. Clearly discernible elevations of rectal temperature in laboratory animals can occur at thermal loads as low as 20–30 percent of the BMR; 3. Though numerous behavioral and endocrine effects as well as heart and respiration rate changes have been observed at SARs below the equivalent of an animal's BMR, there is little evidence that these observed effects are anything but manifestations of normal physiological responses to mild thermal stress; 4. When RF induced thermal loads exceed about twice the BMR in small laboratory animals, the thermal stress, when maintained on a continuous and protracted basis, leads to significant shifts in various physiological indices that indicate unacceptable chronic strain if maintained for indefinitely long periods of time (order of days, months, and years); 5. There are no data which indicate that pulsed electromagnetic fields are any more hazardous than an equivalent average power CW field. This conclusion is based on relatively little pulsed field work and more research on pulsed effects is called for to strengthen this conclusion.

THERMODYNAMIC AND DOSIMETRIC CONSIDERATIONS

We find of particular interest the recent work of de Lorge (1978a), Guy et al. (1978) and Durney et al. (1978). In determining the effects of microwave exposure on changes in operant behavior in three different species (rats, squirrel and rhesus monkeys), de Lorge (1978a) observed that a noticeable shift occurred within one hour when the rectal temperature was elevated 1°C this time being on the order of the equilibration time for body temperature rise due to a step function increase in thermal load to man (Emery, 1975; Stolwijk and Hardy, 1966). de Lorge observed the interesting fact that the exposure power density required to elevate the animal's rectal temperature 1°C in 60 min appeared linearly proportional to the logarithm of the animal's body mass.

Table 3 Selected thermogenic effects of radiofrequency irradiation according to measured or estimated specific absorption rate (SAR) in W/kg

SAR	Observed Effects	Investigators
190	Produced 45°C in dog thyroid gland, localized thyroid exposure at 2.45 GHz, 2 h, thyroxin release rate 10X control value	Magin et al. (1977)
131	Produced 41°C in dog thyroid gland, localized thyroid exposure at 2.45 GHz, 2 h, thyroxin release rate 3X control value	Magin et al. (1977)
80	Highest incidence of congenitial anomalies in mouse fetuses after 4 min exposure on day 8 and 10 of gestation	Rugh (1976)
58	Produced 39°C in dog thyroid gland, localized thyroid exposure at 2.45 GHz, 2 h, thyroxin release rate 3.5X control value	Magin et al. (1977)
40	Severe heat stress in rats at 2.45 GHz, evidence of blood vessels being sensitive tissue	Polson et al. (1974)
35	In SAR range of 30–40, body temperature was 42.5 — 43.0°C in guinea pig; brain temperature sometimes as much as 2°C lower than rectal temperature, 2.45 GHz	Bruce-Wolfe et al. (1979)
28	5°C increase in brain temperature in rats after 2 h of exposure at 1600 MHz. 3°C increase in body temperature in 10 min, norepinephrine content of hypothalamus reduced below that of hyperthermal controls	Merritt et al. (1977)
25	Reduced oxygen consumption by mice with apparent heat stress at ambient temperature of 24°C, 2.45 GHz	Ho and Edwards (1976)
12	Increased respiration in rabbit 20X greater than heart rate, 2.45 GHz	Birenbaum et al. (1975)
12	Increased heat dissipation rate in mice, 2.45 GHz	Ho and McManaway (1977)
11	Rectal temperature of 42.4°C in rats at 2.45 GHz accompanied by severe heat stress	Phillips et al. (1975)
11	Bradycardia after 1-h exposure in rats at 2.45 GHz, acclimation after repeated exposure	Phillips et al. (1973)
8	Plasma corticosterone levels elevated in rats after 30 min at 2.45 GHz	Lotz and Michaelson (1978)
8	Growth hormone levels lower in rats at 2.45 GHz, 30 or 60 min	Lotz et al. (1977)
7	Change in mitogen stimulated response after 4 h exposure/day *in utero* of rats at 425 MHz	Smialowicz et al. (1977)
6.5	Observed threshold for depression of metabolic rate in rats at 2.45 GHz (lower oxygen consumption)	Phillips et al. (1975)
6.4	No apparent effects in rats in offspring or litter size at 2.45 GHz, 1 h on day 9 and 16 of gestation	Michaelson et al. (1976)
5.6	Upper level of dose rates *in utero* producing some exencephaly in mice, 2.45 GHz, 100 min daily during organogenesis	Berman and Carter (1978)
5.5	No heart rate changes in turtle or tortoise whole-body exposure at 960 MHz	Flanigan et al. (1977)
5.0	Change in mitogen stimulated response after 4 h exposure/day *in utero* of rats at 2450 MHz	Smialowicz et al. (1977)
5.0	Reduced oxygen consumption in rats at 2.45 GHz at ambient temperature of 24°C	Ho and Edwards (1976)
4.9	1°C rise in rectal temperature in rats at 2.45 GHz after about 60 min, ambient temperature of 22.5°C	Houk et al. (1975)
4.8	Noticed transient elevation in plasma corticosterone levels on rats at 2.45 GHz, 30 min	Guillet et al. (1975)
4.8	Ambulatory activity decreased in rats at 2.45 GHz	Sanza and de Lorge (1977)

Table 3 continued

4.3	1°C rise in rectal temperature in rhesus monkey after 60 min at 2.45 GHz	de Lorge (1976)
4	No metabolic effects in rat at 2.45 GHz	Phillips et al. (1975)
3.5	Threshold for elevation in rat rectal temperature after 2 h at 1600 MHz	Merritt et al. (1977)
3.2	Plasma corticosterone levels elevated in rats after 60 min at 2.45 GHz	Lotz and Michaelson (1978)
3.2	Threshold for increase in rectal temperature in rats after 1 h at 2.45 GHz, no changes in adrenal or thyroid gland weights up to 8 h exposure	Lu et al. (1976)
3.1	0.70°C rectal temperature rise in rats at 2.45 GHz at ambient temperature of 22.5°C	Houk et al. (1975)
3.0	"few" W/kg influenced neural output in isolated neural preparations	Seaman et al. (1975)
2.9	Ambulatory activity decreased in rats at 2.45 GHz	Sanza and de Lorge (1977)
2.7	"Not thermally significant" in mice after 100 min at 2.45 GHz	Berman and Carter (1978)
2.5	Rectal temperature elevated 1°C in squirrel monkey in 60 min at 2.45 GHz	de Lorge (1977)
2.5	Lower threshold for latency changes in neuron conduction at a range of different frequencies	Guy et al. (1974)
2.4	Obvious signs of thermal stress in rats after 1 h, for 5 days 2450 MHz	Diachenko and Milroy (1975)
2.1	Bradycardia in isolated rat heart, 960 MHz	Olsen et al. (1977)
2.0	Colonic temperature significantly increased in rats after 60 min at 2.45 GHz	Lotz and Michaelson (1978)
2.0	0.7°C rise in rectal equilibrium temperature after 1.5 h at 26 MHz	Frazer et al. (1976)
1.6	Observable changes in rectal temperature in rats at an ambient temperature of 27.5°C and 2.45 GHz	Houk et al. (1975)
1.6	Circulatory thyrotropin levels depressed in rats after 1 or 2 h at 2.45 GHz	Lu et al. (1977)
1.6	Threshold for some measured parameters in rats exposed for 10 days, 2 h/day at 2400 MHz	Dordevic (1975)
1.6	No difference in body mass of mice exposed 2 min/h daily, for 36 days, 2.45 GHz	McAfee et al. (1973)

In Fig. 4 we plot de Lorge's power density-temperature threshold data and extrapolate the curve to man's body mass of 70 kg and then find that the expected exposure intensity at 2.45 GHz producing a 1°C rectal temperature rise in man would presumably be about 92 mW/cm², assuming that man's thermoregulatory system would function as well as that of the lower animal. Michaelson[1] observed a similar relation when he correlated power density with surface area of the body. It must be recognized that the projected 92 mW/cm² exposure for man does not consider the fact that the principal heating will be surface heating and although the body core temperature may in fact not rise appreciably, localized tissues near the body surface may approach a dangerous level, i.e., that of irreversible denaturation. Thus, great caution and judgement is necessary when trying to evaluate the thermal load placed on an individual from a RF field. In proposing limits for RF exposure it is necessary, therefore, to establish that the thermal load and temperature excursion of local tissues is not sufficient to cause injury or unacceptable stress. Even so, it seems rather obvious that the present safety standard of 10 mW/cm² in use in the US and UK provides an adequate margin of safety both for deep body core and surface temperature elevations in occupational environments at 2.45 GHz.

Our reasoning is predicated on the basis that the depth of penetration for 2.45 GHz radiation is such that about 90 percent of the energy is deposited within the first 4 cm of tissue and that if all of the incident energy were absorbed with no reflection, a maximal rate of energy deposition on the order of 2.5 W/kg would result from a 10 mW/cm² exposure. In a static system, with no thermal diffusion or dissipation mechanisms operative, this rate would lead to no more than a 2-3°C rise in the outer layers of tissue in a 3-h period. In the dynamic system of man with an ability to equilibrate core temperature within 1-2 h (Emery, 1975; Stolwijk and Hardy, 1966) it would be surprising to see a 1°C rise in these tissues. The time required for at-

[1]Personal Communication at 1978 IMPI Meeting, Ottawa, Ontario, Canada, June 27–30, 1978.

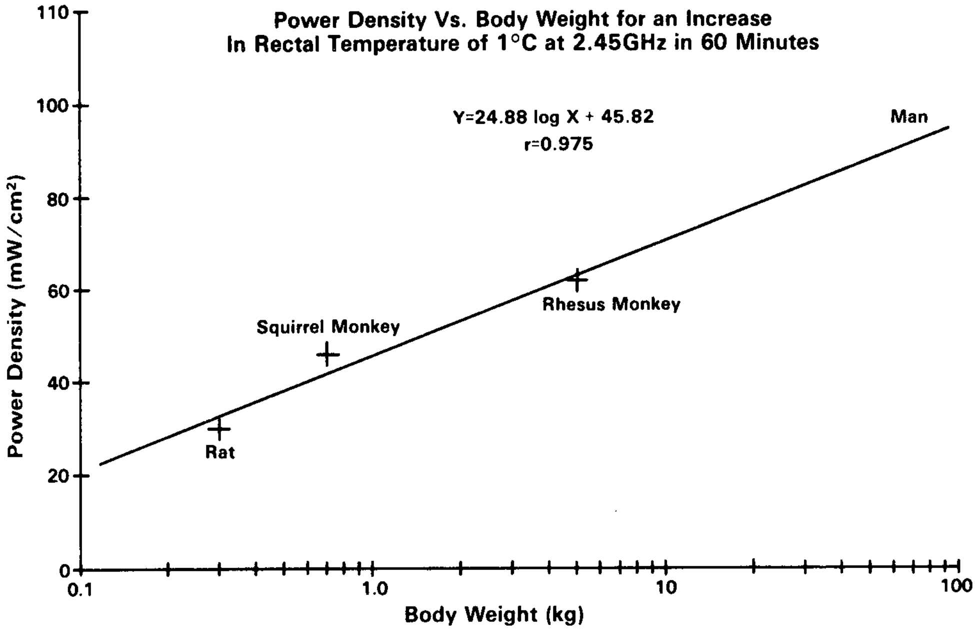

Figure 4 Power density capable of elevating rectal temperature 1°C in 60 min of radiofrequency exposure as a function of body weight using data of de Lorge (1978).

tainment of thermal equilibrium in localized tissues may be quite short and considerably less than 1 h (Kritikos and Schwan, 1979). A pertinent observation by Ely and Goldman (1957) which involved human whole body exposure to high intensity (~ 100 mW/cm^2) microwave radiation at 3 GHz showed a slight net decrease in rectal temperature after sufficient time had elapsed and body sweating was activated.

Durney and his co-workers (1978) have provided us with a convenient means of gleaning additional insight from the data of de Lorge and Michaelson. We found it instructive to form the ratio of the RF thermal load placed on the animal to it's BMR and plotting this quantity vs. body mass. Figure 5 shows the results of this operation and illustrates another way of viewing

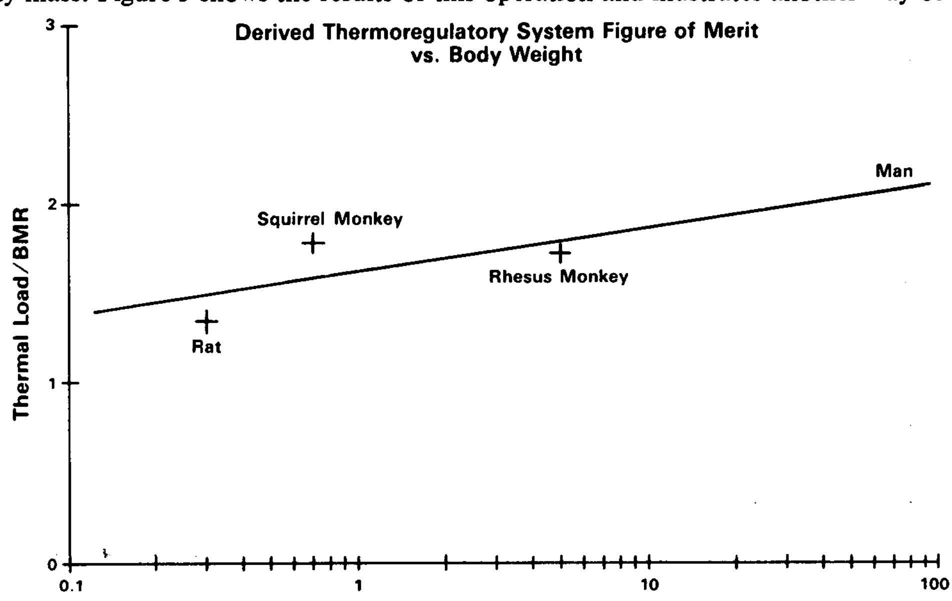

Figure 5 Derived thermoregulatory system figure of merit vs. body mass. The figure of merit is defined as the ratio of the radiofrequency induced thermal load to the basal metabolic rate of the animal resulting in a 1°C rise in rectal temperature in 60 min.

the apparently greater thermoregulatory capacity of man compared with smaller animals. The ordinate of Fig. 5, which could be referred to as a figure of merit of the thermoregulatory capacity, was developed by using the specific absorption rates (SAR) and BMR data from Durney et al. (1978) in conjunction with the experimentally determined power densities, i.e.:

$$\text{Thermal load (W/kg)} = \text{SAR} \left(\frac{\text{W/kg}}{\text{mW/cm}^2}\right) \times \text{S(mW/cm}^2\text{)}$$

By using the BMR expressed in terms of W/kg, we obtain a dimensionless quantity plotted as the ordinale. SARs were obtained by referring to Fig. 6 where we have taken the whole body SAR values as given by Durney et al. (1978) for different sized animals and man found at 2.45 GHz and determined the linear regression line through these data. This figure was then used to read values of SAR for different body masses of animals used by de Lorge. Values of the BMR of the different animals were obtained by fitting a linear regression line through the many values of BMR provided by Durney et al. (1978). We obtained the expression

$$\log R = 0.74 \log M + 0.59 \text{ where}$$

R is the metabolic rate in units of watts and M is the body mass in kg. A correlation coefficient of 0.996 was obtained. Some differences in unique thermoregulatory behavior as suggested by de Lorge (1978b) may account for some of the scatter seen in Fig. 5. Figure 5 illustrates that there seems to be an interesting commonality between the thermoregulatory capacities of the different animals for RF exposure when normalized to their BMR values. The figure suggests that for man, as well as for the smaller animals, when the thermal load developed by RF energy alone is some 1.5–2.0 times the BMR, a 1°C rise in rectal temperature would be expected, presuming that the thermal load is generally distributed in a similar way as it is in the smaller animals. We have projected, via a least-squares fit of the small animal data, a value for the so called thermoregulatory figure of merit for man of some 2 x BMR. Obviously, at 2.45 GHz this thermal distribution will not be similar but at lower frequencies where the depth-of-penetration to body-size ratio is proportionately similar in respect to that in the rat at 2.45 GHz, the figure of merit should hold. By using the methods of Durney et al., we estimate this lower equivalent

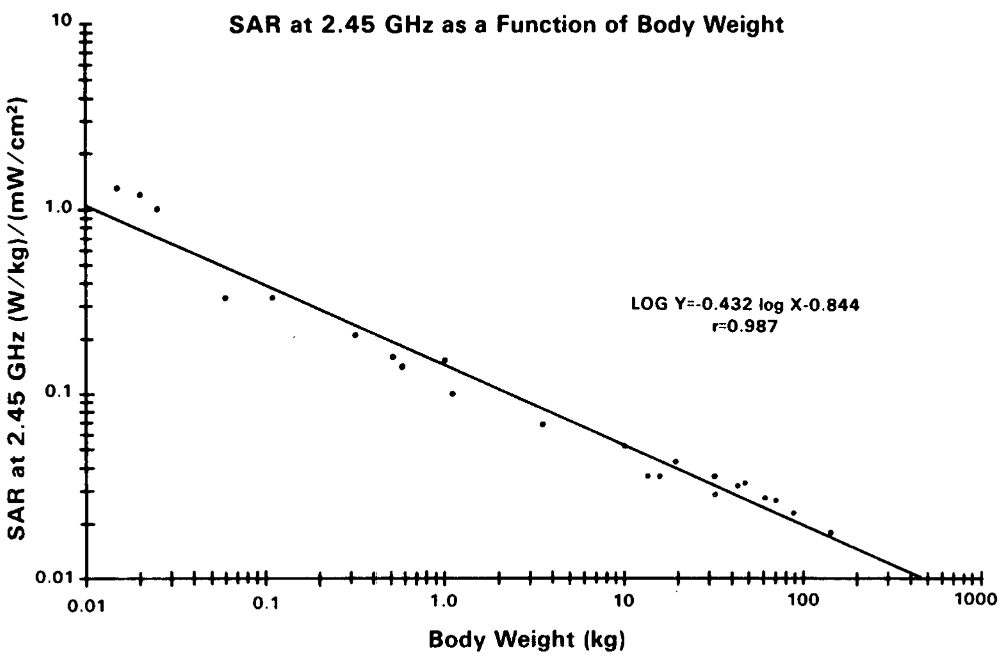

Figure 6 Specific absorption rate (SAR) as a function of body mass at 2.45 GHz with body axis aligned with the electric field using data of Durney et al. (1978).

frequency to be around 350 MHz. Thus, the extension of the above reasoning to lower frequencies than 2.45 GHz seems justified and we suggest that as a convenient boundary, occupational exposures at 10 mW/cm^2 time averaged power density above 1 GHz would appear unquestionably thermally safe.

Due to a lack of pertinent experimental data on elevation of animal's body temperatures at lower frequencies, it is not clear how low in frequency this approach can be taken. The problem of the thermodynamic modelling of the human body has received considerable attention (Fan et al., 1971), but the first attempt to consider the addition of RF energy as a thermal load in a model of man was performed by Guy et al. (1973). Subsequently, Guy et al. (1978) made use of Emery's modeling technique (Emery, 1975) to determine the increase of body temperature in man exposed at two different frequencies. Figure 7 taken from their work shows the results of exposing man at the whole-body resonant frequency of about 80 MHz at 10 mW/cm^2. Thermographic determinations of the distribution of energy at 80 MHz were used to provide input to the thermodynamic model. Results show temperatures at various anatomical locations of the body. Attention is drawn to the hypothalamic temperature, which starts near 36.9°C and reaches an equilibrium value of 37.9°C, thus showing a 1°C rise. If we assume that the hypothalamic temperature is essentially equal to the rectal temperature or no more than about 0.2°C lower, then absorption of RF energy at the observed rate of 170 W leads to a rise of rectal temperature near 1°C in a period of about 3 h. Figure 8 (from Guy et al., 1978) illustrates predicted body temperatures as a function of time for a metabolically generated value of 275 W (170 W due to exercise + 105 W BMR), which could be accomplished by work activity. Good agreement is observed between the predicted 1°C rise of hypothalamic temperature obtained by Guy et al. (1978) and that of Givoni and Goldman (1972), who used an external work level of almost the same value (205 W vs. 170 W) (compare Fig. 8 with Fig. 3). These results indicate a general agreement with the assumption that the irradiation-induced thermal load can be equated to an equal level of work activity (exercise) in terms of the expected increase in general, deep-body temperature.

We have employed the highly useful formulae developed by Givoni and Goldman (1972), which relate body heat production, environmental conditions described by air temperature, vapor pressure, and wind speed, the thermophysical properties of clothing, and the resulting equilibrium rectal temperature in man. These relationships were developed from extensive tests with men and represent an empirical approach to the solution of the heat balance equation for man. They found that:

$$T_{reeq} = 36.75 + 0.004\,M + (0.0218/\text{clo})\,(T_{DB}-36) + 0.8\exp 0.0047(E_{req}-E_{max}) \tag{3}$$

where

T_{reeq}	=	the equilibrium rectal temperature
E_{req}	=	required evaporative cooling = $M + (11.6/\text{clo})(T_{DB}-36)$
E_{max}	=	maximum possible evaporative cooling = 25.5 $(\text{im}/\text{clo})(44-\phi Pa)$
M	=	total metabolic rate (W)
T_{DB}	=	dry bulb air temperature
clo	=	thermal resistance of clothing system
im/clo	=	permeability index of clothing
ϕPa	=	vapor pressure of air (mmHg)

The clo and im/clo values are in turn functions of the effective air velocity given by

$$\text{Veff} = \text{Vair} + 0.004\,(M-105);\ \text{m/s}$$

and for a man clothed only in shorts with no shirt, Givoni and Goldman (1978) state values for clo and im/clo as

$$\begin{aligned} \text{clo} &= 0.57\,\text{Veff}^{-0.30} \\ \text{im/clo} &= 1.20\,\text{Veff}^{+0.30} \end{aligned} \tag{4}$$

For a standard military uniform consisting of fatigues they provide

$$\begin{aligned} \text{clo} &= 0.99\ \text{Veff}^{-0.25} \\ \text{im/clo} &= 0.75\ \text{Veff}^{+0.25}. \end{aligned} \tag{5}$$

We have made use of equation 3 to examine the anticipated rise of core temperature under an applied intensity of RF radiation where M includes the heat load provided by RF energy. We assumed a comfortable environment as defined by ASHRAE (1967) consisting of $T_{DB} =$ 25.0°C, ϕPa = 12 mmHg or relative humidity of 50%, and an air velocity of 0.13 m/s. Figure 9 presents the results where the equilibrium rectal temperature is plotted as a function of the incident power density *at body resonance*. It is apparent that above approximately 30 mW/cm² the human thermoregulatory system is potentially overloaded and uncontrolled excursion of rectal temperature may occur for sustained exposures. We point out that these calculations assume that the individual is at rest and thus any additional physical activity will reduce the duration of the induction period before overheating occurs.

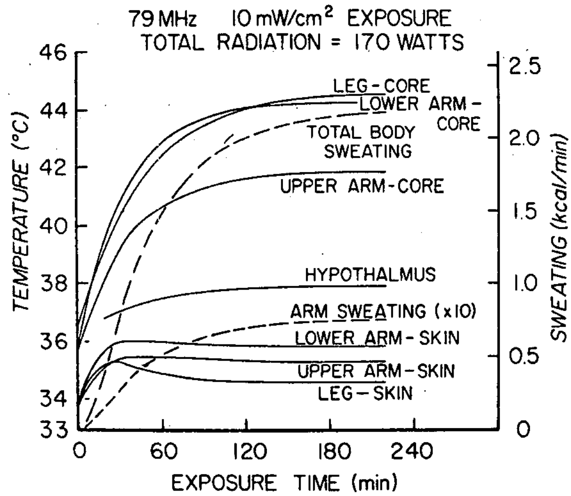

Figure 7 Change in temperature and sweating of man exposed to 79 MHz electromagnetic fields at 10 mW/cm². From Guy et al. (1978).

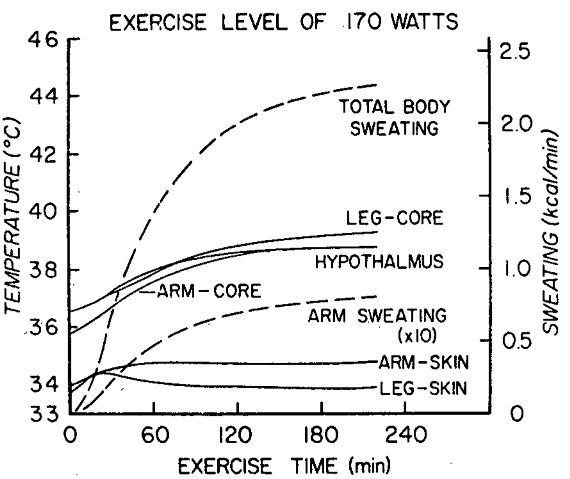

Figure 8 Effect of exercise on tissue temperature and sweating. A total metabolic rate of 275W (170W due to exercise plus 105 basal metabolic rate) is assumed. From Guy et al. (1978).

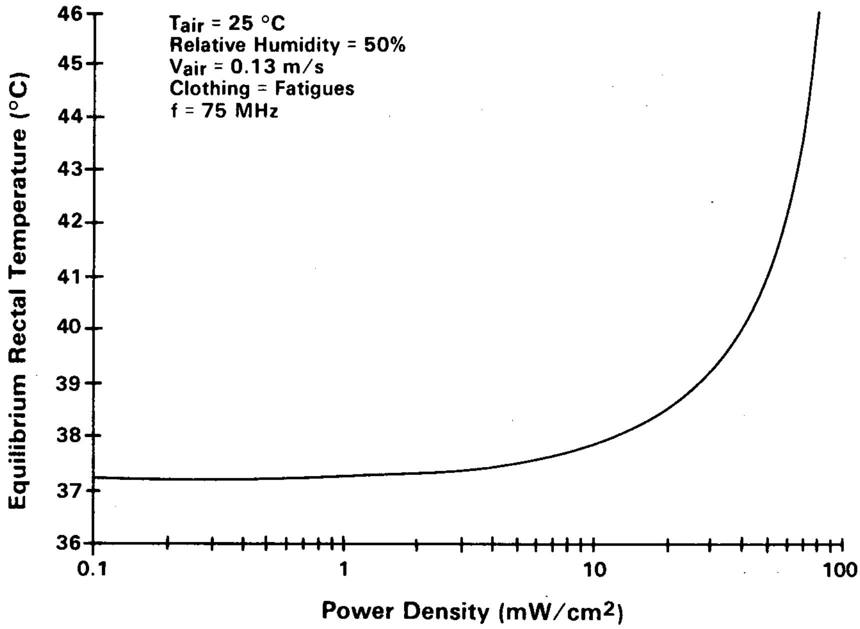

Figure 9 Equilibrium rectal temperature in man dressed in fatigues, at rest in a thermally comfortable environment as a function of incident power density of an electromagnetic field at 75 MHz.

It is informative to also examine the effect of the climatic environment on man's tolerance to applied RF heat stress and we have developed in Fig. 10 a plot of the relative increase in equilibrium rectal temperature in a resting man associated with a fixed RF exposure level of 10 mW/cm^2 *at body resonance* for various values of the WBGT. Mumford (1969) first questioned this influence of the thermal environment on permissible RF induced heat stress. The comfort zone is normally taken approximately around 20°C WBGT. It should be noted that WBGT's of more than 30°C represent extreme environmental conditions such that only light work should be carried out and the duration of the work should be closely controlled. Again we emphasize the importance of considering the combined action of the applied RF heat load and the ongoing work activity. Finally, using the methods of Givoni and Goldman (1978) we have determined for man wearing shorts, and no other clothing, the applied RF-induced heat load required to elevate his resting rectal temperature by 1°C as 268W or approximately 2.6 x BMR. We observe again the encouraging convergence of values obtained for increasing man's body temperature by approximately 1°C by noting the figure of merit projected for man from small-animal data

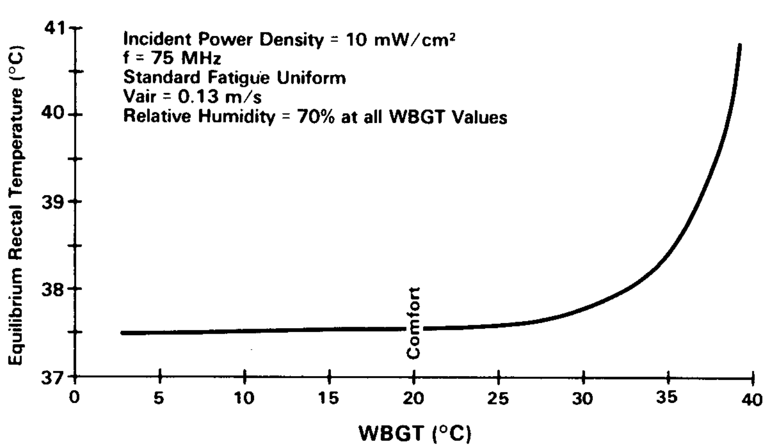

Figure 10 Equilibrium rectal temperature as a function of the WBGT for a constant exposure to a 75 MHz, 10 mW/cm^2 electromagnetic field.

in Fig. 6 of about 2 x BMR and the Guy et al. (1978) value of 1.6 x BMR. We conclude that for man, when the heat load imposed by a RF field is between about 1.6 and 2.6 times the BMR, deep core body temperature will rise 1°C.

Unfortunately, these findings are not of themselves sufficient to estimate the total extent of possible thermal injury. Figure 7 also shows that the highly localized absorption of radiofrequency energy in man's leg combined with limited themoregulatory capacity will cause internal thigh temperatures to increase to about 44°C within 180 min. Such a temperature may result in irreversible tissue damage and is not acceptable. These interesting thermal modeling results have been corroborated recently by Deffenbaugh et al. (1979); their results, obtained from a cell approach to the computation of internal fields and a cylindrical thermodynamic model, substantiate the finding that the localized SAR, when effective over a large enough tissue volume, will severely reduce thermoregulatory efficiency to the affected area, resulting in an unacceptable rise of tissue temperatures. It is important, however, to distinguish between electromagnetic and thermal hotspots. Kritikos and Schwan (1979) point out the thermal smearing effect of blood circulation which will tend to lessen the thermal impact on specific tissue areas which might be predicted solely on the basis of local SAR values. Kritikos and Schwan (1979) also revealed a potential hot spot temperature elevation of 0.5°C with normal cerebral blood flow and an incident field of 10 mW/cm² in a 10 cm diameter spherical model of the human brain.

Using the data of Guy et al. (1978) we adopted the conservative assumption of a linear relationship between the temperature of various anatomical parts of the body and exposure power density to estimate the intensity that would be associated with a maximum tissue temperature rise of about 1°C, which near body resonance in free space means areas particularly in the region of the thigh. Under this conservative assumption, a limiting exposure of about 1.5 mW/cm² would be suggested. A rise of core temperature of 1°C as a limiting criterion for RF exposure is obviously not sufficient to completely protect the body from thermal injury and it is clear that as frequencies approach body resonance, the present 10 mW/cm² standard is too permissive for sustained exposure. The standard should in fact be modified to become more restrictive through the body-resonance range.

At frequencies below body resonance the rate of energy absorption falls as the square of frequency and it seems to us that considerable progressive relaxation of the safe limit is warranted, with the proviso that local temperatures are not excessive. Tell et al. (1979) have recently provided experimental confirmation of highly localized current densities in man immersed in low-frequency fields, which indicates that local tissue SARs in small cross-sectional areas may exceed whole body averages by two orders of magnitude. Significant enhancements of SARs, particularly at lower frequencies, are likely to take place within a wavelength of the source where reactive fields will predominate. The selection of a frequency below which permissible levels are allowed to rise might reasonably embody consideration of operational characteristics of sources. Such considerations could help avoid practical problems of implementing protective guides and provide the required safety without being unnecessarily restrictive.

For people concerned with radiation protection an inversion of the whole-body SAR curves of Durney et al. (1978) for man may prove useful in visualizing the implications of the frequency dependence of body absorption on permissible exposures as illustrated by Tell(1978). Figure 11 shows curves of exposure levels that restrict whole body RF loading to 3 W/kg. This is an average value of the thermal load indicated by the preceding analyses that would be expected to raise a resting individual's rectal temperature by about 1°C for exposure durations of the order of 1 h or more to E and H polarized fields. The spread of results given in Fig. 11 reflect the range of SARs appropriate to different body dimensions for men, women and children.

For frequencies above about 500 MHz the curves of Fig. 11 suggest that the precise polarity of the radiation is unlikely to be important for the more probable kinds of far-field (plane-wave) exposures — orientation of the body parallel either to the E or to the H vector. Below 500 MHz, polarity becomes progressively more important as resonance is approached and at 70–80 MHz there is a factor of 10–20 between field polarizations. At these lower frequencies, of course, localized tissue heating as opposed to global rise of body temperature may be the critical

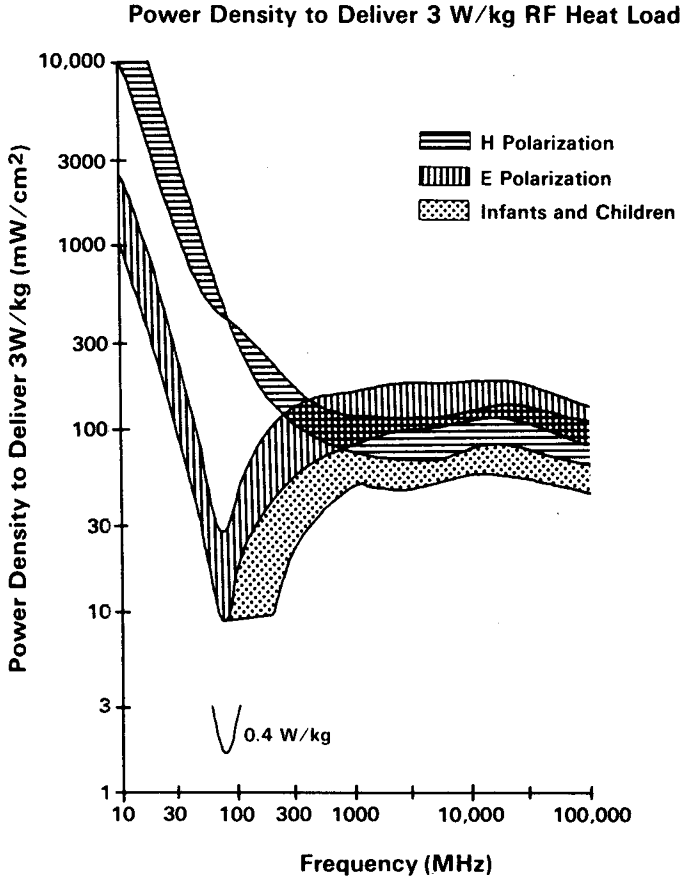

Figure 11 Power density as a function of frequency that will produce a thermal load of 3 W/kg in men, women and children for electric (E) and magnetic (H) field polarization.

factor, and Fig. 11 shows also the values of power density around the region of resonance that would restrict the whole body SAR to less than 0.4 W/kg and temperature rise in the thigh below about 1°C. However, these frequencies correspond to wavelengths in air of about 4 m and it is likely that the more significant exposures will be at distances of less than a wavelength from the source. At distances of less than a wavelength power density is a rather meaningless concept. The E and H fields are no longer in phase. There will be components of various polarizations and the reactive components, which vary much more rapidly with distance than the resistive "radiated" components, will tend to predominate. Further research is needed on these near-field exposures, on partial-body exposures and on the consequences of non-uniform energy deposition in man.

CONCLUSIONS

In the final analysis, it is extremely difficult to relate changes in health to small changes in body temperature. In keeping with the philosophy that if we are to err, it is better to err on the safe side, we find attractive the concept of limiting exposures such that there is no increase in body core temperature, if the cost is acceptable. When an observable increase in body temperature occurs, this must be interpreted as an indication that the physiological system is under some stress and for the general population no significant increase in body core temperature from exposure should be allowed. In the context of diurnal temperature changes in individuals of about 1.5°C, any core temperature increase estimated for exposure to 10 mW/cm² of 2.45 GHz radiation can surely be regarded as insignificant. In the case of extremely high frequencies, where only surface heating occurs, tolerable levels could well be established on a basis similar to that used in setting light and infrared radiation safety guides.

In occupational exposures, it seems reasonable to accept some degree of thermal stress and, for exposures above 1 GHz, to base exposure limits on elevation of core temperature. There is, however, no need to change the limit of 10 mW/cm² as this is quite workable occupationally and it may also be adequately safe for environmental exposures. The data of Kritikos and Schwan (1979) would suggest a possible frequency boundary of 1–3 GHz. Below approximately 1 GHz localized tissue temperatures are likely to be the limiting factor but exposure limits will be unnecessarily restrictive unless reasonable temperature excursions are allowed — relatively small volume heating on a local basis is significantly less stressing than a similar increase in body core or average temperature. The present averaging time of 6 min seems rather short as compared with the exposure durations of an h or more for attaining body core thermal equilibrium implied in much of the work described in this report.

We would hasten to agree that our level of knowledge about RF-energy induced thermal stress in man is small. We are struck by the very small number of pertinent research papers within the literature on biological effects of radiofrequency energy which provide much meaningful insight to this problem. It would appear highly appropriate to bring the experiences reported on in the large, classical heat stress literature to bear on problems relating to exposure to radiofrequency radiation. Physiological research aimed at identifying threshold exposure levels which cause just observable body temperature rises in man and experimental animals at different frequencies is needed. Much useful information may be derived by re-evaluation of old animal experimental data using recent dosimetric insights as suggested by Michaelson and Lu (1979). Extension of work on modeling the properties of man's thermoregulatory system is needed to give greater insight to the complicated thermal distributions which occur in man under different conditions of exposure. The very difficult task of assessing and generalizing about the physiological impact of localized tissue temperature elevations in animals and man should be attempted because of characteristically non-uniform deposition of radiofrequency energy, especially at frequencies lower than 1 GHz. We have almost no knowledge of the correlation of energy deposition and exposure when this takes place in the reactive fields less than 1 wavelength from the source.

Our conclusion then is that above perhaps 1 GHz we can conceive of no damaging thermal stress in man at an intensity of 10 mW/cm² — the currently accepted guideline in many Western countries for occupational exposure. At lower frequencies the margin of safety can be much lower in localized tissues and unacceptable temperatures are theoretically possible when the exposure duration encompasses several h. This problem is most critical near body resonance. A lowering of the permissible level for continuous whole body exposures to perhaps 1 mW/cm², for E field polarization, seems justified on the basis of present research results. The consideration of both core temperature and localized body temperature seems desirable in establishing frequency-dependent exposure limits to RF waves, but we emphasize the need to investigate more carefully the possibility of adverse reactions in animals that may be due to localized heating in the absence of significant whole-body heating.

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