Organism of Men and Animals. Leningrad, USSR: Meditsina Press, 1970, NASA TTF-708, 1972.
[20] Z. V. Gordon, *Biological Effect of Microwaves in Occupational Hygiene*, 1966, translated from Russian, NASA TTF-633, 1970.
[21] M. N. Sadchikova, "Clinical manifestations of reactions to microwave irradiation in various occupational groups," in *Biologic Effects and Health Hazards of Microwave Radiation*, P. Czerski, K. Ostrowski, C. Silverman, *et al.*, Eds. Warsaw, Poland: Polish Medical Publishers, 1974, pp. 261-267.
[22] M. Siekierzynski, C. Czarnecki, E. Dziuk, *et al.*, "Microwave radiation and other harmful factors of working environment in radiolocation: Method of determination of microwave effects," *J. Microwave Power*, vol. 11, pp. 144-145, 1976.
[23] C. Silverman, "Nervous and behavioral effects of microwave radiation in humans," *Amer. J. Epidemiol.*, vol. 97, pp. 219-224, 1973.
[24] —, *The Epidemiology of Depression*. Baltimore, MD: Johns Hopkins Press, 1968.
[25] R. Rugh, E. I. Ginns, H. S. Ho, *et al.*, Responses of the mouse to microwave radiation during estrous cycle and pregnancy," *Rad. Res.*, vol. 62, pp. 225-241, 1975.
[26] A. T. Sigler, A. M. Lilienfeld, B. H. Cohen, *et al.*, Radiation exposure in parents of children with mongolism (Down's Syndrome), *Bull. Johns Hopkins Hosp.*, vol. 117, pp. 374-399, 1965.
[27] B. H. Cohen, A. M. Lilienfeld, S. Kramer *et al.*, "Parental factors in Down's Syndrome-results of the Second Baltimore Case-control Study," in *Population Cytogenetics, Studies in Humans*, E. B. Hook, and I. H. Porter, Eds. New York: Academic, 1977, pp. 301-352.
[28] P. B. Peacock, J. W. Simpson, C. A. Alford *et al.*, "Congenital anomalies in Alabama," *J. Med. Ass. State AL.*, July 1971, pp. 42-50.
[29] J. A. Burdeshaw and S. Schaffer, "Factors associated with the incidence of congenital anomalies: A localized investigation. Environmental Protection Agency, Final Rep. Contract No. 68-02-0791, Mar. 31, 1976.
[30] J. Daels, "Microwave heating of the uterine wall during parturition," *Obstet-Gyn.*, vol. 42, pp. 76-79, 1973.
[31] —, "Microwave heating of the uterine wall during parturition," *J. Microwave Power*, vol. 11, pp. 166-168, 1976.

Soviet and Eastern European Research on Biological Effects of Microwave Radiation

DONALD I. MCREE

Abstract—A large amount of literature on the biological effects of microwave radiation has been obtained from the Soviet Union and other Eastern European countries since 1973. This literature reports changes in almost all biological systems at exposure power densities less than 10 mW/cm². Since 1976 an increased amount of data using long-term microwave exposures at power density levels below 10 mW/cm² has been published. An overview of research results reported since 1976 are presented in this paper.

INTRODUCTION

FOR MANY YEARS literature from the Soviet Union and other Eastern European countries have reported biological effects of microwave radiation on humans and animals at low levels of exposure (less than 10 mW/cm²). Effects on almost all biological systems have been reported. Unfortunately the Soviet literature in general does not provide details into their experimental design and research methodology. The normal research paper usually includes the frequency of exposure (sometimes not the exact frequency but only the designation *microwave* or a frequency band in the microwave region), the incident power density of the radiation, the duration of exposure, and animal species. Very little if any information is given on how the animals are exposed, or field characteristics, or energy absorption, or how control animals are maintained, and or other important experimental design parameters which are required for describing the research. In most cases, the bulk of the paper presents many biological changes with little description of the techniques used for measuring the observed alterations. In cases where effects on *humans* are reported, the exposure frequency, usually designated in broad terms such as *microwaves*, sometimes the range of levels measured within the general area, and sometimes the length of time the person has worked in the area are given. Little or no discussion on how the exposed and control groups are constituted and the possible presence of other environmental factors, both chemical and physical, is provided. Most of the reported results are subjective in nature and techniques used to obtain the results are often not given.

In spite of these difficulties with the Soviet and Eastern European research, this large volume of data has been one of the important driving forces in the U.S. producing concern over the biological effects of microwave radiation and generating the necessity for continued research to evaluate the significance of microwave exposure. In attempts to replicate some of the Soviet and Eastern European work, Western investigators have not obtained, in most cases, the same biological changes. However, due to the lack of information in the Soviet and Eastern European literature, it is technically impossible to duplicate in all aspects their research.

REVIEW OF RECENT LITERATURE

Although numerous review articles and books have been published, only a limited number of Soviet and East European

Manuscript received July 16, 1979; revised August 13, 1979.
D. I. McRee is with the National Institute of Environmental Health Sciences, Research Triangle Park, NC 27709.

TABLE I
GENERALLY USED MICROWAVE FREQUENCY DESIGNATION OF SOVIET AND EASTERN EUROPEAN COUNTRIES

Frequency (MHz)	Wavelength (cm)	English and American	Designation Soviet Literature	Metric, used in U.S.S.R. Poland and Czechoslavakia
300–3000	100–10	Ultra high frequency (UHF)	Super high frequency (SHF)	Decimeter waves
3000–30 000	10–1.0	Super high frequency (SHF)		Centimeter waves
30 000–300 000	1.0–0.1	Extra high frequency (EHF)		Millimeter waves

TABLE II
SOME RESULTS OF EXPERIMENTAL STUDIES ON THE BIOLOGICAL EFFECTS OF VERY LOW INTENSITY MICROWAVES (UP TO 150 μW/cm²) [6]

Investigated Function	Radiation intensity $\mu W/cm^2$	Character of Changes	Investigator
Body Weight	150	Lag in weight (chronic experiment)	V. V. Markov
Arterial Pressure	150	Biphasic course with marked hypotension (chronic experiment)	V. V. Markov
Reproductive Function	150	Decreased fertility, decreased litter size, increased number of defective progeny, increased embryonic mortality etc. (chronic experiment)	A. N. Bereznitskaya *et al.*
Central nervous system	10–20 and higher	1) EEG changes with predominant synchronization (acute experiment)	Z. V. Gvozdikcova *et al.*
	150	2) Bivariant shifts with predominance of activation (acute experiment)	
	150	3) Bivariant shifts in the subcortical-basal structures (chronic experiment)	
Electromyography	150	Increased electrical activity of active unit	V. V. Markov
Hypothalamus-adrenal cortex system	150	1) Weight change of endocrine glands hypophysis adrenals) 2) Change in the neurosecretory function of the hypothalamus 3) Tendency for increased levels of norepinephrine in the adrenals	N. K. Demokidova
Metabolism	150	Changes in water and electrolyte metabolism (Na, K, water, and total nitrogen excretion)	N. K. Demokidova
Immunology	150	Inhibition of neutrophils phagocytic activity	A. P. Vokova and V. V. Markov

references dated after 1973 are cited in these publications [1]–[5]. In this paper, primarily work reported since 1976 will be reviewed. For this review, microwaves will be considered as including electromagnetic (EM) radiation in the frequency range of 300 MHz to 300 GHz. Baranski and Czerski [1] have reported the designation of specific microwave frequency bands usually used in the Soviet and Eastern European literature (Table I). Since the exact frequency at which the experiments are performed often is not given in the Soviet and Eastern European reports, the designations in Table I will be used when discussing reports when frequency is not specified.

Although the Soviet occupational exposure standard of 10 $\mu W/cm^2$ for a working day was formulated in 1957, almost all the Soviet data prior to this time was in the 1- to 10-mW/cm^2 range. Only a very small amount of data at levels below 1 mW/cm^2 was reported in the literature prior to 1973. In 1974 Gordon [6] reported low-level biological effects (up to 150 $\mu W/cm^2$) which had been observed at the Institute of Industrial Hygiene and Occupational Diseases in Moscow (Table II). In 1975 Minin [7] presented additional low-level bioeffects data in his review of the literature. He reported data on a power density scale which goes from 1 W/cm^2 down to 20 $\mu W/cm^2$ and includes both human and animal data (Table III). Shandala *et al.* [8] stated in 1975:

> We should note that the effect of a high-intensity SHF field on the animal and human organisms has been thoroughly researched. The syndrome caused by these fields has been named the radio wave sickness. Considerably less research has been done on the biological effect of low-intensity microwaves. No research has been done on the health of populations living in a low-intensity SHF field.

By this statement Shandala meant that no research had been done at intensity levels found in populated living areas and for continuous exposures over a long period of time.

For additional details on research by the Soviet and Eastern European investigation prior to 1976, the reader is directed to references [1]–[5]. The remainder of the discussion on biological effects will be concerned with work published since 1976 at exposure power densities of 10 mW/cm^2 and lower.

Effects on Humans

An investigation on the threshold of color discrimination and the temporary threshold of light sensitivity was performed on workers responsible for repair of SHF sources in the centi-

TABLE III
SOME DATA ON THE EXPOSURE ON MAN AND ANIMALS TO MICROWAVE FREQUENCY FIELDS (ARRANGED ON INTENSITY SCALE) [7]

Power Density		
W/cm^2	1	Eye cataracts in dogs after exposure for 3-5 h.
	800	
	600	(*L*, *M*)* pain sensation during exposure.
	300	Brief increase in blood pressure; after 20-60 min marked decrease (cat, rabbit, dog).
	200	(*L*) Malformation of offspring after exposure for 10-15 min (chicken eggs, $\lambda = 12.6$ cm), death of cats and rabbits (t = 20-60 min). Reduction of redox in tissue.
mW/cm^2	100	(*M*) Increase in blood pressure with subsequent marked decrease; in case of chronic exposure–stable hypoxia. Stable morphological changes in the cardiovascular system. Bilateral cataracts.
	40	(*L*) Increase in blood pressure with subsequent marked decrease; multiple hemorrhages, λ = 3-10 cm, in liver (dilation of vessels and hemorrhages λ = 10 cm). Increase in blood pressure of 20-30 mm Hg (exposure for 0.5-1.0 h).
	10	(*M*) Changes in conditioned reflex activity, morphological changes in cerebral cortex (*L*). Vague shifts on blood pressure (exposure time 150 h), change in blood coagulability. Hyperplasia of liver cells, λ = 3-10 cm (chronic exposure). ECG changes (wavelengths other than DTsV–expansion not given). Change in receptor apparatus.
	5	Threshold intensity at which there are changes in the testis and blood pressure changes (multiple exposure). Brief leukopenia and erythropenia. Darkening of the crystalline lens.
mW/cm^2	3	(*M*) Decrease in blood pressure, tendency to quickening of pulse, fluctuation of cardiac blood volume.
	1	(*M*) Decrease in blood pressure, tendency to quickening of pulse, insignificant variations in cardiac blood volume. Decrease in blood pressure level; decrease in ophthalmotone (t; daily, 3.5 months). Disadaptation, disorders of immunological protection control mechanisms (*L*).
	400	Depression of secretions in dogs.
	300	(*L*, *M*) Some changes in the nervous system in case of exposure for 5-10 years.
	200	Neurons in dogs.
	100	(*L*) Tendency to decrease in blood pressure with chronic exposure.
$\mu W/cm^2$	40	(*L*) Tendency to decrease in blood pressure with chronic exposure
	20	(*M*) Thinning of pulse, tendency for a decrease in arterial pressure. Cases of body sensitivity observed. Well expressed increase in skin temperature in persons earlier exposed.
	*M	Data applies to man–all other to animals.
	L	Lowest power density indicated by authors.

meter wave range [9]. The investigators characterized the power density at different locations using an instrument called PO-1 [7]. From these measurements they were able to divide the workers into three groups: first group (25 workers) power density ranged from 235 to 370 $\mu W/cm^2$; second group (22 workers), power density ranged from 10 to 50 $\mu W/cm^2$; and a third group (19 workers), power densities below 10 $\mu W/cm^2$. The duration of exposure were approximately the same for each group and ranged from 60 to 90 min during each work day. The work of the three groups was the same type and was not connected with a considerable strain of the eye. A fourth group which was doing the same type work but not exposed to SHF waves was used as the control group. Statistically significant increases ($P > 0.001$) in the threshold of color discrimination of red, green, and blue were observed in the first group. The greatest change was in the discrimination of red which increased 87.8 percent. A temporary threshold of light sensitivity among this first group of workers was also statistically higher than members of the control group. Statistically significant changes in the threshold of color discrimination were also measured in the second group, but no shifts in the temporary threshold of light sensitivity was observed. No statistical difference was observed in group three when compared to the control group.

In a study to determine ophthalmologic changes in persons exposed to microwaves, 269 healthy young women under the age of 40 were systematically exposed to microwaves of power densities no greater than 10 $\mu W/cm^2$ [10]. A total of 21.6 percent of the women examined had a length of service of up to 5 years; 33.4 percent, 5 to 9 years; 21.5 percent, 10 to 14 years; 13.8 percent, 15 to 19 years; and 9.7 percent, 20 to 23 years. When they begin working, their visual acuity and state of deep refractive media and ocular fundus were determined and eye pressure was measured. As of 1971 all the women examined began to receive biomicroscopic examinations with 1-percent pupil dilation with homatropine. The data obtained was compared with results of examinations of 245 healthy women 22 to 40 years of age who had received no radio-frequency (RF) radiation or other unfavorable occupational factors. The observations showed that in biomicroscopic investigations of lens opacities of varying nature and intensity, changes were encountered almost with the same frequency in the exposed and control groups (70.2 percent in the exposed group and 82.4 percent in the control group). The authors concluded that microwaves of power density of 10 $\mu W/cm^2$ had no effect on the eyes of the examined workers.

A study to determine the effects of millimeter waves on 72 engineers and technicians aged 20 to 50 who were exposed while servicing generators was carried out by observing the workers for 3 years [11]. The workers had been exposed from 1 to 10 years to power densities which sometimes reached 1000 $\mu W/cm^2$. A group of 30 workers without any exposure within the same age range was used as controls. The exposed workers complained of fatigue, drowsiness, headaches, and loss of memory. No changes in pulse or arterial pressure were observed in exposed workers. During studies of morphological composition of the peripheral blood, a decrease in the amount of hemoglobin and the number of erythrocytes and tendency toward hypercoagulation were observed. A significant decrease in the total number of leukocytes and increase in the number of lymphocytes were measured, and the number of segmentonuclear neutrophils decreased by 20 percent. At the same time, the number of reticulocytes and thrombocytes were reduced and the osmotic resistence of erythrocytes decreased by 18 percent and the acid resistance by 26 percent. On testing the immunobiological reactivity, the seeding of the oral cavity with autoflora microbes increased considerably, the bactericidal action of the skin decreased, lysozyme and complement titers in the blood serum were lowered by one-half and the phagocytic activity of neutrophils decreased. The authors concluded that inhibition of the humoral and cellular factors of nonspecific immunity occurred in the exposed workers.

Metabolic Effects

Albino purebred Wistar male rats weighing 180 ± 20 g were exposed to 2375-MHz CW microwave radiation. Ten animals each were exposed to 10 $\mu W/cm^2$, 100 $\mu W/cm^2$, and 1000 $\mu W/cm^2$ with a fourth group used as controls [12]. The animals were exposed for 8 h/day for 3 months. Before the end of the experiment the rats were placed in special metabolic cages where urine and feces were collected for 5 days. At the end of the experiment, the animals were decapitated. The levels of Cu, Mn, Ni, and Mo in tissues were determined by quantitative spectrography. A change in balance and distribution of the four trace elements was measured in different organs. With increased power density, a decrease in excretion of trace elements from the organism and increased changes in interorganic metabolism of the trace elements were reported. Significant changes in distribution of some trace elements in organs were detected at the 10 $\mu W/cm^2$ exposure level.

Minayev *et al.* [13] studied the effects of 2000-MHz CW radiation on enzymatic activity and pyridoxine levels in organs of white male rats. Pyridoxal deficiency was created in 24 animals by administering 4-deoxypyridoxine for 15 days. Twelve pyridoxine dificient animals and twelve normal animals were exposed 3 h/day for 15 days to 570 $\mu W/cm^2$. Blood levels of pyridoxine were determined by a microbiological method, and the activities of aspartate aminotransferase and alanine aminotransferase were determined in the blood and various organs (brain, liver, kidneys, heart, and muscles). In addition, the activity of succinate dehydrogenase was determined in the organs. The investigators reported that the exposure to microwaves resulted in pyridoxine deficiency as well as riboflavin deficiency. They state that it appears that the microwave fields act on the coenzyme portion of the enzyme, but not on the protein portion.

The effects of EM radiation in the millimeter range on metabolism of liver mitochondria have also been studied [14]. Wistar rats were exposed to 6.50-mm waves at a power density of 1 mW/cm^2 for 10 min/day for 30 days. Liver mitochondria were then isolated by means of centrifugation in a medium containing 0.25-M sucrose and 1-mM ethylene diaminetetraacetate (EDTA), pH 7.4. It was reported that the oxidation and energy characteristics of liver mitochondria changes, and conjugation of the processes of oxidative phosphorylation were lowered. The authors stated that the decrease in the oxygen consumption rate in a liver mitochondria could have been the result of the inhibition of electron transfer where phosphorylation was disturbed. When ADP was added, the respiration rate decreased more than the respiratory rate after the exhaustion of ADP or against the background of the substrate because these rates were regulated also by the phosphate potential.

A study to determine the effects of 2375-MHz CW microwaves on enzymatic processes in subcellular fractions of the brain and liver was performed by Dumanski *et al.* [15]. Three groups of rats were exposed to 10, 100, and 1000 $\mu W/cm^2$ for 2 h/day for 4 months, respectively. Analyses were performed at 1, 2, and 4 months after the start of irradiation. The authors reported that at power densities of 100 and 1000 $\mu W/cm^2$, a certain complex of biochemical changes reflecting disturbances in the body metabolism were observed when exposures were for an extended period. A decline in cytochrome oxidase activity in mitochondria, an increase in glucose-6-phosphate dehydrogenase activity in liver and brain hyaloplasm, and activation of *mixed function* oxidase in the microsomal fraction of rat liver were measured. Maximum changes were observed following one month of irradiation and as the exposure time increased, the magnitude of the changes became less, indicating an adaptation to the microwaves. Two months after irradiation, the levels were back to control values. No statistically significant changes occurred in the indices being measured at an exposure of 10 $\mu W/cm^2$.

Another study on the functional activity of liver mitochondria after exposure to 12-cm microwave radiation has been performed by Soviet investigators [16]. Six groups of six rats each were exposed to 10, 25, 50, 100, 500, and 1000 $\mu W/cm^2$ 3 times/day for 40 min for 4 months (5 days/week). The authors stated that this exposure regime corresponded to the operating conditions for household microwave ovens. Disturbances in the respiration and phosphorylation processes in liver mitochondria were measured for exposure power densities of 50 $\mu W/cm^2$ and higher. This effect was reported to be characterized by intensification of nonphosphorylating oxidation of metabolites of the Krebs cycle and decrease in oxygen consumption rates during phosphorylating respiration.

Central Nervous System Effects

Chronic low-level investigations of 12-cm waves on the central nervous system have been performed by Yershova and Dumanski [17] who stated that prior to 1975 practically no data was available at exposure intensities of the order of 10 $\mu W/cm^2$. They exposed both rabbits and white male rats for 8 h/day for 3 to 4 months to CW radiation at 1 $\mu W/cm^2$, 5 $\mu W/cm^2$, and 10 $\mu W/cm^2$ power densities. At both 5 and

10 μW/cm^2 changes in the spontaneous electrical activity of the cerebral cortex of rabbits were measured. The conditioned reflex response was also found to be altered in rabbits, whereas a developed feeding reflex to a bell was unchanged. The authors concluded that chronic exposure to 5 and 10 μW/cm^2 caused a disturbance in the functional state of the higher regions of the central nervous system of both rabbits and rats.

In an experiment to determine the effects of 460-MHz CW microwave radiation on central structures of the brain, the heads of chinchilla rabbits were exposed to power densities of 2 and 5 mW/cm^2 [18]. The bodies of the animals were protected from the radiation by a special covering. Tests were conducted in the following way: 5 min of recording of background activity of the neuron; 10 min of irradiation; 5 min of recording of activity of the neuron after irradiation. After 24 h the experiment was repeated in the same sequence but with recording of activity of a neuron located at a distance of 0.2 to 0.5 mm from the preceding one. This procedure was repeated on seven consecutive days. Experiments on control animals were made the same way but without radiation. The peak potentials of the neurons were recorded using glass micropipettes (tip diameter 0.2–2 μm) filled with a 2.5 M solution of KCl. The activity of a total of 193 neurons in different parts of the brain (dorsal hippocampus, specific and nonspecific nuclei of the thalamus, hypothalamus, and reticular formation of the midbrain) was measured. An analysis of the activity of the neurons indicated that the radiation exerted a selective action on central structures of the brain. The largest number of neurons which actively responded to the radiation was observed in the hippocampus, the least in the reticular formation of the midbrain. The different directions of responses of the neurons of the reticular formation of the midbrain and the nonspecific nuclei of the thalamus was interpreted by the authors as a weakening of the inhibiting effect of the cortex of the large hemispheres upon subcortical structures.

Another experiment by the same authors [19] using chinchilla rabbits was performed at 460 MHz with power densities of 2 and 5 mW/cm^2 and exposure duration of 10 min. The effects of the radiation on the overall and spontaneous activity of neurons on the central structures of the brain were measured. Nichrome electrodes were used to measure the overall electrical activity and the above described microelectrode for spontaneous activity. As in the previous experiment, only the head of the animals were exposed. At exposures to 2 mW/cm^2 the authors reported that an EEG activation reaction was elicited, adoption of the rhythm of a flashing light at the frequency of 13–25 Hz was alleviated and an increase in frequency of neural discharge was induced. At exposure power density of 5-mW/cm^2 synchronization of electrical activity made it difficult to adopt to the rhythm of light flashes at high stimulation frequencies and led to a decrease in frequency of brain neuronal discharges. The authors concluded that the nature of the neurophysiological reactions is dependent upon the intensity of the radiation. The hippocampus and hypothalamus were identified as the brain structures with the greatest sensitivity.

Effects of microwaves on catecholamine metabolism in the brain were studied in male albino rats exposed to 2375 MHz at power densities of 50 and 500 μW/cm^2 [20]. The exposures were for 7 h/day for 30 days. Biological changes in the brains of exposed rats were examined on the 5th, 10th, 15th, 20th, and 30th days. With 50-μW/cm^2 exposure no change in epinephrine was observed until the 20th day when a 25-percent rise was measured; but by day 30 it had returned to baseline levels. There was a distinct, but not marked, increase in other catecholamines (norepinephrine, dopamine) in brain tissue throughout the exposure period. The changes reported for 500 μW/cm^2 were different in nature. The levels of all catecholamines initially increased at the 5th day and then decreased continually to the 30th day. The authors state that this is indicative of exhaustion of both the adrenal and sympathetic branches of the adrenosympathetic system.

Neuroendocrine Effects

Effects of 2860–2880-MHz microwave radiation on pituitary function has been reported by a Polish investigator [21]. Twelve 35-day-old male rats were exposed 6 h/day, 6 days/week for 6 weeks to 10-mW/cm^2 incident power density. Twelve 35-day-old rats which were caged and handled in the same manner as the exposed animals were used as controls. No distinguishable influence on general growth was observed in the exposed animals. No significant change in the amounts of FSH and GH was found in the anterior pituitary. However, the average amount of LH was significantly higher in pituitaries of animals in the irradiated group. The author suggests that the increased amount of LH could be the result of a stimulation effect of microwaves on the LH production in the pituitary gland and/or the result of an inhibitory effect of microwaves on the available LH-releasing hormone in the hypothalamus.

Cardiovascular Effects

Rabbits were exposed to 2375-MHz microwave radiation for a period of 60 days to microwave field intensities ranging from 0–6 V/m (approximately 0–10 μW/cm^2) [22]. Exposures to 3–6 V/m resulted in a significant increase in the heart rate in the initial stages and a marked decrease at the longer periods of exposure. Exposures to intensities of 0.5 and 1.0 V/m caused slowing of the heart rate. Animals exposed to 0.2 and 0.05 V/m did not differ significantly from the control group. Along with the changes in the rate of cardiac contraction, changes in the individual components of the EKG were also detected in the irradiated animals. They were especially pronounced with respect to the spikes.

Blood Effects

In an experiment designed to determine the effects of microwaves on blood serum butyryl cholinesterase activity, 15 rats were exposed 1 h/day up to 42 days to 3000-MHz pulse radiation [23]. The pulsewidth was 3 μs and the pulse repetition rate was 350 Hz. The average power density was 10 mW/cm^2. No changes in general activity were observed for exposures up to 29 days. At 42 days a statistically significant decrease in general activity ($P < 0.01$) was observed. The investigation determined that the decrease in general activity of butyryl cholinesterase under conditions of chronic exposure of animals was due to a decrease of the enzyme concentration in the blood while the molecular activity remained unchanged.

A study to determine the effects of 12.6-cm microwaves on cytochemical indices of leukocytes was carried out at power densities of 10, 50, and 500 μW/cm^2 [24]. Ten mongrel albino rats weighing 180–200 g were exposed to each power density for 7 h/day for 30 days. Blood was taken from the caudal vein after 3, 7, 10, 14, 21, and 30 days of exposure. Exposures to 10 and 50 μW/cm^2 increased the processes of energy metabolism in neutrophils for the first three weeks as indicated by a statistically significant increase in alkaline phosphatase and glycogen content of the cells. By the end of the exposures, the levels had returned to those of the control animals. Exposures to 500 μW/cm^2 activated glycolysis in neutrophils, and this resulted in a decrease in glycogen content of cells by the end of the fourth week of irradiation.

The results of a study to determine the effects of pulse microwaves on blood counts of growing rats have been recently reported by Czechoslovakian investigators [25]. Twenty male rats were irradiated for 4 h/day, 5 days/week for 7 weeks. The working frequency was 2736 MHz pulsed at 395 Hz with a pulsewidth of 2.6 μs. The average power density was 24.4 mW/cm^2. Blood was taken from the animals at the end of the 1st, 3rd, 5th, and 7th weeks of irradiation and at the end of the 1st, 2nd, 6th, and 10th weeks after completion of irradiation. In the second half of the irradiation period, the exposed animals had significantly lower mean hematocrit values, lower number of leukocytes, and lower absolute numbers of lymphocytes. These changes gradually returned to control levels within 10 weeks after exposure. Activity of alkaline phosphatase in neutrophil leukocytes was significantly increased in the first week of irradiation and transiently after the irradiation.

Effects on Immunology

The immunocompetence of mice exposed to 6.50-mm waves for 15 min each day for 20 days at a power density of 1000 μW/cm^2 has been studied [11]. The number of leukocytes in the peripheral blood decreased and the indices characterizing the nonspecific resistance of the body were changed. Lysozyme and complement titers, as well as the phagocytic activity of neutrophils were lowered by one-half and the bactericidal properties of the skin were inhibited. A drop in the total mass of lymphoid organs and morphological changes in the thymus, spleen, and lymph nodes were observed. The number of plasma cells decreased in regional lymph nodes and the spleen. Resistance to infections induced with typhoid antitumor, a tetanic toxin, decreased, and specific immunity developed by immunization with a typhoid vaccine or a tetanic antitoxin were inhibited.

In another study [26], guinea pigs were exposed to 2375-MHz microwave radiation daily for 30 days to 1, 5, 10, and 50 μW/cm^2. Immunological analyses were performed prior to irradiation, 2 and 4 weeks after beginning irradiation, and 2, 4, and 8 weeks after termination of irradiation. Dynamics of the principal indicator of the body's nonspecific immunological reactivity, the phagocytic reaction of neutrophils in serum, was studied. It was determined that microwave exposure promotes stimulation of phagocytosis, the phagocytic reaction being higher at the lower power densities. Higher power densities elicited a decline in the phagocytic activity of neutrophils. Therefore, a power density of 1 μW/cm^2 caused the most highly pronounced rise in complement titer. By the end of two months after termination of exposure, the blood serum complement titer of irradiated animals did not differ from control values.

Reproductive Effects

Mice were used to study the effects of microwaves on the function and morphology of reproductive organs [27]. The intent of the study was to determine the effects of 12.6-cm microwaves at incident power densities of 10, 20, and 50 μW/cm^2 on the ability of females to conceive and on the offspring of the irradiated animals (litter size, survival rate, postembryonic development, number of stillborn mice, and number of deformities). For all power densities, a decrease in the reproductive function of females, a decrease in the litter size and changes in the postembryonic development of the offspring were observed. The magnitude of the changes increased with power density. The number of stillborns increased from 1.1 percent at 10 μW/cm^2 to 7 percent at 50 μW/cm^2.

Effects on Cells and Viruses

Changes in cell composition of bone marrow has been studied. Eighty male mice were exposed to 2.5 mW/cm^2 to microwaves with a wavelength of 7.1 mm for 1 h [28]. Imiphos (group of alkylating compounds) was given peritoneally prior to irradiation. It was found that the microwaves, combined with imiphos, did not protect erythroblast cells and elicited some depression in their development. A negligible decrease in the number of myelocytes occurred only on the first day after irradiation, followed by a rapid increase. By days 3 to 5, a rapid increase above normal levels was observed. Almost three times more germinal cells were observed in exposed animals than control animals for the first 3 days after exposure and their numbers remained above control levels to the 10th day.

Effects of 12-cm microwaves on bone marrow of inbred albino rats exposed to power densities of 50 and 500 μW/cm^2 have been reported [29]. The animals were exposed for 7 h/day for 10 days. Both exposure power densities resulted in a significant initial increase in frequency of cells with chromosomal aberrations, mainly in the form of polyploidy, aneuploidy, chromatid deletion, accentric fragments, and chromatid gaps. The incidence of the aberrations was higher two weeks after the irradiation than immediately following irradiation in the group exposed to 50 μW/cm^2. In the group exposed to 500 μW/cm^2, the aberration frequency decreased by the end of the second week due to the elimination of damaged cells.

Cell cultures of RH (embryonic human kidney cells), SPEV (embryonic pig kidney cells), and Hep-2 cells were exposed to 6.5-mm microwaves at a power density of 1 mW/cm^2 [30]. The exposures were performed in teflon trays incubated at 37°C for a duration of 45 min. Nucleic acid synthesis in cells was studied using autoradiography. Precursors of DNA, ^{3}H-thymidine, and RNA, ^{3}H-uridine, were utilized at the rate of 10 μCi/ml of medium. The isotopes were added to the cells after exposure. The activity of the redox enzymes, glucose-6-phosphatase and ATPase, was determined. As a result of these cytological analyses, the authors reported a cytopathic effect, which was manifested by a general impairment of the cell monolayer; appearance of degenerative forms of cells with increased affinity for eosin by protoplasm; stellate, fragmental, vacuolized and pyknotic nuclei; and a destroyed cell membrane. A 30–50-percent decrease in postradiation survival of RH, SPEV, and HEP-2 cells was reported. A 37-percent reduction in uptake of ^{3}H-thymidine and 43-percent reduction in ^{3}H-uridine incorporation were measured. The authors summarized their results by stating that exposure to millimeter waves caused a decrease in survival rate and a development of substantial morphological and functional disturbances in tissue culture cells.

An investigation to determine the effects of 6.5-mm microwaves on adenovirus was performed by Kiselev and Zalyubovskaya [31]. The exposures were made in teflon cuvettes for 2 h at a power density of 1 mW/cm^2. The exposed adenovirus were then used to infect a culture of intermingled embryonic human kidney cells (RH line). A retardation was observed in the development of the viral infection as noted by a delayed cytopathic effect. Along with the delayed manifestation of a cytopathic effect, these cells showed no change in protein content up to 20 h after infection with the irradiated adenovirus. Development of an infectious process and the change associated with this protein content were not noted until the 24th hour. The authors conclude that millimeter waves of 6.5 cm had an inhibitory effect on viral particles.

Membrane Effects

An investigation to determine the involvement of sodium ions in the mechanisms of action of SHF fields on membrane potentials of smooth muscle cells was conducted by Mirutenko *et al.* [32]. In previous articles the authors had reported that exposure of smooth muscle cells of the stomach of rats and guinea pigs depolarized the cell membrane which was manifested by a reduction of membrane potentials (MP). This study was performed using the smooth muscle cells of the gastric fundus of guinea pigs. The mucosa was removed from the smooth muscle layer and the MP were examined on the internal side of the stomach. MP were measured using an intracellular glass microelectrode and recorded on an oscillograph and digital millivoltmeter. A generator operating at a frequency of 37 500 MHz ($\lambda = 8$ mm) with an integrated power output of 1 mW was the source of microwave energy. The exposures were for 5, 10, 15, and 20 min. The authors concluded from their experiment that the 8-mm EM radiation lowers the MP of smooth muscle cells of the guinea pigs stomach due to an increase in permeability of the cell membrane mainly to sodium ions, and depression of active transport of these ions out of the cell. The changes were found to be irreversible and increased with increase duration of exposure.

Mechanism of Interaction

Ismailov and Zubkova have reviewed a significant number of articles in the international literature [33]. Since many of the articles were published before 1975, no specific experiments will be described but rather quote some conclusions made by the authors of the review.

1) Microwaves affect the molecular organization of unexcitable biomembranes, as well as the function of unexcitable, excitable, and electrontransferring membranes, but their influence is not connected with temperature change of the system or its individual parts. This influence is due to the preferential absorption of SHF energy both on the membrane surface (chiefly at the expense of conductivity losses), as well as in the membrane itself (at the expense of dielectric losses).

2) The published data makes it possible to conclude that, for effective utilization of microwaves in biology, medicine, and agriculture, as well as for revealing the degree of unfavorable effect of this factor on living organisms, it is necessary to conduct studies at all levels of organization of living systems: body, organ, cellular, subcellular, and molecular levels. To achieve this, it is necessary to conduct further studies on the effects of microwaves on the structure and functions of biological membranes and properties of artificial membranes, as well as to develop radio-spectroscopic methods for study of biological membranes and investigate the role of hydrophobic interactions in the stabilization of their structure.

Concluding Remarks

The overview of the Soviet and Eastern European literature indicate a large number of bioeffects at exposure levels below 10 mW/cm^2. A significant number of biological changes were reported below 1 mW/cm^2. Most of their papers do not give details concerning the experimental design and exposure techniques. Because of these unknowns, a strong motivation to ignore much of the Soviet and Eastern European results exists in the U.S. In order to discourage this understandable tendency, an example from the U.S.–USSR program on the biological effects of microwave radiation will be used.

In the early stages of this program, the cooperation mainly consisted of an exchange of results on projects related to the central nervous system and behavior. The U.S. research included in the cooperation consisted primarily of acute experiments with exposure levels generally of 5 mW/cm^2 and above while the Soviet experiments were long-term low-level experiments at 500 μW/cm^2 and below. At the end of the first year of the cooperation, the Soviets reported changes in bioelectric brain activity at 10, 50, and 500 μW/cm^2 in rats and rabbits exposed for 7 h/day for 30 days to 2375-MHz CW radiation. Levels of 10 and 50 μW/cm^2 stimulated brain activity while 500 μW/cm^2 suppressed activity as seen from an increase of slow high-amplitude Δ wave in rabbits. At a 500-μW/cm^2 decrease in capacity for work, in investigative activity, and sensitivity to electric shock threshold in rats were reported. Research by the U.S. investigators on rats exposed to 5 mW/cm^2 for shorter durations of exposure to 2450-MHz CW radiation showed no statistical difference in EEG, no change in locomotion activity in a residential maze, and no change in performance on a fixed-ratio schedule of reinforcement below 5 mW/cm^2 (0.5 and 1.0 mW/cm^2) but a trend toward decrease in performance at 5 mW/cm^2 and a large decrease in performance at 10 and 20 mW/cm^2.

It became obvious that, except for our being more familiar with Soviet experimental design, we were no closer to understanding differences between the U.S. and USSR results. It was then decided to perform a duplicate experiment in order to determine if similar effects could be observed. Rats were exposed from above for 7 h/day, 7 days/week for 3 months to 500 μW/cm^2. Dr. Richard Lovely of the University of Washington, project leader on the duplicate project, spent 4 weeks in the Soviet Union to observe the behavioral and biochemical tests being performed on the animals. The results of these duplicate investigations are very interesting. The U.S. study found a drop in sulfhydryl activity and blood cholinesterase as was reported in the Soviet study. Blood chemistry at the termination of 3 months exposure indicated that the exposed animals, relative to controls, suffered from aldosteronism. The latter interpretation of the high-sodium–low-potassium levels found in the blood was confirmed by necropsy and histopathology of the adrenal glands, revealing that the zona glomerulosa was vacuolated and hypertrophied. In addition all behavioral parameters assessed at the end of 3-month exposures revealed significant differences between groups in the same direction as those reported in the Soviet study, i.e., increased threshold to footshock detection, decreased activity in an open field, and poorer retention of an avoidance response when reassessed following conditioning. This replication of the Soviet results at 500 μW/cm^2 emphasizes the need for performing long-term low-level microwave bioeffects research by U.S. investigators and the necessity of evaluating seriously the results of Soviet and Eastern European research before it is considered invalid. These experiments should also be replicated by independent investigators in the U.S. since the health implications of the above effects could be serious.

References

The JPRS reports can be obtained from the Joint Publications Research Service, 1000 North Glebe Road, Arlington, VA 22201.

[1] S. Baranski and P. Czerski, *Biological Effects of Microwaves.* Stroudburg, PA: Dowden, Hutchinson, and Ross, 1976.

[2] Z. R. Glaser and C. H. Dodge, "Biomedical aspects of radiofrequency radiation: A review of selected Soviet, East European, and Western references," *Selected Papers of the USNC/URSI Annual Meeting* (Boulder, CO, Oct. 1975), HEW Publication (FDA) 77-8010/8011, pp. 2-34, Dec. 1976.

[3] S. F. Cleary, "Biological effects of microwave and radiofrequency radiation," *CRC Crit. Rev. Environ. Contr.*, pp. 121-166, June 1977.

[4] C. H. Dodge and Z. R. Glaser, "Trends in nonionizing electromagnetic research and related occupational health aspects," *J. Microwave Power*, vol. 12, no. 4, pp. 319-334, 1977.

[5] *Health Aspects of Radio Frequency and Microwave Exposure, Part 2, Environmental Health Criteria Document,* Ministry of National Health and Welfare, Ottawa, Ont. Canada, Mar. 1978.

[6] Biological effects of radiofrequency electromagnetic fields," Z. V. Gordon, Ed., U.S. Joint Publications Research Service Rep., JPRS 63321, Oct. 30, 1974.

[7] B. A. Minin, "Microwaves and human safety," U.S. Joint Publications Research Service Rep. JPRS 65506-1, Aug. 20, 1975.

[8] M. G. Shandala, Yu. D. Dumanski, and V. M. Popovich, "Microwave radiation: Its biological effect and impact on health in inhabited localities," Review written under the U.S.-U.S.S.R. Cooperative Program, NIEHS, 1975.

[9] R. D. Gabovich and O. M. Zhukovskiy, "Effects of radiofrequency electromagnetic waves on humans," U.S. Joint Pub. Research Service Rep. JPRS L/6791," pp. 1-5, Jan. 12, 1977.

[10] V. G. Artamonova, L. M. Samorodova, and A. S. Saykina, "Ophthalmologic changes in persons exposed to microwaves," U.S. Joint Pub. Research Service Rep. JPRS L/6791, pp. 47-50, Jan. 12, 1977.

[11] N. P. Zalyubovskaya and R. I. Kiselev, "Effect of radio waves of a millimeter frequency range on the body of man and animals," U.S. Joint Pub. Research Service Rep. JPRS 72956, pp. 9-15, Mar. 9, 1979.

[12] R. D. Gabovich, "Effects of super high frequency fields of different intensity on the balance and metabolism of copper, manganese, molybdenum and nickel in the organs of experimental animals," U.S. Joint Pub. Research Service Rep. JPRS 66512, pp. 33-42, Jan. 7, 1976.

[13] V. V. Minayev, N. V. Zhdanvich, and Yu. F., Udalov, "Effects of SHF fields on enzymatic activities and pyridoxine levels in the organs of white rats," U.S. Joint Pub. Research Service Rep. JPRS 66512, pp. 77-82, Jan. 7, 1976.

[14] N. P. Zalyubovskaya, R. I. Kiselev, and L. N. Turchaninova, "Effects of electromagnetic waves of the millimetric range on the energy metabolism of liver mitochondria," U.S. Joint Pub. Research Service Rep. JPRS 70107, pp. 51-52, Jan. 7, 1977.

[15] Yu. D. Dumanski and Tomashevskaya, "Investigation of the activity of some enzymatic systems in response to a superhigh-frequency electromagnetic field," U.S. Joint Pub. Research Service Rep. JPRS 72606, pp. 1-7, Jan. 12, 1979.

[16] Yu. D. Dumanskii and V. F. Rudichenko, "Dependence of functional activity of liver mitochondria on microwave radiation," U.S. Joint Pub. Research Service Rep. JPRS 72606, pp. 27-32, Jan. 12, 1979.

[17] L. K. Yershova and Yu. D. Dumanskii, "Physiological changes in the central nervous system of animals under the chronic effect of continuous microwave fields," U.S. Joint Pub. Research Service Rep. JPRS L/5615, pp. 1-4, Feb. 10, 1976.

[18] V. R. Faytel'berg-Blank and G. M. Perevalov, "Selective action of decimeter waves on central structures of the brain," U.S. Joint Pub. Research Service Rep. JPRS L/7467, pp. 16-23, Nov. 15, 1977.

[19] —, "Effects of superhigh-frequency electromagnetic fields on central structures of the brain," U.S. Joint Pub. Research Service Rep. JPRS L/7899, pp. 5-7, July 19, 1978.

[20] A. N. Grin', "Effects of microwaves on catecholamine metabolism in brain," U.S. Joint Pub. Research Services Rep. JPRS 72606, pp. 14-16, Jan. 12, 1979.

[21] H. Mikolajczyk, "Microwave-induced shifts of gonadostropic activity in the anterior pituitary gland of rats," HEW publication No. 77-8010, pp. 377-383, 1977.

[22] A. M. Serkyuk, "State of the cardiovascular system under the chronic effect of low-intensity electromagnetic fields," U.S. Joint Pub. Research Service Rep. JPRS L/5615, pp. 8-12, Feb. 10, 1976.

[23] V. M. Shtemler, "Effects of microwaves on blood serum butyryl cholinesterase activity *in vivo*," U.S. Joint Pub. Research Service Rep. JPRS 66512, pp. 60-66, Jan. 7, 1976.

[24] N. M. Gonchar, "Distinction referable to the effects of electromagnetic energy in the superhigh-frequency range on cytochemical blood indices," U.S. Joint Pub. Research Service Rep. JPRS L/7957, pp. 12-16, July 15, 1978.

[25] J. Pazderova-Vejlupkova and M. Josifko, "Changes in the blood count of growing rats irradiated with a microwave pulse field," *Arch. Environ. Health*, pp. 44-50, Jan./Feb. 1979.

[26] M. G. Shandala and G. I. Vinogradov, "Immunological effects of microwave action," U.S. Joint Pub. Research Service Rep. JPRS 72956, pp. 16-21, Mar. 9, 1979.

[27] N. V. Il'chevich and S. F. Gorodetskaya, "Effects of the chronic application of electromagnetic microwave fields on the function and morphology of the reproductive organs of animals," U.S. Joint Pub. Research Service Rep. JPRS L/5615, pp. 5-7, Feb. 10, 1976.

[28] L. A. Sevast'yanova, S. L. Potapov, N. N. Vosil'eva, *et al.*, "Changes in cell composition of bone marrow under the influence of super-high frequency radiation combined with imiphos," *Biol. Nauki*, no. 7, pp. 36-39, 1976.

[29] A. A. Kapustin, M. I. Rudnev, G. I. Leonskaia, and G. I. Knobecva, "Cytogenetic effect of variable electromagnetic SHF field," *Tsitol. Genet.*, vol. 10, no. 5, pp. 400-402, 1976.

[30] N. P. Zalyubovskaya and R. I. Kiselev, "Biological oxidation in cells under the influence of radiowaves in the millimeter range," U.S. Joint Pub. Research Service Rep. JPRS L/7957, pp. 6-11, Aug. 15, 1978.

[31] R. I. Kiselev and N. P. Zalyubovskaya, "Study of inhibiting effect of superhigh frequency millimeter wave on adenovirus," U.S. Joint Pub. Research Service Rep. JPRS L/5615, pp. 71-76, Feb. 10, 1976.

[32] V. I. Mirutenko and P. G. Bogach, "Involvement of sodium ions in mechanisms of action of superhigh-frequency electromagnetic fields on membrane potential of smooth muscle cells," CSO Rep. 8144/0418B, 1977.

[33] E. Sh. Ismailov and S. M. Zobkova, "Physiochemical mechanisms of the biological activity of microwaves," U.S. Joint Pub. Research Service Rep. JPRS 7010, pp. 33-50, Nov. 7, 1977.