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A Review of International Microwave Exposure Guides

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The use of higher frequency microwave generating equipment has increased considerably since the development of radar and range-finder equipment in the early 1940's. Occupational exposure criteria were not officially proposed in the United States until 1958 when a maximum exposure of 10 milliwatts per square centimeter was established for United States Air Force operations. Since then, many organizations have proposed or adopted criteria which have expanded on the concept of a single exposure limit to incorporate other factors involved in a biological response. A review of representative exposure criteria used in the United States is presented along with those adopted in other countries such as England, Russia, and Poland, and others. Where criteria differ from United States guidelines, a short review of the scientific evidence is provided.

Introduction

SINCE THE EARLY 1940's the development and use of higher-powered electronic equipment emitting electromagnetic energy in the microwave region has increased considerably. Although definitive boundaries for the microwave region have not been established, the United States of America Standards Institute defines this region as that portion of the electromagnetic spectrum encompassed by frequencies of 10 to 10,000 megahertz (MHz)[1] while most European countries[2] consider the frequencies of 300 to 300,000 MHz in the microwave region. This wide range of frequencies serves television, radio, and commercial and military radar. Microwave energy is also used to dry thermosetting glues, to dry chemical and biological samples, to cook or heat foods in microwave ovens, and as a medical application in diathermy and microthermy. Practically no country can be found today without some form of microwave generating apparatus.

Biological effects resulting from microwave exposures are primarily a thermal response produced by the absorption of the energy and its conversion to heat. Areas of the body which cannot dissipate heat rapidly are more susceptible to thermal injury from microwave energy. Of special interest is the lens of the eye, where exposure may result in the production of cataracts,[3] and the reproductive organs, in that temporary sterility or degenerative changes have been reported in exposures involving research animals and man.[4-6]

The amount of heat generated in the tissues is primarily a function of the strength of the microwave field expressed as the average power flow per unit area measured in milliwatts per square centimeter (mW/cm^2), the length of time exposed, and the type of tissue exposed. The type of tissue exposed is, in part, determined by the depth of penetration of the microwave energy which is a function of the frequency of the energy. The lower the frequency, the greater will be the depth of tissue penetration. Thus, the range of frequencies from 150 to 10,000 MHz is of primary concern in evaluating potential hazards to microwave exposures.

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Microwave Criteria

United States of America

Although many different organizations have promulgated or adopted microwave exposure criteria in the United States,[7-9] the following four standards are representative of the various exposure control limits employed in the United States in the past ten years. The remaining standards represent a majority of the existing criteria used throughout the world.

Tri-Service Conference—1957. The first microwave exposure standard to gain widespread usage, and to be considered by segments of the United States Government, was presented in July, 1957, at a Tri-Service (U. S. Army, Navy, and Air Force) Conference on the Biological Hazards of Microwave Radiation.[10]

Information presented at this Conference was based on observations and tests at random frequencies and at differing power density levels performed by various investigators. It was the opinion of those participating in the Conference that there were not sufficient data to determine safe exposure levels for each frequency, or ranges of frequencies, within the microwave region; therefore, a level of 10 mW/cm^2 was selected for all frequencies. The U.S. Air Force, in adopting this exposure level in May, 1958, applied it to the frequency range of 300 to 30,000 MHz[11] and established it as a maximum permissible exposure level which could not be exceeded. The only factor considered in this criterion is the power density level. Such factors as time of exposure, ambient environmental temperatures that could have an increased or decreased effect on the body's thermal response, the frequency of the microwave energy, effects of multifrequency exposures, differing sensitivity of various body organs, and effect of air currents on cooling the body are not considered, although they are all recognized as factors that might affect biological response.

Bell Telephone Laboratories—1960. The Bell Telephone Laboratories reviewed the data concerning the biological effects of microwaves and qualified the military's maximum exposure level of 10 mW/cm^2 to establish in 1960 the following criteria:[12]

> "1. Power levels in excess of 10 mW/cm^2 are potentially hazardous and personnel must not be permitted to enter areas where major parts of the body may be exposed to such levels.
>
> 2. Power levels between 1 and 10 mW/cm^2 are to be considered safe only for incidental, occasional or casual exposure, but are not permissible for extended exposure.
>
> 3. Power levels under 1 mW/cm^2 are safe for indefinitely prolonged exposure."

These criteria were based on data that indicated the formation of cataracts at power density levels of 100 mW/cm^2 and on the lethal effect of 50 mW/cm^2 on dogs, rabbits, and rats with only a 40% absorption of incident energy.

U.S. Army/Air Force Standard—1964 and 1965. In 1964, the U.S. Air Force established additional microwave exposure criteria which began moving away from the concept of a maximum permissible exposure limit to that of a time-weighted average.[13] In the case of pulsed radar systems, the time on, time off, could be averaged if the power density did not exceed 100 mW/cm^2.

In 1965, the U.S. Army and Air Force developed an exposure standard[14] which permitted, under certain conditions, personnel exposures to microwave energy in excess of 10 mW/cm^2. This standard was the first to relate completely the individual's exposure time to the incident power density. The two parameters are related by the formula:

$$T_p = 6000/W^2$$

where T_p is permissible exposure time in minutes during any 1-hour period, and W is power density that the worker is exposed to in milliwatts per square centimeter.[2] This standard is applicable between exposure levels of 10 and 100 mW/cm^2. At an exposure level of 10 mW/cm^2 the allowable exposure time is 60 minutes per hour, or continuously, but at 100 mW/cm^2 the allowable exposure time is 0.6 minute per hour. In actual applications, the standard states: "It is not feasible to control limited exposures of less than 2 minutes, and consequently this formula should not be applied to intensities over 55 mW/cm².”

If workers are exposed to power densities greater than 10 mW/cm², this criterion requires that they receive a specific preplacement and periodic medical examinations. The medical surveillance program should include a routine physical examination and a comprehensive ophthalmological examination that includes an evaluation of ocular motility, media, and fundus, and corrected visual acuity for near and far vision and a slit-lamp examination of the lens with the pupil widely dilated.

United States of America Standard—C-95.1. 1966. The United States of America Standards Institute (USASI) in November, 1966, developed a standard entitled *Safety Level of Electromagnetic Radiation with Respect to Personnel.*[1] This standard sets the protection guide at 10 mW/cm², as averaged over any possible 0.1-hour period. This standard is based on a power density of 10 mW/cm² for exposure times greater than 0.1 hour, and on an energy density of 1 milliwatt hour per square centimeter (mWh/cm²) for periods less than 0.1 hour. The energy-density concept is a time-weighted exposure criterion by which the allowable exposure time in hours per 0.1 hour can be determined by dividing 1 mWh/cm² by the incident power density, expressed in milliwatts per square centimeter. Thus, for a power density of 60 mW/cm², the allowable exposure time (ET) is

$$ET = \frac{1 \text{ mWh/cm}^2}{60 \text{ mW/cm}^2} = \frac{1}{60} \text{ hour},$$

or 1 minute per 0.1 hour.

In addition to considering exposure time, the USASI standard attempts to consider environmental factors that may affect biological response. The USASI standard guide numbers are applicable for moderate environments; however, “Under conditions of moderate to severe heat stress the guide number given should be appropriately reduced. Under conditions of intense cold, higher guide numbers may also be appropriate after careful consideration is given to the individual situation.” The standard also indicates that exposures to microwave energies characterized by a power level smaller by a factor of 10 will not result in any noticeable effect on mankind.

United Kingdom

Standards recommended by British officials are found in the booklet *Safety Precautions Relating to Intense Radio-Frequency Radiation.*[15] These recommendations cover radio-frequency equipment operating in the frequency range of 30 to 30,000 MHz. This document limits continuous daily exposure to an upper permissible limit of 10 mW/cm² with no reference to a time-weighted average. Where the radiation is pulsed, the level should be averaged over the pulses including any intervals between the pulses. Further, if it can be shown, beyond a doubt, that no radiation intensity of 1 mW/cm² can be attained at any point where anyone may reasonably and normally have access, then radiation measurements do not have to be made. Subsequent sections cite precautions for (1) the public, prohibiting access to an area of radiation intensity exceeding 10 mW/cm²; and (2) research, experimental, and testing personnel, providing the same limitations, but pointing out special precautions which might not be necessary.

In the event of an overexposure exceeding 10 mW/cm², a medical examination is required along with measurements of the radiation intensity to which the individual was exposed.

France

Military guidelines have been the subject of a recent decision[16] by the Ministry of Armies fixing microwave exposure criteria similar to the U.S. Army/Air Force standard of 1965. Thus, French military norms fix a safety limit of 10 mW/cm² for exposure of 1 hour or longer. The formula $T_p = 6000/W^2$ is used for periods of exposure less than 1 hour where power levels are between 10 and 100 mW/cm², but, in fact, a 55-mW/cm² limit is recognized, owing to the difficulties in controlling exposures of less than 2 minutes' duration. For rest areas and public areas, a limit of 1 mW/cm² is considered desirable.

Poland

A large amount of research on the health effects of microwave radiation has been conducted in Poland, especially at the Institute of Occupational Medicine in Lodź.[6] On the basis of clinical and experimental research, Polish officials set levels of permissible intensity for microwave radiation with frequencies between 300 and 300,000 MHz. These levels were officially published in an Order of the Council of Ministries[17] in 1961 and contain many prescriptions for work with microwaves. The principal articles state:

"The following maximum allowable mean values of the power intensity of the electromagnetic field of microwaves are laid down for areas where people are present:

1. Intensity 10 $\mu W/cm^2$—no limitation for time of work or sojourn in this field.
2. Intensity between 10 and 100 $\mu W/cm^2$—cumulative time of work or sojourn not to exceed 2 hours in every 24 hours.
3. Intensity between 100 and 1000 $\mu W/cm^2$—cumulative time of work or sojourn not to exceed 20 minutes in 24 hours.

No person shall remain in an electromagnetic field of an intensity exceeding 1000 $\mu W/cm^2$ unless in cases of emergency and on the condition that special protective measures, as decided for each case by the person in charge of the undertaking, are taken."

Other articles of this order include items requiring an annual medical examination for exposed workers, safe placement of microwave generating installations, protective screening, personnel protection, site surveillance, and safety education.

The medical standards which must be fulfilled prior to work with microwaves are listed in a 1963 regulation of the Minister of Health and Social Welfare.[18] This regulation forbids work with microwave radiation for young people (age not provided), pregnant women, and other people suffering from certain diseases which are listed in the regulation. Preplacement medical examinations are required for all workers who will be exposed to microwaves and include neurological and ophthalmological examinations.

Union of Soviet Socialist Republics

The vast amount of research and experiences with microwaves in the Soviet Union was recently reported on by Professor Z. V. Gordon of the U.S.S.R. Institute of Occupational Health and Hygiene.[19] Microwave radiation is now used on a wider scale approaching the experiences of other industrialized countries. This fact has promoted the need for regulations specifying maximum permissible intensities and preventive measures consistent with Soviet research and philosophy of worker health protection. Frequencies between 300 and 300,000 MHz are considered as microwave, and the following values are listed as maximum permissible intensities for frequencies greater than 300 MHz.

10 $\mu W/cm^2$	for a working day
100 $\mu W/cm^2$	for 2 hours daily
1000 $\mu W/cm^2$	for 15 minutes daily

The U.S.S.R. is also one of the first to propose exposure standards for low-frequency electromagnetic radiation, which heretofore had been considered as having no effect on the human body. These levels are:

Medium wave
(100 kHz– 3 MHz)—20 v[illegible]meter
Short wave
(3 MHz– 30 MHz)— 5 volts/meter
Ultra short wave
(30 MHz–300 MHz)— 5 volts/meter

Medical examinations also are regulated in the Soviet Union for persons exposed to electromagnetic radiation. Medical counterindications are enforced so that workers are not allowed to be exposed to microwave radiation if specified diseases exist. Heavy emphasis is placed on blood disorders, neurological disturbances, and chronic eye diseases.

Preventive measures of an engineering nature are utilized by Soviet health and epidemiological centers to ensure compliance with their health regulations. Decreasing the amount of radiated energy, reflective and absorptive screening, and personnel protection measures are all reported to be widely used for personnel operating microwave equipment. Where equipment is used for thermomachining, for drying dielectric material, and for other industrial processes, the Soviet regulations specify area requirements for installing the generating equipment. For example, new generators require a separate room with an area greater than 25 square meters where the power of the generator is greater than 40 kW.[6]

Czechoslovakia

Human exposure criteria in Czechoslovakia was officially cited in a 1965 regulation[20] which set the following exposure levels for microwave radiation in frequencies greater than 300 MHz:

25 μW/cm^2	(continuous generation)
10 μW/cm^2	(pulsed generation)

However, an extensive review of the literature and the results of Czechoslovakian experiences were published in 1968 by Marha, *et al.*[2] This book has stimulated a review of the existing standard resulting in a new proposal[20] which was placed in the legislative process during 1968. This new proposal covers both high frequencies and microwaves, with the latter being defined as the range from 300 to 300,000 MHz. In this range, the new proposal uses values which are a multiple of energy flow per unit area and time. The proposal states:

"1. The following values are considered for workers with vf (high frequency) and vvf (microwave) as tolerable doses of radiation not to be exceeded in the working place during one calendar day:

• • • c. *for continuous generation in the vvf (microwave) frequencies*—value = 200
where the energy is expressed in microwatts per square centimeter and the time in hours [$N(\mu\text{W/cm}^2) \times t(\text{hours}) < 200$; therefore eight hours working time corresponds to an average energy flow of 25 μW/cm^2].

d. *for pulsed generation in the vvf (microwave) frequencies* — value = 80
where the energy is expressed in microwatts per square centimeter and the time in hours [$N(\mu\text{W/cm}^2) \times t(\text{hours}) < 80$; therefore eight hours working time corresponds to an average pulse energy flow of 10 μW/cm^2].

"2. The following values are considered for the general population and other workers not employed in generation of electromagnetic energy as tolerable doses of radiation not to be exceeded at the person's location during one calendar day:

• • • c. *for continuous generation in the vvf (microwave) frequencies*—value = 60
where the energy is expressed in microwatts per square centimeter and the time in hours [$N(\mu\text{W/cm}^2) \times t(\text{hours}) < 60$; therefore twenty-four hours exposure time corresponds to an average energy flow of 2.5 μW/cm^2].

d. *for pulsed generation in the vvf (microwave) frequencies* — value = 24
where the energy is expressed in microwatts per square centimeter and the time in hours [$N(\mu\text{W/cm}^2) \times t(\text{hours}) < 24$; therefore twenty-four hours exposure corresponds to an average pulsed energy flow of 1 μW/cm^2]."

Further articles of this proposal define continuous and pulsed generation, where continuous generation is defined as operation with the ratio of on to off time as 0.1 or greater. Another section of the proposal outlines a standard method for measurement of electromagnetic radiation with Czechoslovakian measuring equipment.

West Germany

The German Association for Radar (Direction Finding) and Navigation has published a guide[21] which is considered authoritative in the Federal Republic of Germany. This guide, entitled *Health Damages by Radar and Similar Appliances and Their Prevention,* sets the critical limit of microwave radiation intensity at 10 mW/cm^2 for human exposure. No allowance is made for time of exposure.

N.V. Philips–Eindhoven, Netherlands

Private industry was requested to supply information for this survey. Philips appears to be the only European industry with extensive criteria outlined for the protection of their employees. Their Labour Protection

Department issued a safety regulation[22] for work with microwave radiation (30 to 300,000 MHz) in 1967 which must be complied with in the Netherlands by Philips' employees. This regulation states:

"Radiation intensities higher than 10 mW/cm^2 should be considered dangerous. Safety precautions should, however, be based on a permissible level of 1 mW/cm^2 (average values)."

Further clarification of these values by the Philip's Industrial Medical Department places the limit for human exposure at 10 mW/cm^2 for radiation lasting longer than 6 minutes and at 1 mWh/cm^2 for all radiation of less than 6 minutes' duration.[23] Medical examinations, protective clothing, warning signs, and other measures are included in their protection program. Using these guidelines the medical department has not detected any harmful effects to the eyes or bodies of Philips' workers who are engaged in the production of radar sets and microwave ovens.

Summary

A review of microwave exposure criteria used in the United States and other western countries in the past ten years indicates a general acceptance of a power density exposure level of 10 mW/cm^2. The U.S.S.R. and Poland specify permissible levels lower by a factor of 1000 at 10 μW/cm^2, while Czechoslovakia has proposed a sliding scale allowing 25 μW/cm^2 for an average working-day exposure. The basis for these differences was not discussed in this paper, but in general they arise by the acceptance of data showing nonthermal functional changes from microwave radiation exposure of animals and humans.

The first standards developed in the United States considered the 10 mW/cm^2 value to be a maximum permissible level which should not be exceeded. These standards considered only the power density level of microwave energy and did not consider other factors affecting biological response such as multifrequency exposures, time of exposure, frequency used, and environmental factors such as the heat load or cooling capacity of the workplace. Several countries have maintained this concept of a permissible value, while others have incorporated exposure time. The two latest exposure criteria which have been developed in the United States since 1965 permit exposures to power densities in excess of 10 mW/cm^2; however, the duration of such exposure is limited. This concept has been accepted by France for military guidelines. Czechoslovakia has also accepted this newer concept incorporating exposure time by proposing a sliding scale of allowable radiation intensity but retaining their much lower allowable daily exposure level as the starting point.

In applying the concept of a time-weighted exposure the health specialist must consider how far the dose–time relationship can be extrapolated. The biological response to extremely high microwave power densities, even though such exposure may be for a very short time period, must be considered. The effects of severe heat stress or intense cold on the body's cooling capacity are noted in the latest United States standard, although definitive recommendations for applying the concepts are not provided. Future standards should reflect environmental stress as well as other factors found to affect the biological response to microwave energy.

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