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Technical Note

An Analysis Of Radiofrequency And Microwave Absorption Data With Consideration Of Thermal Safety Standards

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AN ANALYSIS OF RADIOFREQUENCY AND MICROWAVE ABSORPTION DATA WITH CONSIDERATION OF THERMAL SAFETY STANDARDS

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April 1978

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PREFACE

The Office of Radiation Programs of the U.S. Environmental Protection Agency carries out a national program designed to evaluate population exposure to ionizing and nonionizing radiation, and to promote development of controls necessary to protect the public health and safety. This report presents an analysis of existing data on radiofrequency and microwave absorption by humans and examines the absorption of nonionizing radiation as a thermal load on the body tissues. The thermal viewpoint presented in this report represents one possible approach to the development of realistic public health safety standards. Readers of this report are encouraged to inform the Office of Radiation Programs of any omissions or errors. Comments or requests for further information are also invited.

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AN ANALYSIS OF RADIOFREQUENCY AND MICROWAVE ABSORPTION DATA WITH CONSIDERATION OF THERMAL SAFETY STANDARDS

ABSTRACT

An analysis of existing radiofrequency and microwave radiation absorption data has been performed to examine the frequency dependent phenomenon of biological tissue heating. This analysis restricts itself to thermal considerations and examines the exposure field intensities associated with various levels of RF and MW induced thermal loading on both the body as a whole and specific, selectively absorbing tissues in adult humans and infants. An underlying absorption factor of 1W/kg, this being equivalent to the basal metabolic rate for the adult averaged over total body mass, is used for comparative purposes in the analysis. A method of specifying safety standard limits based on the electromagnetic field energy density rather than the plane wave, free-space equivalent power density is presented. The analysis reveals a particularly important resonance frequency range, 10 MHz $\leq$ f $\leq$1000 MHz, in which RF and MW absorption may lead to whole body thermal loads several times the whole body basal metabolic rate for exposures equal to the present safety standard in use in the United States. A discussion is developed for applications of this analysis to occupational environments and short duration exposure conditions. Some implications of this thermal analysis of RF and MW energy are discussed in terms of existing safety standards in use in the United States and the Union of Soviet Socialist Republics (USSR) and to typically encountered exposures in the United States.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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The author would like to acknowledge the kind cooperation in providing copies of technical papers, preliminary results of significance, and informative comment from Dr. Arthur W. Guy at the University of Washington, Seattle, Dr. Om P. Gandhi, Dr. Peter W. Barber, and Dr. Carl H. Durney at the University of Utah, Salt Lake City, and Dr. Claude M. Weil at the Health Effects Research Laboratory, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. Stimulating discussions are gratefully acknowledged with Dr. Elliot Postow, EMR Project Office, Naval Medical Research and Development Command, Bethesda, Maryland, Dr. A. Richard Dassler, Naval Medical Research Institute, Bethesda, Maryland, Dr. Elanor R. Adair at the John B. Pierce Research Foundation, New Haven, Conneticut, and Dr. Maria A. Stuchly at the Radiation Protection Bureau, Health and Welfare, Canada.

INTRODUCTION

The U.S. Environmental Protection Agency (EPA) has for the past five years been studying the exposure of the population to radiofrequency (RF) and microwave (MW) energy. These studies have focused principally on measuring the exposure of the population and determining if presently employed voluntary standards for the industry as proposed in ANSI C95.4 1966 (1) and as adopted in the Occupational Safety and Health Administration (OSHA) standards 29 CFR1910.97 (2), 29 CFR1910.268 (3), 29 CFR1926.54 (4), and as modified in ANSI C95.4 1974 (5) would adequately provide RF and MW protection to the general population as well as to RF and MW workers. Such a concern is prompted by the fact that the original ANSI proposals were developed because of concern for radiation safety within the industrial and military work place for those purposefully employed for work with high power RF and MW sources. Realizing that these groups presumably possess several important distinctions from the general population as a whole, such as age, physical fitness for specific jobs, general health status, and knowledge of predisposing conditions such as the administration of drugs and medical treatment, that are generally under the control of the employer, it is rational to perhaps permit somewhat higher exposure levels to RF workers. It is not clear that these distinctions from the population as a whole are properly accounted for when applying such industrial guidelines to everyone. Mumford (6) has recommended that the present occupational safety level for continuous exposure be appropriately reduced according to the ambient heat stress already present. Mumford's fundamental thermal approach to the problem is a clear reminder that pre-existing thermal stress may be viewed as that created by the external thermal environment on the individual, or the inherently variable susceptibility to added heat stress (thermal sensitivity) which may be a characteristic of particular individuals within the population.

This paper addresses itself to what we presently understand about the complicated problems of the absorption of RF and MW energy by humans and how this absorbed energy is deposited spatially as a volumetric heating load on the body tissues. The resulting frequency dependence of whole body and tissue specific RF and MW power deposition is presented in terms of exposure field intensities which will provide a given level of RF and MW induced thermal loading. The analysis is accomplished for normal sized human adults and owing to the frequency specific nature of body dimensions also treats the case of infants.

The present analysis restricts itself to thermal considerations and determines those exposure field intensities which, in light of present knowledge, are associated with a given value of RF and MW heating potential as it pertains to specific tissues within the body as well as the total thermal loading of the body. For purposes of this analysis, a fundamental, limiting criteria for power deposition of 1W/kg was chosen and applied to the subsequent determination of fields. The analysis examines the concept of limiting exposure based on the thermal load provided to specific tissues which may absorb at a preferentially high rate, or the thermal load placed on the body as a whole. The selection of 1W/kg power deposition as a limiting criteria is based on the observation that the metabolic processes of the human body give rise to a value of about 1.05W/kg when averaged over the total body mass for the sleeping state (Haines and Hatch, 7; Belding and Hatch, 8; U.S. Air Force, 9; Guy, 10). This Basal Metabolic Rate (BMR) for the whole body differs from those of individual organs; for example, the heart muscle has a metabolic rate of 33W/kg, the brain 11W/kg, the kidney 20W/kg, the liver 6.7W/kg, skeletal muscle 0.7W/kg, and skin 1W/kg (10).

Though individual tissues may exhibit metabolic rates over one order of magnitude greater than that averaged over the entire body mass, it is noted that in laboratory-controlled, heat loss studies of young men, physically fit and acclimatized to heat stress studies, the apparent maximum rate of energy expenditure for humans on a continuous basis, defined as 4-6 hours, is comparable to a metabolic loading of about 5W/kg averaged over the total body (8). Thus the figure of 1W/kg maximum power deposition to any given tissue was viewed as being a very conservative approach for limiting the externally applied heat stress of RF and MW radiation. A figure of 1W/kg maximum power deposition as averaged over the whole body, implies a doubling of the BMR on a whole body basis, or a doubling of total body heat content. It is interesting to note that on a theoretical basis, an RF or MW heat load of 1.4W/kg delivered to the total body mass may potentially increase the head core temperature by as much as 0.2°C and body muscle temperature by as much as 1.5°C (Emery et al., 11). This is roughly comparable to the elevation expected due to physical exercise. Body temperature changes associated with a total body RF/MW loading of 1W/kg are assumed to be noticeable to most individuals. The conservative approach of limiting exposures by limiting specific tissue power deposition to 1W/kg seems to incorporate a potentially desirable safety factor by typically keeping the maximum possible total body heat loading to less than a factor of two of the BMR since the deposited energy is usually distributed in a non-uniform manner. An absorption rate of 1W/kg in muscle tissue would lead to a temperature rise of 0.00024°C/sec if no cooling mechanisms were present, e.g., conduction and blood circulation. Thus we would tend to protect the total body heat loading by limiting the absorption rate of certain tissues to 1W/kg while the remainder of the body mass might be absorbing energy at a significantly lower rate. It is recognized, however, that such an approach may be overly conservative in that the normal cooling effect of the blood plays an important role in maintaining a constant mean body temperature; i.e., the thermal impact on specifically heated tissues will tend to be mitigated by the perfusing blood. But this degree of conservativeness is also undoubtedly determined, at least in part, by the variance in magnitude of local hot spots distributed throughout the bodies' mass.

The philosophy of heat loading as it applies to safe RF and MW exposure standards is not new. The ANSI standard itself has been characterized as limiting body heat loading via RF and MW exposure to a value of two times the BMR of the human adult body (Michaelson, 12; Schwan, 13). It was argued that since the BMR of the human body is on the order of 75 watts for a 70kg man with a body surface area of about $1.9m^2$, this represents an equivalent areal heat production rate of about $4mW/cm^2$. Since half of the surface area would be available for single sided exposure to a MW field, by limiting the maximum continuous MW exposure to $10mW/cm^2$, we would expect no more than a doubling of the BMR in the body, even if the incident MW field power were totally absorbed. This simplistic analysis may be plausible at high microwave frequencies wherein absorption phenomena may be described in terms of a geometrical optics formulation, but it becomes less convincing at lower frequencies where recent studies have shown that the human body will exhibit effective absorption cross sections well in excess of the geometrical shadow area of the body, being in fact on the order of 4.2-8.4 times the shadow area (Gandhi, 53; Gandhi et al., 54).

The thrust of this paper is to present a thermally based framework for construction of realistic RF and MW exposure limiting values, using the concepts of controlling either specific tissue volume energy absorption or total body energy absorption. The resulting analysis reveals that limits on whole body exposure in the frequency range of 10 to 1000 MHz could be two orders of magnitude below the presently accepted safe limit (5) if conservative, thermal protection at the specific tissue level is desired. Less restrictive, and perhaps more realistic, limits are suggested by controlling total body thermal loading and these are discussed. The use of lower field intensities than specified in the current ANSI guide as safety limits for the general population would seem to provide the necessary safety factor required by conservative health oriented controls on radiation and, even in the case of the most conservative analysis, would not appear overly restrictive in terms of present day deployment of electromagnetic radiation sources.

The analysis permits the ready determination of exposure levels associated with any selected degree of increased thermal burden to the human. Though the presented data pertain to a fixed level of thermal loading which might lead to only slight temperature elevations of certain tissues, this analysis does not treat the case of so-called non-thermal effects. In light of the various reports in the literature that suggest the possibility of non-thermal biological effects, the available data appear inconclusive at present and require additional research to better define these effects and assess their biological significance (Cleary, 14). Baranski and Czerski (15) have discussed in depth considerations of the non-thermal interaction of RF and MW energy with biological systems. The recent review by Cleary (14) indicates the evidence is persuasive that, in large part, almost all observed biological endpoints used in experiments to date can be explained on the basis of a thermal origin. Such evidence lends weight to a selection of the thermal approach used in this particular analysis but the potentially more complex problem of addressing non-thermal interactions still remains.

STUDIES OF RF AND MW POWER DEPOSITION IN MAN

During the last five years extentions of the state-of-the-art in RF and MW dosimetry have undoubtedly outstripped the progress made in biological effects research. The literature revealing RF and MW absorption studies is extensive. Initial studies by Schwan and his colleagues (Schwan and Li, 15; Schwan et al., 16; Schwan and Piersol, 17) first showed the phenomenon of MW field coupling to tissue systems for purposes of evaluating hazards to radar and the heating properties of diathermy. These analytical studies showed the variation in localized heating due to variations in tissue electrical properties and tissue layer thicknesses for a planar slab model system. This simplified tissue system was studied again later (Tell, 18; Livenson, 19; Bernardi et al., 20) and extended to other frequencies throughout the MW region above 1 GHz as well as finitely bounded slab systems (Livesay and Chen, 21). Additional analytical work with the slab model was supplemented by actual measurements to experimentally verify the spatial temperature distributions which would result from the practical application of diathermy treatment (Lehmann et al., 22; Brunner et al., 23; Lehmann et al., 24; Guy and Lehmann, 25). Figure 1 illustrates the variation in localized power deposition obtained from a typical multi-layered slab model analysis.

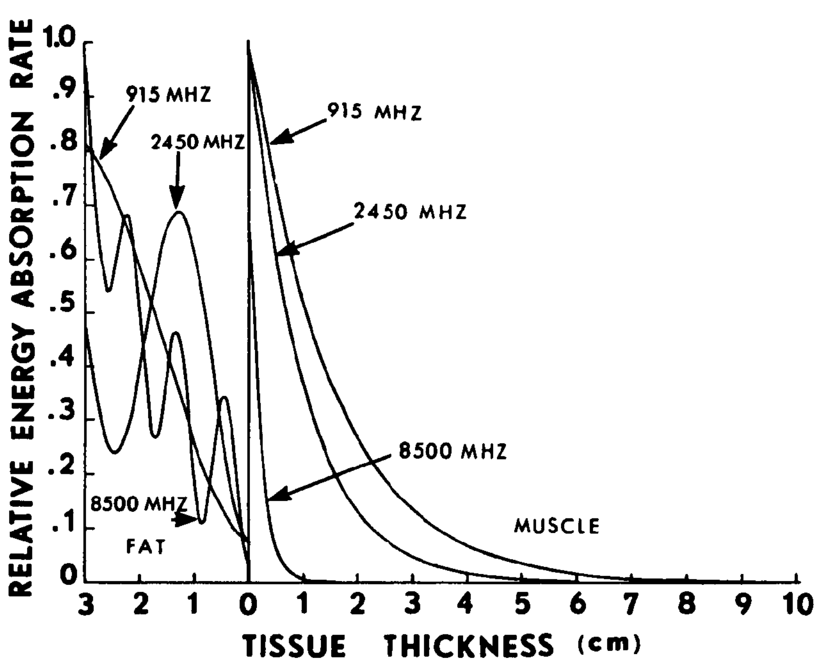


Figure 1. Relative microwave energy absorption rate in a two layer slab model of a tissue system at three different frequencies; taken from Tell (18).

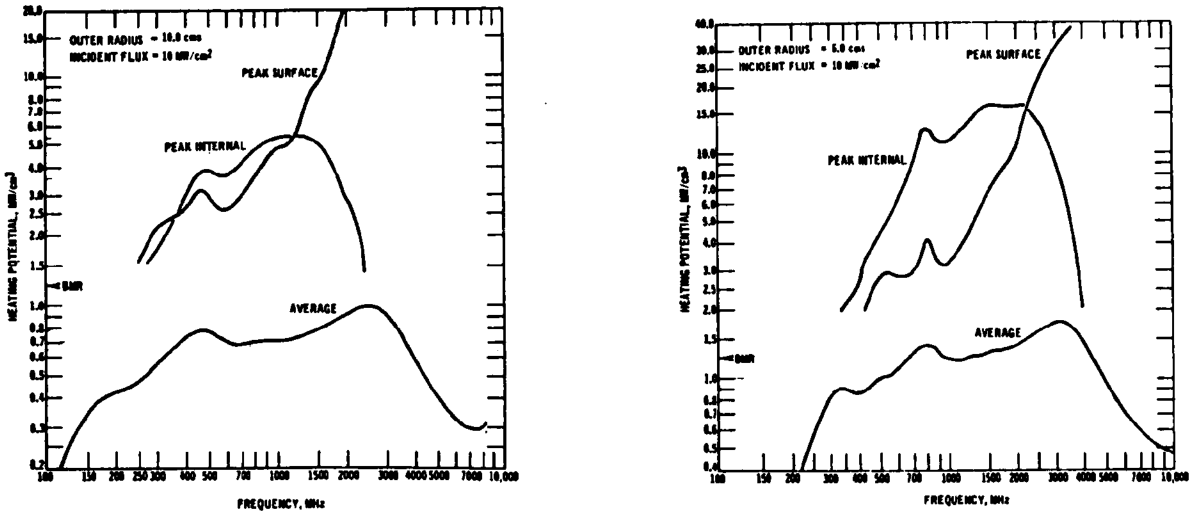
The figure illustrates the dramatic increase in relative heating which can occur at the boundary separating biological tissues of highly different dielectric properties. Though it was recognized that such simple planar slab models could not adequately describe RF and MW absorption in complicated biological structures with irregular geometry such as man, the approach indicated that MW absorption in man would likely reveal nonuniform power deposition and correlated variations in local tissue heating.

Early analytical and experimental studies by Anne (26) and Anne et al.(27), this time with spherically shaped dielectric absorbers, illustrated the severe restraints of the planar slab approach by pointing out the strongly resonant properties of spherical objects whose dimensions are comparable to the wavelength of the incident radiation. These studies presented the concept of the relative absorption cross section for dielectric absorbers; the phenomenon by which certain geometrically shaped and sized objects absorb more MW power than can be accounted for by the simple product of incident wave power density and the geometrical shadow cross sectional area. The use of relative absorption and scattering cross sections has been used for many years in electromagnetic radiation scattering work. Often it is referred to as efficiency. The concept of effective electromagnetic cross section is prominent throughout the literature of RF and MW absorption effects and has become a popular method of describing the physical interaction of RF and MW radiation with absorptive biological systems (Johnson and Guy, 28; Blacksmith and Mack, 29; Schwan, 30). The question of non-uniform power absorption in homogeneously constructed spherical models was answered by Kritikos and Schwan (31), Lin et al.(32,33), and Ho et al. (34). These early studies of spheres did not concern themselves with inhomogenity of human type anatomical structures. Only recently have more sophisticated studies been made of the more realistic situation (Shapiro et al., 35; Joines and Spiegel, 36; Kritikos and Schwan, 37, 39; Lin, 38; Neuder et al., 40).

These studies point out the development of internal hot spots due to spherical body resonances and describe the enhanced coupling of external fields into the interior absorptive medium commonly used to represent brain tissue in a model of the human head. This is due to the effects of varying permittivity of surrounding tissue layers and supports the somewhat more simplistic studies of internal energy distribution conducted for homogeneous spheres.

In an attempt to estimate total body absorption of RF and MW energy by man, several of these studies have considered an adult human as a spherical mass of high water content tissue, i.e. muscle. These studies, though attractive because of the simplified analytical formulation of the problem, must be considered crude as indicators of absorbed power in man but do provide insight to the rough absorptive properties of humans.

Weil (41) has recently analyzed a multilayered spherical model of the head composed of a central brain core surrounded with five layers of cerebral spinal fluid, bone, fat, and skin-dura tissues. This analysis, similar to that of Shapiro (35), has presented the important results in a convenient format for application to practical problems. Weil's computed results for the frequency range of 0.1 to 10 GHz for head dimensions with radii of 10 and 6cm have been taken as representative of head absorption in human adults and small children respectively. Data are provided for determining the average, maximum, and surface absorption power densities throughout the frequency range for these models and are shown in Figure 2. These data are incorporated in the analysis of limiting exposure values presented in this paper.



A B

Figure 2. Average, peak internal, and surface specific absorption rate in mW/g for an incident microwave field power density of 10 mW/cm^2, as a function of frequency, for an isolated, multilayered spherical model of the adult head, r=10cm(A) and the small child's head, r=6cm(B); taken with permission from Weil (41).

Improved analytical techniques have been developed and applied to the numerical analysis of absorption properties of more realistic models of man in the form of prolate spheroids (Durney et al., 42; Johnson et al., 43; Lin and Wu, 44; Massoudi et al., 45,47; Barber et al., 46). Very recent formulations have even modeled man using a cell approach to best fit the actual contour of the human body (Chen et al., 48; Hagmann et al., 49). It has been found that the ellipsoidal model, although more complicated than most numerical approaches to date, seems to more conveniently represent the actual form of man and certain experimental test animals (Allen et al., 50). Extensive computations of ellipsoidal and prolate spheroidal models of man and animals have been compiled by Durney et al.(51) for conditions of free space irradiation and are presented in Figures 3 and 4 for models corresponding to an adult man and the Rhesus monkey which has been taken for the purposes of this analysis as representative of a human infant. These data conform closely to the experimental work of Gandhi et al.(63). These data, utilizing results from the ellipsoidal analysis for adults below 30 MHz and for the Rhesus monkey below 100 MHz and from the prolate spheroidal analysis above these frequencies, are subsequently utilized in this analysis. The ellipsoidal results are considered more accurate but due to precision restraints imposed by presently available computing machinery, the numerical results are not available for adult human models above 30 MHz or the Rhesus model above 100 MHz. Experimentally derived absorption rates have been obtained for ellipsoidal models for frequencies up to 500 MHz (Gandhi et al., 63). A major result of these detailed calculations is the finding of a whole body resonance frequency for a model height of about 0.4λ. Experimental results which support these findings have been obtained which not only confirm the presence and magnitude of the resonance absorption property but also

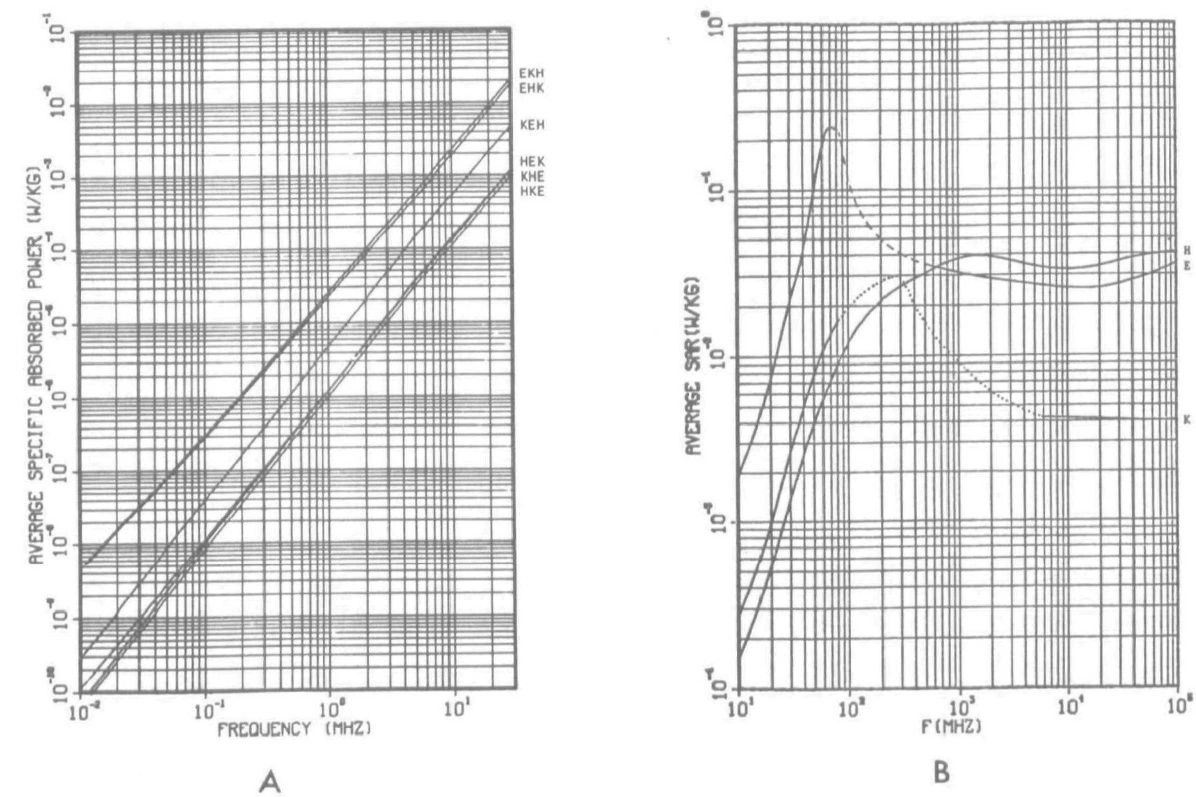


Figure 3. Whole body specific absorption rate in W/kg for an average sized man (70 kg, 1.75m tall) exposed in free space to an incident power density of $1 mW/cm^2$ and modeled as an ellipsoid (A) and a prolate spheroid (B); taken with permission from Durney et al.(51).

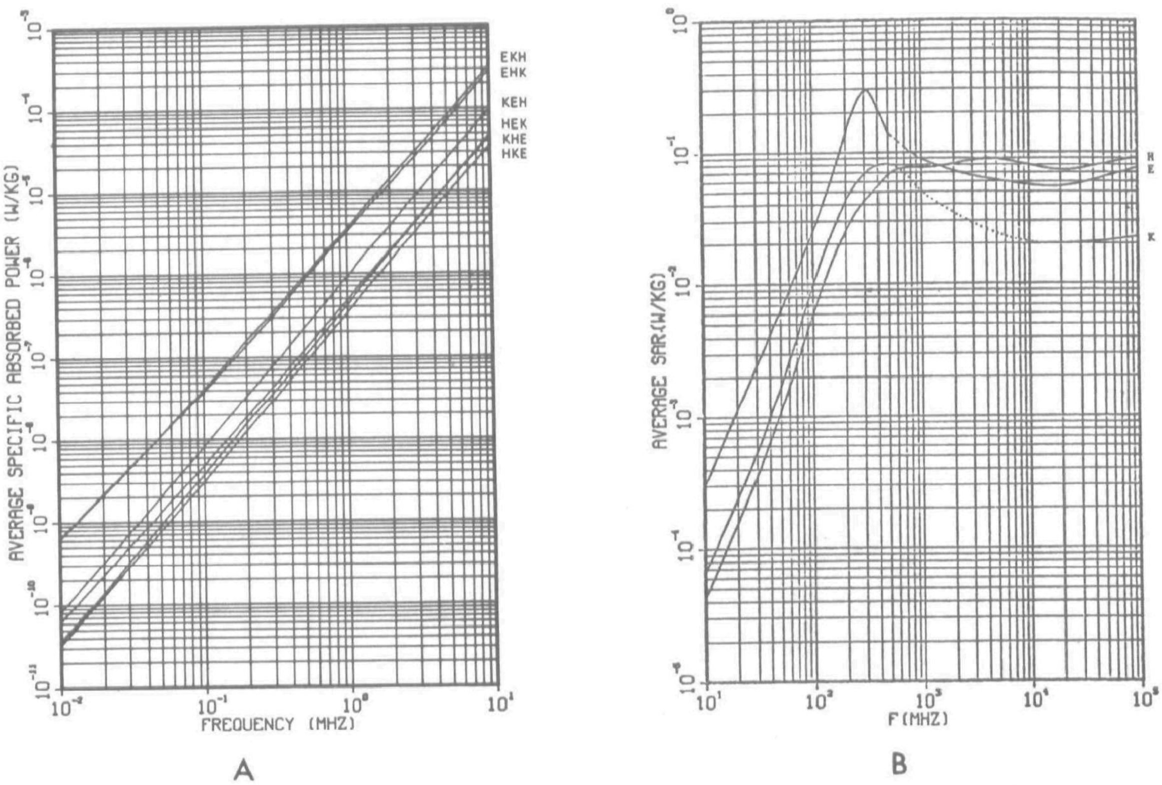


Figure 4. Whole body specific absorption rate in W/kg for a sitting Rhesus monkey (3.5kg, 0.40m tall) exposed in free space to an incident power density of 1mW/cm^2 and modeled as an ellipsoid (A) and a prolate spheroid (B); taken with permission from Durney et al.(51).

illustrate the important dependence of absorption on the polarization of the body with respect to the incident field (Gandhi, 52,53; Gandhi et al., 54). Neukomm (102) has recently provided direct experimental confirmation of the full body resonance frequency of about 75 MHz in his studies with actual human subjects.

Several modifications and extensions to these mathematical techniques have been proposed (49), (Rowlandson and Barber, 55; Massoudi et al., 56). Recent results by Barber et al.(99) show that a more sophisticated, multilayered model of man may exhibit slightly enhanced absorption characteristics over the homogeneous model in the post resonance region. This is presumably due to the impedance matching properties of the various body tissue layers. A major effort now appears to be the experimental verification of the numerical results obtained for man in free space and in the presence of a ground plane and nearby reflective structures which indicate the possibility of significantly enhanced RF and MW energy absorption rates (54), (Gandhi et al., 57; Hagmann et al., 58). Gandhi (53) obtained some experimental verification of these ground interaction absorption phenomena in scale models of the human body. A significant aspect to the study of power deposition within the human is the extensive thermographic investigation of the spatial distributions of the heating potential in scale models by Guy and his colleagues (Guy, 59; Guy et al., 60;62; Chou and Guy, 61; Gandhi, 54;63). These studies demonstrate the extreme importance of knowing the spatial distribution of absorbed power density, illustrating the areas of the body susceptible to high localized heating effects which may exceed by a factor of 30 the power absorption rates when averaged over the total body mass (54,60). Presently utilized thermographic measurement techniques employed by Guy (64) provide a limiting volume heating resolution of about 2 cm^3 when applied to the full sized adult. Consequently, the limiting volumetric heating load used in this analysis is interpreted to mean 1W/kg averaged over no greater than 2 cm^3 tissue volume. The neck and ankle regions exhibit enhanced local absorption for free-space and ground plane irradiation conditions, respectively. Figures 5 and 6 taken from the work of Guy et al.(60) and Gandhi et al.(54) illustrate typical variations of localized field intensification found in figurine scale models of man when exposed to free-space fields and ground plane conditions. Figure 5 from Guy's work shows that under the right conditions the ankle, as an example here, may exhibit a local absorption rate of 26 times the whole body average. It should be noted that the experimental measurement of high specific absorption rates (SAR) in models presents a difficult problem in that the high localized heating in the modeled tissue tends to smear with time, creating the potential of underestimating the actual energy absorption rate. A rough index of the spatial variability in local hot spot occurrence has been found by forming the ratio of the standard deviation of localized SAR values in scale models of man to the mean value of the SAR

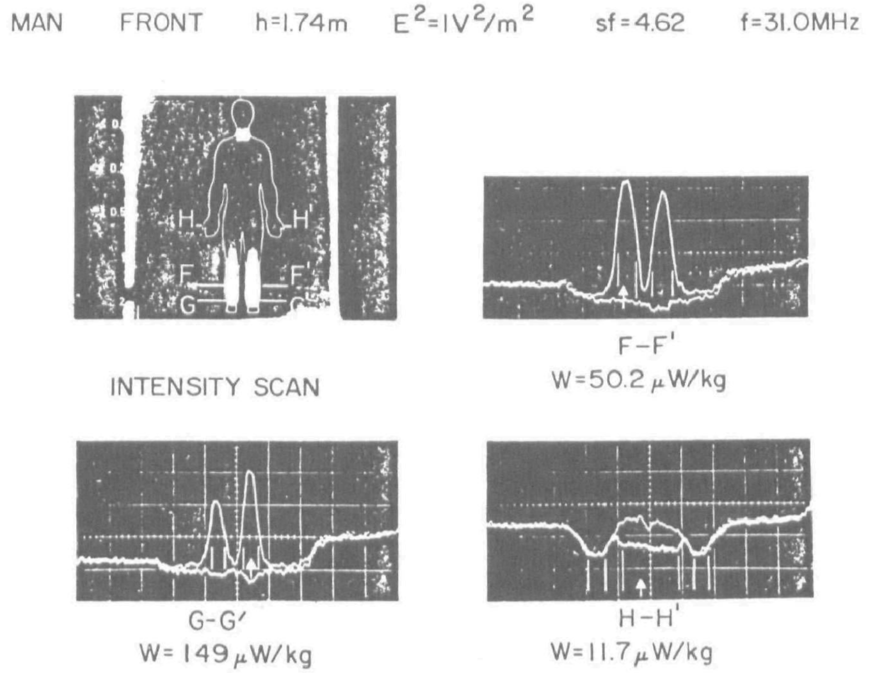


Figure 5. Scale model thermogram and measured peak absorbed power densities for 70kg, 1.74m height man frontal plane exposed to 31.0 MHz electric field: Vertical division = $2^{o}C$; horizontal divisions = 4cm. Note that an equivalent volume ellipsoid would have a whole body specific absorption rate of 5.8μW/kg and here the ankle has a value of 149μW/kg and the neck, not shown here, has a value of 29.6μW/kg; taken with permission from Guy et al.(60).

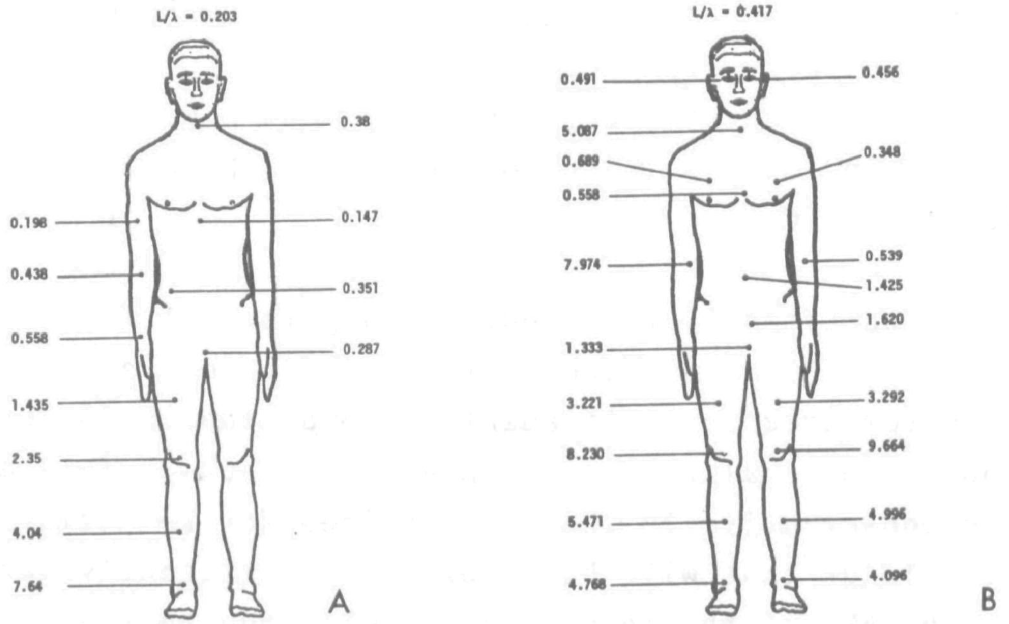


Figure 6. Distribution of power deposition for a human in electrical contact with ground (A) and in free space (B). The numbers are relative to a whole body average specific absorption rate of 4.5W/kg for a 1.75m tall man exposed to $10mW/cm^2$ incident fields; taken with permission from Gandhi et al.(54).

as determined by averaging of the local values. Under non-resonant conditions this ratio is fairly constant at a value of about 1 while under conditions of resonance this value may increase to 1.5. It is clear that limiting exposure on the basis of total body absorption can underestimate the significance of specific tissue heating within the body. Recent numerical results by Hagmann et al.(58), have suggested even higher localized tissue energy deposition rates, but these findings remain subject to experimental verification and analysis from the standpoint of practically achievable ground plane situations for man. An estimate of practicably obtainable total body power absorption by man at resonance on a high conductivity ground plane appears to be on the order of two times the whole body absorption under free space conditions, i.e., when the individual is not grounded (Gandhi, 65). Additionally, local internal field enhancement leading to a maximum power deposition of approximately 8-10 times the average whole body absorption has been found for ground plane conditions and appears to be a good practical estimate of this phenomenon (Gandhi et al., 54; Gandhi, 65). The further examination of achievable ground plane enhancement in power absorption must be stressed since man may assume, under certain occupational circumstances, body configurations similating a monopole on conducting towers in the presence of substantial field intensities (Tell, 66).

For purposes of this analysis a potential localized power deposition of 30 times the averaged whole body absorption rate is assumed for free space irradiation conditions in order to account for possible localized tissue heating effects. This assumption proves conservative in that it provides for resulting whole body thermal loads that will be generally significantly less than twice the BMR of the body, i.e., whole body thermal loads may be limited to as much as 1/30 of the resting body BMR. For cases of ground plane exposures localized internal power deposition enhancement of ten times the average for the whole body is assumed.

A complicating factor in the analysis of absorbed RF and MW energy is the existence of the near-field zone about radiating structures in which the wave impedance varies from its intrinsic value of 120π ohms in the far field. Such changes in the wave structure, wherein the electric and magnetic field components do not have a necessarily known relationship, can account for different specific absorption rates in man. These differences have been examined by Guy et al.(60) and Durney et al.(51) and have been determined to account for as much as a factor of three times greater absorption for pure H field exposures as opposed to pure E field exposures in an ellipsoidal model of man at a frequency of 30 MHz. Durney et al.(51) show on the basis of limited numerical results that the absorption rates of prolate spheroidal models of man can be 1.4, 4.3, or 3.5 times greater than that under plane wave conditions at 10 MHz depending on body orientation for electric, cross, and magnetic polarizations of the body, this being for a wave impedance of one half the free space value. This characterizes an exposure in which the magnetic field is predominant. Results for higher frequencies are yet to be computed but the trend of the low frequency data suggests a proportionately greater increase in the absorption rate for this wave impedance. The practical significance of intense low impedance field exposure must not be overlooked even at frequencies in the VHF region of the spectrum since such occupational exposure situations do exist Tell (66). Durney et al.(51) have also determined for the same prolate spheroidal model of man that high impedance fields, that is, those in which the electric component is predominant, will generally cause lower total body absorption than that predicted for free space plane wave irradiation. For the cases of electric, cross, and magnetic polarization of the body they have computed, for fields with a wave impedance of 240π ohms or double the free space value, that the whole body power absorption rates are 0.9, 0.3, and 0.3 of the free space values respectively, again at 10 MHz. These types of findings when extended to the VHF region will also provide a method for practically indexing the potential hazard zones about the ends of dipolar or similar radiating structures which are characterized by extremely high impedance electromagnetic fields (Tell, 67). These non-plane wave absorption results are particularly applicable to the occupational environment but probably have less significance in terms of the consideration of safety criteria for the general population. Accordingly, no wave impedance modifications have been used in the analysis in this paper; such considerations should be made when applying the results of this analysis to occupational exposure conditions.

A final confounding factor in RF and MW dosimetry is the recent demonstration of "proximity effects" (Gandhi et al.,63), body reflections which give rise to increased power deposition in the head compared to predictions from the isolated head model or multiple target interactions. Gandhi et al.(68) have reported results of their experimental and numerical studies using more realistic figurine models indicating that body reflections can account for perturbations of the whole body specific absorption rate. Their data show that the intact adult head resonates near 350 MHz rather than at 470 MHz for the isolated head reported by Weil (41). An enhancement in total power deposition to the intact head was found to exceed total absorption determined for an isolated model by a factor of about 3 at the resonance frequency of 350 MHz and to be about equal to or slightly less than the isolated value at 470 MHz. This suggests that analytical results obtained for isolated models of the head, at least on a total absorption basis, may inadequately describe the potential for hazardous exposure conditions. According to Gandhi (65), however, there would appear to be no major change in the relative amplitudes of the internal field distributions of the head. Thus these findings have been taken into account in this analysis. Figures 7 and 8 taken from Gandhi et al.(68) are provided to reveal the kind of variations in localized tissue absorption rates for both free space and grounded conditions of man.

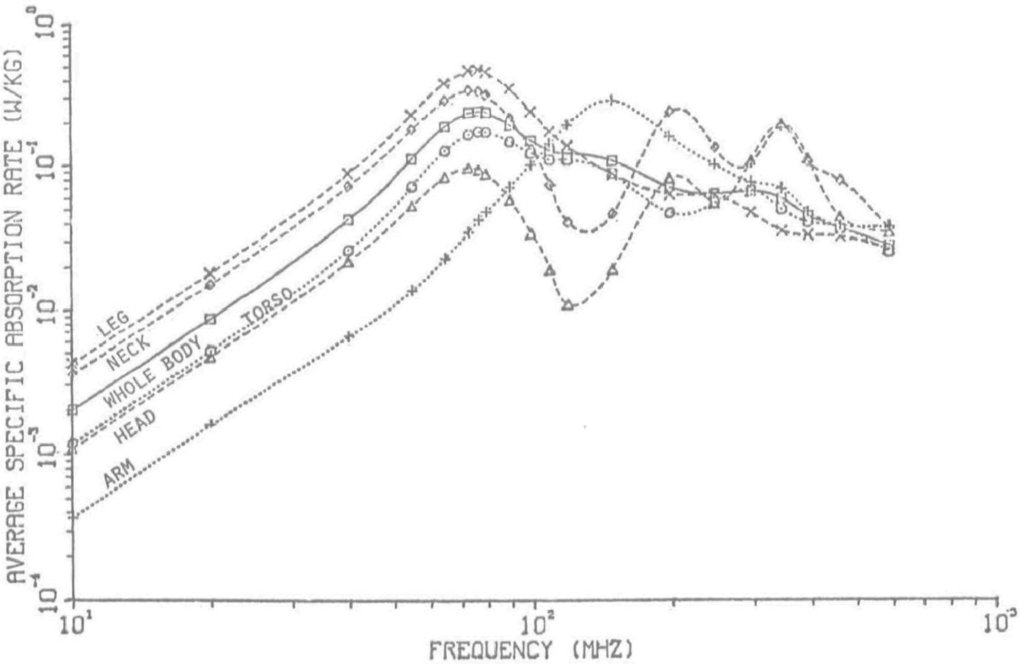


Figure 7. Specific absorption rates for the whole body and some intact anatomical parts of man in W/kg for a free space incident power density of $1 mW/cm^2$; taken from Gandhi et al.(68).

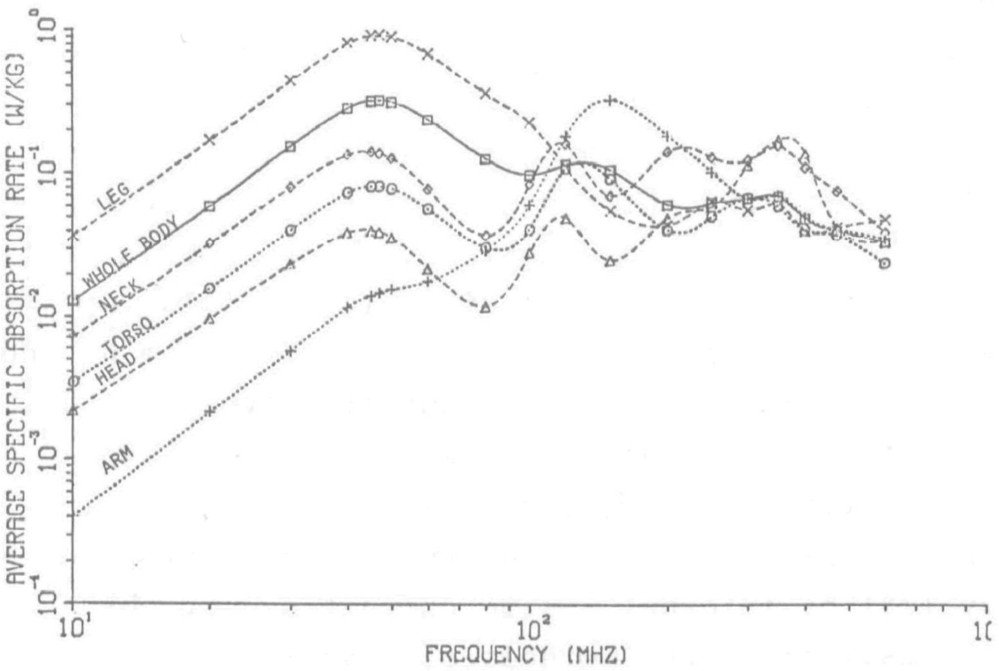


Figure 8. Specific absorption rates for the whole body and some intact anatomical parts of man in W/kg for an incident power density of $1 mW/cm^2$ when man is in good electrical contact with a high conductivity ground plane; taken from Gandhi et al.(68).

The indicated specific absorption rates are those integrated over basic anatomical structures and do not reveal the worst case, very localized absorption which can occur.

The question of near-body interaction with the absorption properties of man are interesting and have been investigated in large arrays of experimental animals by Kinn (69) and Gandhi et al.(68). These observations though somewhat preliminary, suggest a reasonably low probability of significant alteration of isolated body studies when used in practical exposure situations, due to critical separation distances required. Accordingly, no modifications due to multiple target absorption enhancement are used in this analysis.

EXPOSURE FIELDS AND ASSOCIATED THERMAL LOADING

Results from several of the above described investigations have been massed together to form an overall picture of the frequency dependence of RF and MW absorption in man. The data relating to absorption have been used to compute the field intensity which is associated with a maximum power deposition in any body tissue of 1W/kg at any frequency in the range of 10 KHz - 10GHz for adults and infants assuming whole body exposure. These data have been presented graphically in Figure 9. The units for specification of biologically significant field intensities have received much discussion in the literature (Youmans and Ho, 70; Bowman, 71; Schwan, 13). These authors have pointed to the unfortunate choice of using the areal surface power density, or Poynting vector notation, for indicating exposure field amplitude. The uses of absorbed power density in tissue proposed by Johnson and Guy (28) or internal tissue current density by Schwan (13) are obviously preferred methods of quantifying dose-rate-effect results in biological research but such concepts must be replaced by other means of practically specifying the external field for control purposes. That the parameter of power density is inap-

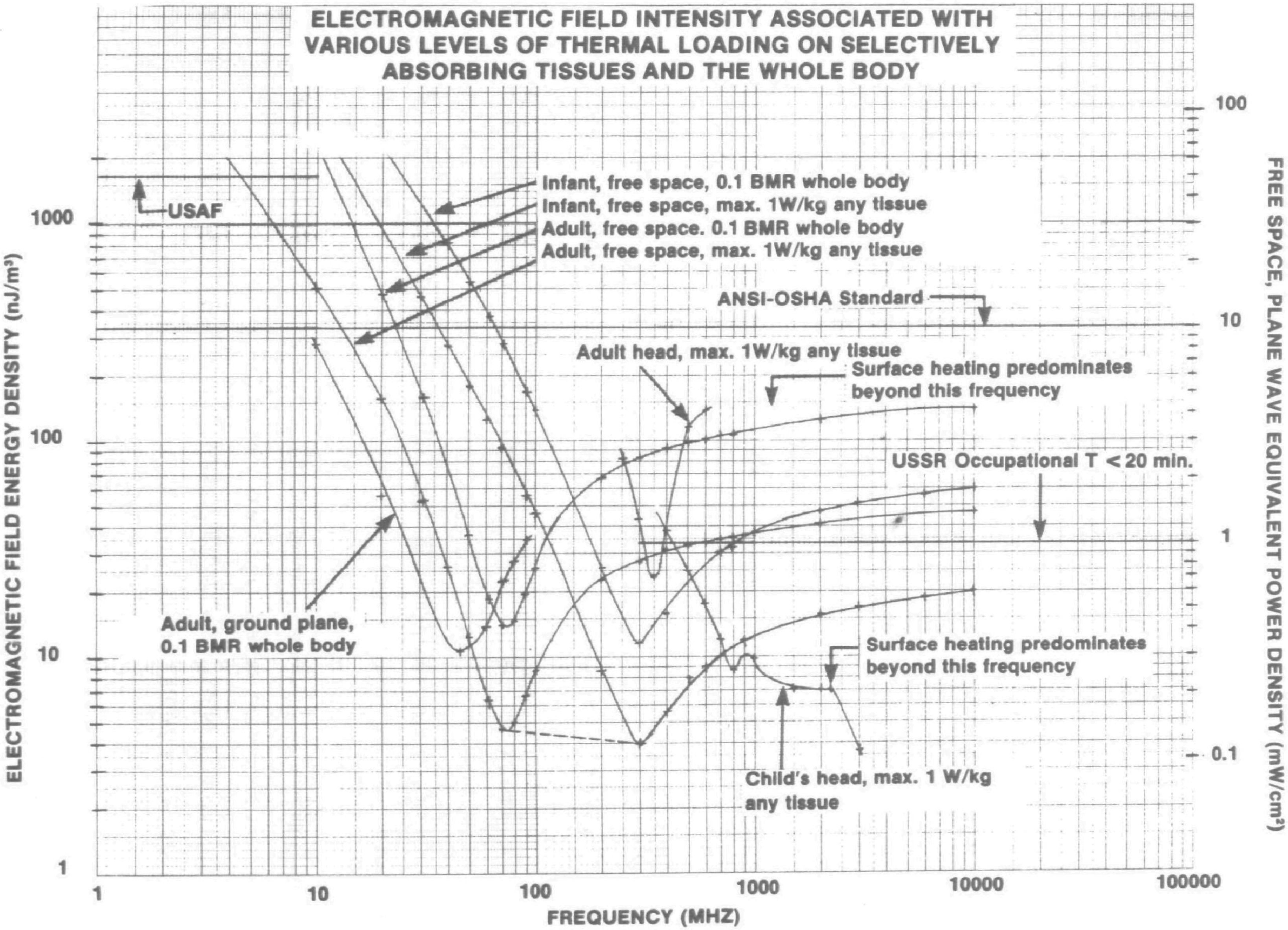


Figure 9. Electromagnetic field intensity associated with various levels of thermal loading on selectively absorbing tissues and the whole body. Note that $U=U_E+U_H$ and that in the far field $U_E=U_H$.

propriate for many exposure situations has been reinforced, notably by Bowman (71), who has, among others (Wacker, 72), proposed that fields be specified in terms of the electric field energy density U_E or more generally in terms of the total electromagnetic field energy density U in units of Joules/cubic meter or more practically nJ/m^3. In the interest of encouraging the sensible and wide spread acceptance of Bowman's recommendation, the field amplitudes on Figure 9 are given in units of electromagnetic field energy density, this being closely related to the quantity measured by most available field meters. This is innately logical since these instruments do not respond to the field power density itself but in most instances (Bowman, 73; Aslan, 74; Hopfer, 75) are sensitive to the square of the electric field strength, which is directly proportional to U_E. Bowman's argument for using a basic quantizing term of the field, i.e., electric or magnetic field energy density, that does not depend on the proximity of an individual to the radiation source is a fundamentally attractive proposition and provides for less ambiguity, particularly when specifying near field exposures. Another advantage to using the total energy density U of the exposure field is that the important hazard potential of the magnetic field, which is typically more predominant at lower frequencies, particularily below 30 MHz, is taken into account. Because almost all work relating to RF and MW hazard analyses has referred to the field power density Figure 9 also carries for convenient reference, plane wave, free space equivalent power density in units of mW/cm^2 on the right hand ordinate. For far field conditions, the areal power density S is related to the electric field energy density U_E and the magnetic field energy density U_H by the relation

$$S(mW/cm^2) = \frac{U_E\ (nJ/m^3)}{16.7} = \frac{U_H(nJ/m^3)}{16.7} \quad (1)$$

In the far field $U = U_E + U_H$. Alternatively, in the near field as well as the far field, U_E and U_H are related to the electric field and magnetic field strengths E and H by the relations

$$U_E(nJ/m^3) = 0.00443\ E^2(V^2/m^2), \qquad (2)$$

$$U_H(nJ/m^3) = 628\ H^2(A^2/m^2). \qquad (3)$$

Bowman (71) has discussed these relationships in detail.

There are several curves which appear in Figure 9 and each of these are discussed. The data points used in plotting the data have been shown. The adult free space curves are developed from Durney's work (51) based on Figure 3. An inhomogeniety intensification factor of 30 has been used in computing the required free space exposure field energy densities to limit maximum tissue absorption to 1W/kg. The infant free space curves are taken again from the same source (51) but are based on computed results for a Rhesus monkey, Figure 4, which has been taken to represent the human infant in terms of size. Curves are shown for both specific tissue power deposition of 1W/kg and whole body deposition of 0.1W/kg averaged over the body. It is apparent that for all intermediate sizes of individuals there will exist an envelope, indicated by the dashed line connecting the resonance dips for man and infant, which defines the limiting exposure levels for in-between cases.

Weil's isolated head absorption data (41) in Figure 2(A) have been used to determine a ratio of peak to average SAR in the adult head model. This ratio has a maximum value of 8 and has been used in conjunction with Gandhi's data (68) found in Figure 7 pertaining to average SAR values for the intact adult head to determine the exposure fields that would be associated with a peak internal SAR of 1 W/kg. The peak, as opposed to average, SAR has been selected as the more important criterion of RF and

MW absorption by the head since tissues of the central nervous system may exhibit higher thermal sensitivities than other tissues of the body.

Lacking information on whole head absorption by the intact child's head, Weil's data (41) on peak internal SAR of the isolated head, Figure 2(B), have been plotted directly with the inclusion of an absorption enhancement factor of 3 suggested by Gandhi's data (68) for the intact adult head compared to the isolated model at resonance. It is noted that above 1200 MHz surface heating predominates for the adult, i.e., internally induced heating will not exceed that on the surface. The same surface heating predominates in the small child's head above 2300 MHz. Continued increase in the frequency would be characterized by the surface heating load being confined to thinner and thinner dermal layers until prohibitively high skin tissue power deposition would occur with increasing frequency except for the fact that surface thermal radiation and blood diffusion preclude excessive skin surface temperatures. It is inconceivable that, on the basis of body surface heat escape properties, the radiation intensity, which limits specific tissue absorption to 1W/kg at the point of predominately surface heating, could create a biologically significant thermal load at the skin surface. For this reason, the limiting values determined at 1200 and 2300 MHz, for adults and small children respectively, are suggested as applicable for all higher frequencies. Data are plotted for adults and small children as designated on the curves.

The curve labeled "Adult, ground plane, 0.1 BMR whole body" is based on the experimental and theoretical data of Gandhi et al.(57) and Gandhi (63) and has been determined by limiting the whole body power absorption to 0.1 BMR. This also limits specific tissue absorption to 1W/kg since a local intensification factor of 10, used by Gandhi et al.(54) exists for the grounded condition.

A similar curve for infants would fall above the other curves and consequently has been eliminated from presentation.

It should be pointed out that at frequencies below about 30 MHz the contribution to RF induced thermal loading due to the magnetic field component can become significant. If the field specification were in terms of U_E only, this important aspect of the potential hazard would not be accounted for.

It is apparent now, that if one limits the maximum tissue energy absorption rate anywhere in the body to a value equivalent to the resting body BMR, that a pronounced region of maximum susceptibility has been identified for man which spans the frequency range of about 10 MHz to 1000 MHz and requires the external field to be limited to about two orders of magnitude below the generally accepted safety limit in the U.S. of 10 mW/cm^2.

It is tempting to draw an envelope of suggested values of electromagnetic field energy density in Figure 9 which would provide a practical definition of thermally safe exposure. Such suggested values have not been indicated but it is clear that the phenomenon of thermal loading is frequency sensitive and as such limiting exposure levels could properly incorporate such a dependence. It is particularly obvious that below 10-20 MHz substantially higher limiting fields are appropriate from a thermal viewpoint. It must be pointed out, however, that at these lower frequencies the likelihood of dangerous transient spark discharge effects due to sizeable voltage inductions on conducting objects in the irradiation field can become significant. In fact there is evidence that good safety practice would dictate an even lower acceptable field level, perhaps significantly below 400 nJ/m^3 (Honolulu Advertiser, 76; Hammett and Edison, 77). In the frequency range 10 MHz $\leq f \leq$ 10000 MHz curves are provided which limit specific selectively absorbing tissues to a maximum of 1W/kg and which limit total body power absorption to 1/10 the BMR. This latter set of curves is introduced to permit rapid estimation of total body heat loading for any suggested exposure field value. It is doubtful that noticeable body temperature increase would occur at RF or MW induced whole body thermal loads less than 1/10 the BMR.

From a thermal point of view safety criteria based on limiting the SAR of selectively absorbing tissues to the resting body BMR would probably be viewed as unnaturally conservative. On the other hand limiting whole body power absorption to several times the BMR would seem to be questionable, depending on other environmental parameters and an individual's thermal sensitivity. Though the subject of multiple frequency components in the exposure field is not treated here, further consideration is necessary for proper specification of acceptable field intensities when more than one frequency is present with significant field amplitude.

SHORT DURATION EXPOSURE

It is reasonable to make some distinction between long and short term exposure limits. The incorporation of exposure time in such a consideration is attractive in that it provides a reasonable approach to dealing with intermittently operated RF and MW sources which for brief periods of time may produce relatively high exposure in their vicinity. Such a proposal has recently been discussed (78) and forms a part of the philosophy of the ANSI standard (1) (5). For application to the general population, it is plausible to assume that the emphasis, for short term exposure, should be on individual tissue protection at some higher intensity, and that this maximum acceptable RF induced thermal load on any selected body tissue should not exceed some multiplicative factor of the BMR. A defining relationship of total body exposure energy density and time would be of the form

$$Q = U\left(\frac{nJ}{m^3}\right) \cdot T(hr) \leq Q' nJ\text{-}hr/m^3 \qquad (4)$$

where Q′ represents the time weighted tissue heating potential in units of nJ-hr/m^3. Maximum total body exposure energy density would be necessarily limited to a value which would insure not exceeding a total body heat load of several times the BMR.

Table 1 provides a summary of some of the critical points on Figure 9. In the case of partial body exposure, i.e., those instances wherein particular parts of the body are predominately exposed when compared to the body as a whole, it is reasonable to permit even higher maximum energy densities when it can be determined that those body tissues subject to maximum absorption could not, because of source limiting restraints, absorb more than perhaps 10W/kg. With the lack of near-field knowledge there is no obvious way to prescribe in general what these exposures will be and therefore this problem remains subject to a case-by-case evaluation.

It is not apparent that relaxation of field amplitude limits below 10 MHz for short duration exposures would be prudent for application to the general population. For occupational RF and MW exposure, a somewhat relaxed controlling level would seem appropriate in view of the presumably greater knowledge of the exact irradiation circumstances.

OCCUPATIONAL EXPOSURE CONSIDERATIONS

Although it is not the intent of this paper to address the evaluation of limiting safety criteria for occupational applications, the basic analysis provides a reasonable approach to evaluating such criteria. And while the definition of absolute limits for safe occupational exposure could be made rather

TABLE 1. ELECTROMAGNETIC FIELD ENERGY DENSITIES ASSOCIATED WITH VARIOUS LEVELS OF THERMAL LOADING IN THE BODY

	Electromagnetic Field Energy Density (nJ/m^3) for Limiting Thermal Loading to Various Levels		
	Free Space Resonance		Grounded Resonance
Nature of Loading	Adult	Infant	Adult
1 X BMR Whole Body	140.0	115.0	107.9
1 X BMR Specific Tissue	4.68*	3.83*	10.79**
0.1 X BMR Whole Body	14.0	11.5	10.79

* A possible field intensification factor of 30 is used for transforming from whole body to specific, selectively heated tissue for free space conditions.

** A possible field intensification factor of 10 is used for transforming from whole body to specific, selectively heated tissues for grounded conditions.

arbitrarily, it seems intuitive that considerable relaxation of the limiting values considered for the general population is in order if care is exercised in determining potentially hazardous exposure areas. That is to say, when detailed knowledge of the exposure situation is available, one can then predict more reliably the actual potential for significant power absorption in the body and therefore, reassessment of the limiting criteria would be appropriate. For example, in physically fit working adults, it does not seem unreasonable to impose, during a working day of 8 hours, a significantlv greater thermal load on these individuals compared with the general population. Partial body exposure, particularly of the extremities such as the hands, would seem to also warrant substantial increases in allowable power deposition; accordingly, partial body exposure needs careful additional evaluation.

Proposals for a model occupational safety guide are not given but it is worthy of note to compare the absorption frequency response curves of Figure 9 with the existing ANSI standard for continous exposure of $10mW/cm^2$ plane wave power density (5). It is seen that above 10 MHz there are regions wherein this allowable exposure level could introduce power deposition in selective tissues of the body 100 times greater than the resting whole body BMR. It is questionable whether this possibility is prudent for the work place let alone the uncontrolled exposure of the general population, since it has been recognized that a tissue power deposition of 50W/kg is associated with a vigorous diathermy treatment Guy (10).

EXISTING SAFETY STANDARDS

A number of intercomparisons of the various RF and MW exposure standards throughout the world can be found in the literature (Michaelson, 12; Cleary, 14; IRPA, 79; Tell, 80). Such intercomparisons are not the subject here but it is worthwhile to make note of several significant features when examining some of these standards in view of the analysis which is the subject of this paper. For reference, a number of the existing RF and MW safety standards are graphically illustrated on Figure 9.

- The U.S. Air Force standard (81) for use at frequencies below 10 MHz would appear to be reasonably conservative in terms of possible body thermal loading. It is noted, however, that the possible influence of ground plane phenomena which might significantly enhance power deposition, particularly in the lower portion of the body, may need to be assessed in practical implementation of this standard in the field to determine the actual margin of thermal safety.

- The ANSI standard (5), as previously pointed out, could be viewed as defining an upper bound for RF and MW induced thermal burdens insofar that certain body tissues, under the right conditions, could experience selective power deposition at definitely thermalizing levels. Such allowances in the uncontrolled general population seem questionable.

- The US microwave oven performance standard (82) promulgated by the U.S. Department of Health, Education and Welfare (DHEW) in its Bureau of Radiological Health (BRH) to control MW leakage from these electronic products appears at first glance to be similar in character to the higher ANSI standard (5). But as pointed out by Czerski (83), Osepchuck et al.(84), and IRPA (79), for practical distances encountered in routine operation of these devices, whole body exposures are in essence limited to about 5-20$\mu W/cm^2$ and thus the oven standard must obviously be considered very conservative from a thermal standpoint. When examined from even a partial body exposure viewpoint, the BRH oven performance standard is unlikely to produce specific tissue power deposition greater than 10W/kg, but detailed analysis of this possibility has not been accomplished.

One of the more interesting findings is that were the approach used in this analysis used to reduce the maximum acceptable possible RF and MW power deposition in any given tissue to no more than an additional 10 percent of the inherent BMR loading, one would determine corresponding exposures equal to the present Soviet occupational exposure standard (85). Though there is essentially no evidence that the Soviet safety guides for the work place (85), and as proposed for the population (Gordon, 86), were developed from a thermal analysis of the problem, the adopted limits in the USSR, it may be speculated, might in fact be related to very subtle manifestations of thermal loading in RF and MW workers. It remains to be determined whether the many reported subjective observations, described in the Soviet literature as the asthenic syndrome (Gordon, 86; Letavet and Gordon, 87; Pressman, 88), can be correlated with very slight, tissue specific, internally generated thermal excursions, which because of a lack of sensitivity in experimental designs have been labeled as non-thermal.

TYPICAL ELECTROMAGNETIC ENVIRONMENTS AND SAFE LEVELS

There are no obvious indications in the literature that the lowest limiting safe values of electromagnetic radiation energy density, as might be suggested by an analysis of this type, would allow undesirable RF or MW thermal stress in man; i.e., the limiting levels of energy density would appear reasonably conservative, biologically speaking. How would these conservative limits then, compare with the presently determined levels of RF and MW exposure typically encountered in the environment? A significant part of the answer to this question can be found in the extensive field measurements made by EPA in large metropolitan areas. Preliminary results of these measurements made with an EPA developed mobile field intensity measurement system (Tell et al., 89) have been discussed previously (Janes et al., 90; Athey et al., 91) and imply that less than 1 percent of the population in 10 large US urban areas are exposed in excess of about 34 pJ/m^3 or 1 uW/cm^2. Figure 10 indicates the latest results of an EPA analysis of 10 U.S. cities (92) and shows that the median exposure of this population group is about 0.2 pJ/m^3 or 0.007 uW/cm^2. Thus ground level exposures do not in general approach the most conservative thermal limitations suggested by this analysis, being typically more than 100 times lower in value.

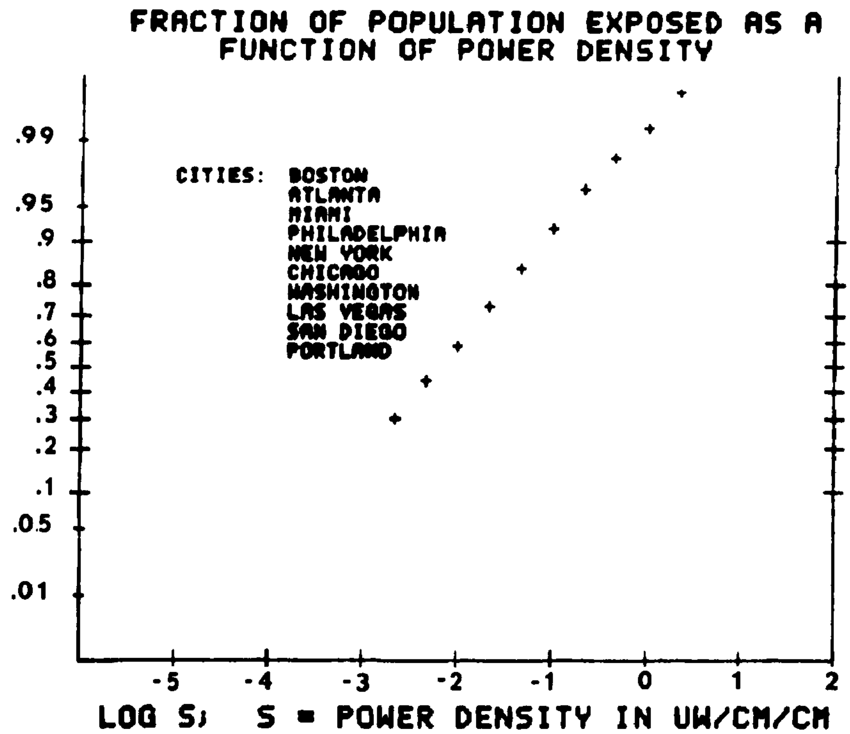


Figure 10. Accumulative fraction of population of 10 large U.S. cities exposed to various levels of RF and MW radiation in the frequency range of 54-890 MHz. The median exposure is $0.007 \mu W/cm^2$ and 0.7 percent of the population are exposed to levels above $1 \mu W/cm^2$.

Field intensity measurements inside of tall buildings situated adjacent to other buildings which support high power broadcast transmission facilities have shown, however, the presence of much higher radiation intensities, in some instances being equal to about 4 nJ/m^3 or .12 mW/cm^2. These higher intensities are due to main lobe illumination from the transmitting antenna and situations involving such proximity effects have been described by Tell and Janes (93). So, in limited areas it appears that broadcast fields might exceed the most conservatively set limits but these cases are probably relatively small in number and there exist economically attractive methods whereby such fields may be substantially reduced in intensity (Tell, 94).

The consideration of other RF and MW transmitting facilities, besides broadcast, has not yet identified many areas wherein a very conservative environmental limit of even 4 nJ/m^3 time averaged energy density would seem difficult to comply with but this subject is still being analyzed within EPA. It is not certain, for example, that major impacts on existing military and civilian radar operations would occur. Presently employed hazard analysis procedures, normally used in the military, often use very conservative methods of defining exclusion zones about radars (95,96,97,98). It is noted that in many instances actual exposures measured at the exclusion zone boundary must be significantly below the predicted, main beam, worst case values providing an inherent degree of latitude in the ability to adjust to a lower acceptable environmental level. The economic impact of any standard setting activity must include a thorough evaluation, but in view of what is presently seen of the deployment of RF and MW radiation emitting sources, it would appear that an environmental exposure limit of even 4 nJ/m^3 would not be unnecessarily restrictive.

SUMMARY

This paper has discussed an analysis of the existing RF and MW absorption data for man as these data relate to specifying electromagnetic power deposition in tissues of the body leading to various levels of thermal loading. A limiting energy absorp-

tion rate of 1W/kg for any tissue within the body was assumed as a conservative criterion for the development of a thermally based RF and MW radiation protection guide, this specific tissue absorption rate being equal to the basal metabolic rate of a human on a whole body basis. The analysis examines the frequency dependent nature of total body absorption, includes the important information on the distribution of absorbed power throughout the body and determines values of the exposure field intensity corresponding to a maximum possible thermal load of 1W/kg placed on selectively absorbing body tissues or on the body as a whole. Ground plane and body reflection effects which can lead to enhanced power absorption are incorporated in the analysis. Base curves are provided, relating given exposure intensities to thermal loading at both the specific tissue and whole body levels, which may be used for convenient thermal evaluation of safety standards. By describing field intensities in terms of the electromagnetic field energy density the ambiguity of specifying near field exposure in terms of power density is removed and the importance of the magnetic field component, particularly at low frequencies is taken into account. A method for modification of limiting values is suggested which incorporates the duty cycle of the irradiation field for short term exposure.

The results illustrate the strong frequency dependent nature of electromagnetic energy absorption in man and the existence of resonance frequencies for the body as a whole and anatomical substructures. For the human adult, at a resonance frequency of about 70 MHz, a free space exposure field of 140 nJ/m^3 electromagnetic field energy density, a far-field equivalent of 4.2 mW/cm^2 power density, will induce a doubling of the heat load due to the BMR. This would probably be detectable as a rise in body temperature by most individuals at rest. While the whole body heat loading is only doubled, the nonuniform nature of the absorption process could potentially lead to localized absorption rates as high as 30 W/kg. Such a high local absorption rate is probably not advisable for the general population.

The results reveal serious reservations for applying the currently used ANSI standard (5) to the population as a whole in that localized power deposition could, under proper conditions of exposure, apparently lead to substantial thermal burdens in various parts of the body. It is noted that the adoption of more conservative limits would not appear in general to impose undue hardships on existing facilities inasmuch as environmentally encountered RF and MW intensities are rarely above 4 nJ/m^3.

The formulation presented provides one possible approach to considering limitations on RF and MW exposure of the population. It is founded on a relatively sound base of analytically and experimentally derived dosimetric data for man and uses the fundamentally attractive thermal concept as a basis for describing electromagnetic radiation effects in man. It must be pointed out that the dosimetric data used is the best available but even so, must be considered as only an approximation to the complex nature of electromagnetic field distribution in man and consequently, the results obtained by using these data undoubtedly contain inherent vagaries when conceptualizing exact human absorption.

Using a thermal concept raises questions of a biological nature which are beyond the scope of the present paper but which must be answered to arrive at a meaningful understanding of the ultimate biological significance of different possible safety levels of RF and MW exposure. At least three biological considerations are important: (a) the heat dissapation properties of the tissues, (b) the tissues' thermal sensitivities, and (c) the thermal regulatory feedback mechanisms of the biological system. These considerations interact in a complex fashion. It is not clear whether thermal protection of the human from RF and MW radiation should be directed at a whole body level or at the specific tissue or organ level or a combination of both. For example, it is conceivable that total body energy absorption in a given field intensity might not perturb the system at all if the deposition were uniform. On the other hand, at the same given field intensity and because of the inherent nonuniform nature of RF and MW absorption by the body throughout much of the frequency spectrum, certain tissues or organs might absorb at a deleteriously high rate. Balancing the possibly detrimental biological impact of heating certain critical tissues against whole body heating is difficult. For example, the extreme thermal sensitivity of the anterior hypothalamic region of the brain wherein a temperature difference of as little as 0.2 °C can ellicit behavioral changes in experimental animals (100) suggests caution in viewing RF and MW absorption from the more simplistic whole body approach. Because the absorption of RF and MW energy by the human body is characterized by significant nonuniformity, it would appear at first glance that attention should be concentrated on examining specific tissue interactions. It has been suggested (101) that using the local BMR values for certain tissues and/or organs might be a first approach to identifying such thermally susceptible targets.

The author would like to indicate that the approach used in this paper treats the absorption of RF and MW fields totally from the viewpoint of the conversion of this energy into heat within the tissues of the body; the significance, if any, of high peak intensity, pulsed fields has not been treated. The literature which suggests that pulsed fields may be more efficacious in inducing biological effects than continuous wave fields demands careful evaluation in that other than direct thermal effects may be involved (Cleary, 103).

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16. ABSTRACT

An analysis of existing radiofrequency and microwave radiation absorption data has been performed to examine the frequency dependent phenomenon of biological tissue heating. This analysis restricts itself to thermal considerations and examines the exposure field intensities associated with various levels of RF and MW induced thermal loading on both the body as a whole and specific, selectively absorbing tissues in adult humans and infants. An underlying absorption factor of 1W/kg, this being equivalent to the basal metabolic rate for the adult averaged over total body mass, is used for comparative purposes in the analysis. A method of specifying safety standard limits based on the electromagnetic field energy density rather than the plane wave, free-space equivalent power density is presented. The analysis reveals a particularly important resonance frequency range, 10 MHz $\leq$ f $\leq$1000 MHz, in which RF and MW absorption may lead to whole body thermal loads several times the whole body basal metabolic rate for exposures equal to the present safety standard in use in the United States. A discussion is developed for applications of this analysis to occupational environments and short duration exposure conditions. Some implications of this thermal analysis of RF and MW energy are discussed in terms of existing safety standards in use in the United States and the Union of Soviet Socialist Republics (USSR) and to typically encountered exposures in the United States.

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