Archiv für Toxikologie 22, 24—35 (1966)

√ Glaser

Biological Effects of Microwave Radiation of 24,000 Megacycles*

WILLIAM B. DEICHMANN

Department of Pharmacology and the Research and Teaching Center of Toxicology
University of Miami, School of Medicine, Coral Gables, Florida, U.S.A.

Received June 20, 1965

* Lecture presented at the Free University of Berlin, June 18, 1965.

Microwave energy, a high-frequency electromagnetic radiation, is emitted as a beam from either a rotating or a stationary antenna. The microwaves which carry telephone conversation and radio and television programs are similar to the microwave energy or the radar beams used by ships and aircraft. In radar, depending on the object or objects that the microwaves strike, a portion, or a fraction, of the radiation is reflected. We may say the waves are "bounced back" and picked up again by the antenna, conducted down the transmission line to the receiver, and processed into useful information which may be displayed or stored for future use. In communication applications, the microwave energy is seldom called upon to make a "round trip" journey; it carries the desired information or program material from source to destination.

The purpose for which microwaves are used determines the wavelength (vibrations per second) and the power required. The total power emitted from a transmitter is measured in watts. In space, the power emitted is referred to as power density. It is measured in watts or in milliwatts per cm^2.

In a radar beam, we are differentiating between the "near field" (Fresnel Zone) and the "far field" (Fraunhofer Region) (Fig. 1). In the "near field" the power leaving the antenna is confined within a cylinder which has the same diameter as the antenna. In the "far field" the flow of power may be thought of (even though this is not entirely true) as a beam confined in a cone which has its apex at the center of the antenna. In this beam, the power density is, by definition and for practical purposes, twice as great on the axis as on the periphery.

The physical properties of microwaves are interesting. The radiation apparently passes uninhibited and without loss through air or through a vacuum. When the waves strike a substance, one or a combination of three effects will occur: reflection, transmission, and/or absorption. Only when the microwaves are absorbed is the energy converted into heat.

It is the molecular structure of a particular substance which determines whether microwave energy of a given wavelength, is reflected, transmitted, or absorbed. Air, plastics, glass[1], and china[1] transmit the energy; and since there is no absorption, there is no heating. On the other hand, metals, brick walls, and clouds[1] reflect the microwaves; and, again, since there is no absorption, there is no heating. But animal and human tissues, as well as foods, absorb the energy. Depending upon the wavelength and power density, and also upon the composition of the tissues, as well as a number of other factors, the microwaves

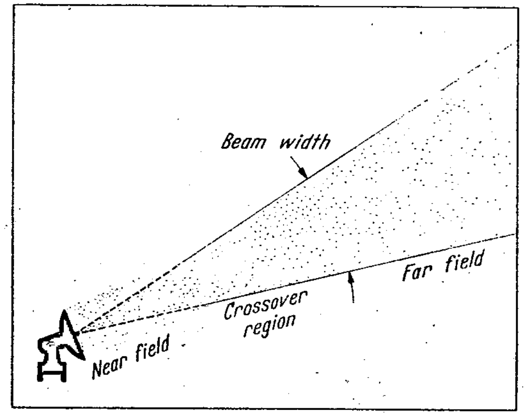

Fig. 1. Radar beam, showing conditions near antenna. "Taken from H. S. Overman"

penetrate and produce instantaneous heat, not only on the surface, but also deep inside. This is in contrast to conventional heating or cooking where only the surface of the tissues or food is heated. Medical diathermy, as well as cooking by microwave radiation, produces another differentiating effect. The metal surfaces of the oven remain cool, since the radiation is reflected. The air surrounding, for instance, a steak or a roast heated in a microwave oven, remains at room temperature; it remains therefore at a lower temperature than the surface of the meat. But since heat radiates from the surface of the roast to the cooler air, the surface temperature of the roast will end up somewhat lower than the temperature just inside the meat.

As may be expected, the period of time required to raise the temperature of any type of food is in almost direct proportion to its weight.

We at the University of Miami, have conducted studies with pulse-modulated magnetrons. These magnetrons were operated at 24,000 mega-

[1] This is not always, and not entirely, true since it depends, in addition to frequency, on the particular composition of the material as well as other circumstances and conditions.

cycles, or a wavelength of 1.25 cm, each with an average power output of 20 watts (DEICHMANN, STEPHENS, KEPLINGER, and LAMPE).

The project assigned to us by the U.S. Air Force was to determine the biological effects of this type of radiation, utilizing various experimental animals. For acute exposure we utilized a chamber lined with absorbent shielding to prevent the escape of stray currents and to eliminate undesired reflections or irradiation. A 10 db standard gain-horn antenna was directed down upon the animal, or upon a specific area of its body. For animals which were to be more or less immobilized, we used microwave transparent plexiglass holders. For chronic total body exposures of rabbits, rats, guinea pigs, mice and chicks, we constructed a turnable which rotated at 1 RPM. Dogs were exposed chronically in a stationary plastic cage. Only in exceptional instances were animals anesthetized.

One of the first studies conducted (controlled temperature and humidity, still air) showed that there is a straight line relationship between power density and period of survival of the albino rat. For instance

Exposure to 170 mw/cm²	— killed in	5 minutes
Exposure to 120 mw/cm²	— killed in	13 minutes
Exposure to 80 mw/cm²	— killed in	19 minutes
Exposure to 55 mw/cm²	— killed in	44 minutes
Exposure to 37 mw/cm²	— killed in	282 minutes

The signs of intoxication included CNS stimulation with muscle spasms, tremors, tail erection and clonic convulsions. CNS stimulation was so marked that it aroused a rat from deep pentobarbital anesthesia. Locally there was marked hyperemia, followed by first, second, and third degree burns. The animals apparently died from respiratory failure.

Subsequent studies demonstrated that not all of the areas of the body are equally sensitive to microwave radiation. With continuous exposure to 300 mw/cm², the time required to kill a rat is reduced from 18 minutes, when the exposure is directed to the head, to 15 minutes with exposure to the lumbar region, and to 13 minutes when the exposure is directed to the abdomen. The radius of the area exposed was kept constant in each of these experiments.

Our studies revealed that a rectal temperature of 42 to 43° C was critical for the survival of a rat or mouse. By using several thermistor thermometers implanted in body cavities and tissues, it was possible to follow the increase in temperature in several organs simultaneously. In the following experiment, exposure (300 mw/cm²) was directed to the lumbar area of the rat. After 12 minutes of continuous exposure, the abdominal temperature had climbed to 46° C, the temperature in the neck to 44° C, while the rectal temperature had risen only to 41° C. These observations are in line with earlier observations that the abdominal area is quite sensitive to injury. This experiment also demonstrates that the temperature in the abdominal cavity rises most acutely.

Of all organs, the testes experience the most marked temperature rise, even when the exposure (75 mw/cm²) is directed to another part of the body as, for instance, to the lumbar region of the rat. During a period of 30 minutes, temperatures in the kidneys, lungs, spleen, stomach and rectum rose 4 to 5° C, while the temperature in the testes rose 10° C. Studies conducted by our colleagues in the Department of Pathology showed that with a single five-minute direct exposure

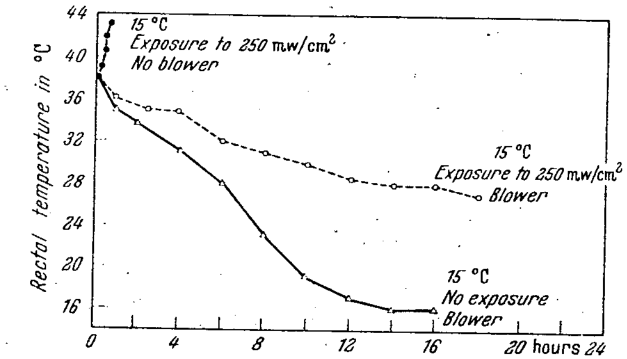

Fig. 2. Effect of air current on survival and rectal temperature of the rat

(250 mw/cm²) to the unprotected testes of the anesthetized rat, the following changes occurred: first and second degree skin burns, rise in testicular temperature from a mean of 33° C to a maximum of 41° C, and enlargement of the testes with marked pallor and edema. There was also a depression (up to 45%) of the Zn^{65} uptake by the dorsolateral prostate, an indication that the testicular damage had affected the Leydig cell function in output of androgen (GUNN, GOULD and ANDERSON).

Since one of the dominant effects of microwave radiation is the production of heat, it seemed obvious to us that the environmental temperature should play a marked role in radiation effects. With an increase in environmental temperature from 5 to 35° C, there is a decrease in the period of survival of rats exposed continuously to 250 mw/cm² from 60 to 15 minutes.

Fig. 2 demonstrates what happens when cooling (loss of body heat) is brought about by an air current. For this experiment, we utilized a 1/15 HP motor, which moved a volume of air of 140 cu. ft./min. at zero pressure. Each of a group albino rats was exposed continuously (restrained in the prone position) until death, to 250 mw/cm² at an environmental temperature of 15° C. In the rats exposed in *still* air, the rectal temperature rose within 30 to 35 minutes to 43° C, and all rats died promptly with signs of hyperpyrexia. Similar microwave exposure at 15° C, but supported by a current of air blown onto the animal, caused an immediate and continuous *drop* of rectal temperature to 28° C. These animals survived, with continuous exposure, for almost 19 hours, showing that "forced" loss of body heat acted as a potent antagonist to radiation effects (DEICHMANN, BERNAL, and KEPLINGER). Since these rats died with a definite subnormal rectal temperature, the question is raised, whether the production of heat is the only systemic

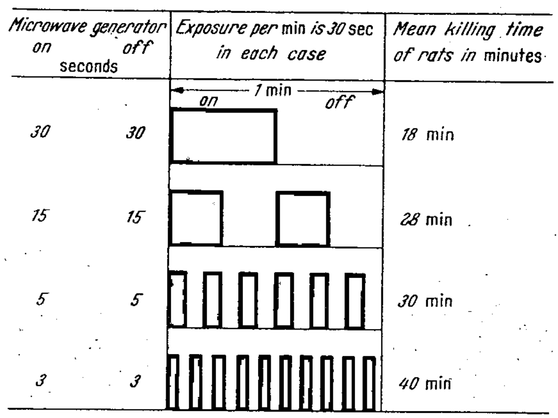

Fig. 3. Irradiation cycle rate and effects. Rats were exposed (individually-lumbar region) until death to microwave radiation —1.25 cm, 300 mw/cm²

effect produced by microwave radiation. The control for this experiment is interesting. No radiation exposure, but blowing of 15° C air onto each of a group of rats, caused their death in about 16 hours. These animals died with rectal temperatures of approximately 16° C. This experiment points out that local or systemic injury or death from microwave exposure can be delayed considerably, or prevented, by methods that support external cooling. This study also emphasizes that not all effects of microwave radiation need be harmful. It is well known that in Arctic areas, radio operators have stepped in front of antennas to warm up.

Our next studies concerned themselves with the effects of various periods of exposure followed by periods of non-exposure and repetition of this cycle (DEICHMANN, KEPLINGER, and BERNAL; DEICHMANN). The results of a series of experiments led to the introduction of the term "*Irradiation Cycle Rate*". This refers to the number or rate at which ON and OFF periods (of irradiation) are repeated per unit of time (one minute). Fig. 3 demonstrates that the briefer (in time) the individual

bursts of radiation and periods of no radiation, or the briefer the period of exposure and non-exposure, the less marked are the local systemic irradiation effects, *even though the total dose of radiation per unit of time (one minute) is kept constant.* The significance of these observations becomes obvious when one considers, for instance, two radars — one rotating at 6 rpm, the other at 12 rpm. If wavelength and power output of these units are identical, then biological effects (if any) should be expected first in personnel exposed to the slower rotating equipment.

All experiments so far conducted make it evident that radiation effects are related directly to the degree of absorption of microwave energy with the resultant production of heat. The question arose whether microwave and infrared radiation were comparable, and suitable for comparison. In the following experiment, each of a group of rats was exposed to microwave radiation, while each rat of another group was exposed to infrared energy. The data demonstrate that discontinuation of infrared exposure was followed with an immediate drop of rectal temperature, while the rectal temperature of the rats exposed to microwaves continued to rise for several (4 to 8) minutes. As far as the production of hyperpyrexia is concerned, one mw/cm² of microwave energy was found to be approximately equivalent to three mw/cm² of infrared energy.

In the next group of experiments, animals were exposed to either infrared energy or microwaves. In half of the rodents of each group, the fur was closely clipped before exposure. These studies brought out the interesting observation that microwaves readily penetrate the fur of the rabbit or rat, while the fur offered a definite (protective) barrier to the rays of infrared energy. Also, local infrared effects were confined to the skin, while the local effects of microwave energy involved the skin and the muscular layers of the areas exposed to a depth of 5—8 mm.

Throughout our studies the question considered was whether microwave effects can be explained entirely on the basis of the heat produced. There has been speculation as to the so-called athermal effects. For instance, what caused the fatalities in the rats which were cooled while irradiated? But since no one has as yet defined "heat" at the molecular level, all observations of this nature have remained speculative.

PAFF, *et al.*, members of our University team, made an additional contribution to this question. They demonstrated that embryonic chick hearts exposed to microwave irradiation suffered irreversible electrocardiographic damage. These hearts are exceedingly sensitive and respond immediately to an increase in temperature with an increase in rate. The fact that no change in heart rate was noted in these exposed chick hearts is accepted as an indication that heat could not have been the prominent factor in these radiation effects.

The question of human tolerance to microwave radiation has been of concern to all those charged with the safety of personnel engaged in the manufacture of radar equipment, or who may suffer exposure in the field. In 1953, SCHWAN recommended that microwave radiation of 10 mw/cm² be accepted as the tolerance dose. This dose was accepted by the military and industries in the USA, and subsequently also recognized by NATO and by the USSR.

The latest studies carried out in our laboratories were concerned with the effects of prolonged or chronic exposure of experimental animals to microwaves at a density equal to or twice the presently accepted tolerance level (DEICHMANN, BERNAL, STEPHENS, and LANDEEN). Two female beagle dogs (age 20 months) were individually exposed to 20 mw/cm² over a period of 20 months. One dog was exposed 6.7 hours per day on five days of the week, for a total of 2631 hours, while the second dog was exposed 16.5 hours per day on each of four days of the week for a total of 3970 hours. Throughout these periods of exposure, rectal temperatures, blood volume, hematocrit, hemoglobin, erythrocytes, total and differential leukocytes, blood cholesterol and protein-bound iodine values remained within normal limits. The animals did not gain in body weight. Whether or not this observation is significant will require additional studies.

Throughout this 20-month experiment, both animals maintained hemeostasis in spite of the fact that the animals were subjected to definite stress. This is evident from the fact that during the individual exposure periods both dogs lost considerable weight (urine, feces, insensible loss of water, breakdown of body tissues). Excluding the weights of urine and feces, the dog exposed 6.7 hrs/day lost 3.5 gram of body weight during each hour of exposure; while the dog exposed for 16.5 hrs/day lost 1.8 gram per hour; or over 6.7 or 16.5 hours of daily exposure, the dogs lost 23 gram and 30 gram respectively. Since both dogs maintained their pre-experimental body weight throughout the experiment, it is obvious that they recovered their daily loss during the daily non-exposure period.

In another study, Osborne-Mendel strain rats were irradiated continuously to 10 mw/cm² for periods of three hours every second day for a total of 11 exposure days (DEICHMANN, MIALE, and LANDEEN). Each three-hour exposure induced significant leukopenia, lymphopenia and neutrophilia, as well as a moderate increase in erythrocytes, hemoglobin and hematocrit values, followed by complete recovery during the 45 hours before the next exposure. The increase in erythrocytes

can be explained on the basis of hemoconcentration; no adequate explanation can be offered for the changes in leukocytes (Fig. 4).

Based on these studies, which were conducted in *still* air and at an environmental temperature of 24° C, microwave exposure to 10 mw/cm² produced temporary hemopoietic effects, while exposure of dogs to 20 mw/cm² was responsible for temporary loss of body weight. (Body

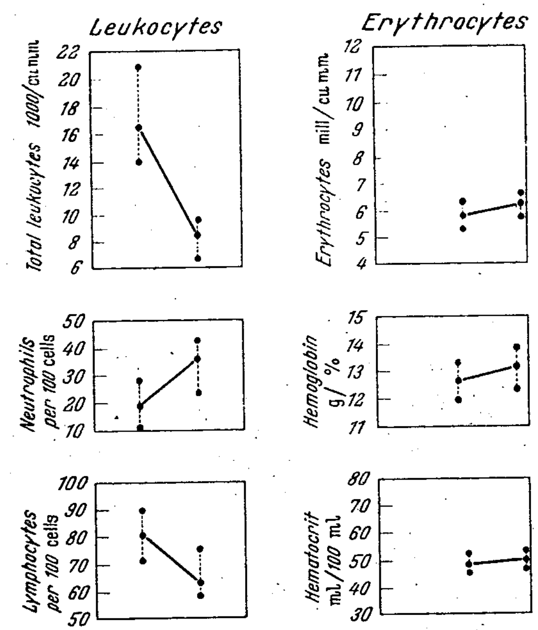

Fig. 4. Effect of microwave radiation of 10 mw/cm² on the peripheral blood of Osborne-Mendel rats. (This procedure presents mean, as well as highest and lowest values, of 36 individual, 3-hour periods, of dorsal total body exposure.)

weight changes were not recorded in rats.) Repeated or prolonged exposure to these radiation intensities demonstrated that a healthy animal can readily adjust to and recover from this stress. Based on these data, if comparison is permissable, maintenance and adherence to a human tolerance level of 10 mw/cm² appears justified.

On the other hand, the supposition that radiation exposure to dosages in excess of 10 or 20 mw/cm² must be expected to induce harmful radiation effects is challenged. Our studies have shown that there is a correlation between dose and biological effect, but only if and when a number of factors are kept constant. One might speculate, and it is believed that this speculation may not be too unrealistic — that an individual stationed at one of the poles and subjected to freezing gale winds can tolerate many times the dose of radiation which may produce undesirable effects in another man exposed in still humid air at the equator.

The suggestion is made to reconsider 10 mw/cm² as the human tolerance dose, and to bring into focus certain modifying conditions or factors which have been demonstrated to influence the effects of a certain dose of radiation (DEICHMANN and STEPHENS).

Some of the following factors may be given consideration.

No.	Factors	Absorption of Energy, or the Production and/or Retention of Heat
1.	*Wavelength or frequency*	Absorption increases with reduction in wavelength. At low frequencies, below 200 megacycles or a wavelength of at least 1.5 meters, "bulk" absorption is of a low degree with the tissues of the body acting as a relatively transparent dielectric medium. From high to very high frequencies, absorption of microwave energy (and heat) increases with an increase in frequency. Maximum absorption occurs at a frequency of 24.5 megacycles, or a wavelength of 1.225 cm.
2.	*Time*	Absorption increases as the period of exposure increases.
3.	*"Irradiation Cycle Rate"*	Per unit of time (one minute) and provided that the total period of exposure (in seconds) per unit of time is kept constant, retention of heat increases as the bursts or periods of exposure and non exposure (in seconds) decrease.
4.	*Air Motion or Currents*	Retention of heat increases the "stiller" the air. The more vigorous the air currents, the more effective the loss of body heat.
5.	*Humidity*	Retention of heat increases with an increase in humidity, thereby reducing loss of body heat.
6.	*Clothing*	Retention of heat increases with clothing that reduces loss of body heat.
7.	*"Protective" Clothing*	Absorption of radiation decreases the more effective the reflective clothing or shielding.
8.	*Environmental Temperature*	Retention of heat increases with an increase in temperature.
9.	*Type of Body Tissues*	Absorption increases a) the "fatter" the individual, b) the more sensitive the body area (abdomen > lumbar region > head), c) the more prone to local injury (testes), or d) the poorer the local circulation (eye). (It was SCHWAN who established in numerous experiments and mathematical investigations that the individual tissues of the body behave between the limits of transparency and opacity.)
10.	*Body Weight, Type or Mass*	A paradox exists among variables, including body size, body surface, body mass and body tissues. Because of differences in absorbing areas, a short, stocky Eskimo might absorb less radiation than a tall, thin African of the same body weight. On the other hand, the Eskimo's body, because of the greater fat content,

(Continuation)

No.	Factors	Absorption of Energy, or the Production and/or Retention of Heat
		will experience a greater rise in temperature with the same heat absorption. The thicker the layer of fat, the greater the depth of penetration of microwaves; in other words, fatty tissues are more transparent to microwave energy than tissues containing a high water content. Yet beyond the fatty tissues, absorption does occur in the tissues with the higher water content. Heat dissipation, however, is reduced by the insulating fatty tissues. Absorption of energy may be further increased through the production of standing waves brought about because of the fatty tissues and their interfaces at other tissues or media (SCHWAN). It is for these reasons that a unit dose of microwave radiation induces a higher temperature in a body covered by a layer of fat. Coming back to the tall, thin African, he can be expected to be better suited to the task of dissipating the excess body heat he might experience from the absorption of microwave energy. But, if we were to include the factors of environmental temperature, the Eskimo in his natural habitat would certainly have the advantage.
11.	*Position in the Field*	Variables exist related to resonant conditions of an exposed subject because of his orientation to the radar beam.
12.	*Reflections*	Absorption increases with an increase in the number of reflections in a complex environment. This factor could become quite important. Because of the ability of microwaves to be readily reflected from many types of surfaces, the possibility exists of encountering a high concentration of microwave energy at some unsuspected point. This is likely to become of particular importance in close quarters, as for instance, aboard ship, as well as in areas where several radars are operating.

Summary

Microwave radiation represents a type of high-frequency (or short wavelength) electromagnetic radiation.

All of us are almost constantly exposed to the lower frequencies of this type of radiation (wavelength > 1.5 meters). With the exception of a most occasional or perhaps most unusual individual, we are not aware of this type of energy. The only proven injury to man has resulted from exposure of his eyes, and this has been much less frequent than was believed several years ago. Injury to the human testes has been claimed but not proven. The literature reports a few isolated incidents of fatal human total body exposure, but according to KNAUF, each of these cases was complicated by unrelated factors.

Our animal studies conducted with pulse-modulated magnetrons, operated at 24,000 megacycles or at a wavelength of 1.25 cm, demonstrated that microwave energy can cause severe local damage, as well as systemic effects related primarily to stimulation of the central nervous system, and death. Hyperpyrexia is prominent in animals exposed to harmful or lethal doses, but there is some indication that microwave energy, or a fraction of this energy, exerts its effect in some other form than heat. And so we occasionally speak of non-thermal or athermal radiation effects. The electrocardiographic changes noted in the radiated embryonic chick heart, and the fatalities induced by microwave radiation in rats with subnormal body temperatures appear to require more than the conventional explanation.

The suggestion is made to give consideration to modification of the human tolerance dose of 10 mw/cm². It is believed that this is important to discourage unrealistic and unjust claims of injury.

The following factors are suggested for primary consideration:

a) wavelength,

b) time (including the "Irradiation Cycle Rate"),

c) environmental conditions (air currents and temperature),

d) body area (total body exposure versus eyes, testes, or abdomen).

References

DEICHMANN, W. B.: Introducing the "Irradiation cycle rate" in microwave radiation exposures. Biochem. Pharmacol. 8, No 1 (1961).

— E. BERNAL, and M. KEPLINGER: Effects of environmental temperature and air volume exchange on survival of rats exposed to microwave radiation of 24,000 megacycles. Industr. Med. Surg. 28, 535 (1959).

— — F. STEPHENS, and K. LANDEEN: Effects on dogs of chronic exposure to microwave radiation. J. occup. Med. 5, 418 (1963).

— M. KEPLINGER, and E. BERNAL: Relation of interrupted pulsed microwaves to biological hazards. Industr. Med. Surg. 28, 212 (1959).

— J. MIALE, and K. LANDEEN: Effect of microwave radiation on the hemopoietic system of the rat. Toxicol. Appl. Pharmacol. 6, 71 (1964).

—, and F. H. STEPHENS jr.: Microwave radiation of 10 mw/cm² and factors that influence biological effects at various power densities. Industr. Med. Surg. 30, 221 (1961).

— —M. KEPLINGER, and K. F. LAMPE: Acute Effects of microwave radiation on experimental animals (24,000 megacycles). J. Occup. Med. 1, 369 (1959).

GUNN, S. A., T. C. GOULD, and W. A. D. ANDERSON: The effect of microwave radiation on morphology and function of rat testis. Lab. Invest. 10, 301 (1961).

KNAUF, G. M.: Industrial medical problems in an electronic research center. Arch. Industr. Health 17, 383 (1958).

PAFF, G. H., R. J. BOUCEK, R. E. NIEMAN, and W. B. DEICHMANN: The embryonic heart subjected to radar. Anat. Rec. 147, 379 (1963).

SCHWAN, H. P.: Private communication with Dr. H. P. SCHWAN, University of Pennsylvania. (Original was submitted by Dr. SCHWAN in May, 1953, to ONR (Mrs. KELLY) and NMRI (Drs. COLE and GOLDMAN).

SCHWAN, H. P.: Molecular response characteristics to ultrahigh frequency fields. ONR Technical Report No 24, 1958.

— Survey of microwave absorption characteristis of body tissues. ONR Technical Report No 25, 1958.

— University of Pennsylvania Electromedical Laboratory, The Moore School of Electrical Engineering: Effects of microwaves on marking. Second Annual Progress Report [Contract AF 41(657)129], March 1, 1959.

—, and K. LI: The mechanism of absorption of ultrahigh frequency electromagnetic energy in tissues, as related to the problem of tolerance dosage. IRE Transactions of the Professional Group on Medical Electronics, PGME-4, February 1956.

— — Hazards due to total body irradiation by radar. Proc. IRE, 44, No. 11 (1956).

WM. B. DEICHMANN, PH. D.
University of Miami, School of Medicine
Department of Pharmacology
Coral Gables, Florida 33134 (USA)

Druck der Universitätsdruckerei H. Stürtz AG., Würzburg