An Operational Safety Program for Ophthalmic Hazards of Microwave

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For many years it has been recognized that microwave radiation can produce biologically significant damage to certain tissues, particularly to the lens of the eye. Many types of devices and systems are capable of producing hazardous levels of microwave radiation.

Microwave radiation lies between the very high radio frequencies and the infrared portion of the electromagnetic spectrum. The wavelength ranges roughly from 10 meters to 1 mm. This radiation is produced and propagated through space in a manner similar to radio waves.

In the presence of microwaves, the body absorbs part of the radiated energy, which can result in raising the temperature of various tissues. The organ most easily injured by this type of elevated temperature is the eye, particularly its lens. The reason appears to be that the cooling effect of the blood circulation within the eye is not sufficient to compensate for the rapid increase in temperature due to the absorption of microwave energy.

The lens, which is a transparent biconvex tissue encased in a thin optically transparent membrane, focuses an optical image on the retina of the eye. Loss of transparency in the lens is known as opacification or cataract.

A number of other conditions can lead to lens opacification. However, prior to widespread lens changes, a distinction can be made, since opacification caused by microwave radiation is usually localized in the posterior portion of the lens capsule. The capsule is a relatively homogeneous and structureless elastic membrane which is not readily seen during routine ophthalmologic examinations, although well developed areas of opacification, if present, can be readily identified.

In its early stages, microwave-induced opacifications are somewhat distinctively irregular and, in some instances, have a honeycomb appearance. Also, the entire lens substance is still transparent and there is no measurable reduction in visual acuity. Subsequently, the lens cortex may become edematous and then opaque.

Numerous authors[1-3] have reported biologically significant damage to the lens from microwave radiation produced by radar and communication systems. Recent advancements in microwave technology have produced an unprecedented high power output. These advancements, coupled with the increasing widespread use of such systems in both civil and military applications, have significantly increased the probability of personnel exposure.

At the Air Force Eastern Test Range (AFETR), many advanced systems are used for missile launch, tracking, data acquisition, and communications. Peak power output can range up to 15 megawatts; average power, which forms the basis for health safety practices, is considerably less and depends upon systems operating factors. The Pan American Aerospace Services Division (Pan Am/ASO) occupational medical program includes an extensive microwave radiation exposure control program.

Biological Hazard Control

The basic objectives of the control program are:

1. To prevent personnel exposure to hazardous levels of microwave radiation and yet retain the maximum possible system

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capability for fulfilling mission requirements.

2. To determine which potentially-exposed personnel have actually incurred damage, evaluate the degree of damage through selective follow-up, and, if necessary, adjust job assignments to preclude further exposure.

Our first objective is achieved by a study of each radar or communication system to evaluate the hazard potential, followed by a systematic on-site survey using instrumentation to measure the microwave power density in areas which may be occupied by personnel. Corrective action is taken as needed to ensure that basic safety criteria are observed. Such action may require that certain areas be restricted during system operation, that radiated power levels be reduced, or that antenna orientation be restricted.

Factors that contribute to the complexity of fulfilling this objective are:

1. Land-based and shipboard systems located world-wide.

2. Scheduling of surveys that will not interfere with the system's primary mission of tracking or space communications. Although mission requirements are scheduled in advance, last-minute changes are made for many reasons, such as malfunctions during prelaunch countdown procedures, unfavorable weather, or failure of a tracking system.

3. Timely transport of survey personnel and equipment to and from system locations. This is of prime importance when surveys must be conducted at sea due to high power density levels, and the ship is scheduled for departure. The port may be located several thousand miles from Cape Kennedy, at places not normally serviced by scheduled airlines.

In addition to conducting surveillance, occasions arise where it is necessary to verify that employees who are performing duties at locations under the control of another organization are not being overexposed. Oftentimes, delicate coordination with the responsible organization is necessary.

An example of this type of surveillance occurred when engineers from Pan American and RCA were conducting surveillance of systems aboard a ship. The ship was under construction at a northern shipyard. Published reports resulting from surveys conducted by the vendor stated that a power density of 10 milliwatts/sq cm did not exist beyond 35 feet from a system antenna. Our calculations indicated that a power density of 40 milliwatts/sq cm would be present at 35 feet from the antenna and would decrease to 10 milliwatts/sq cm at a distance of approximately 1,100 feet.

Survey personnel were sent to the shipyard, and results substantiated values obtained by our calculations. Safety procedures aboard the ship were changed accordingly.

The second objective is achieved through an eye examination program employing an ophthalmologist skilled in the determination and evaluation of microwave injury to the eyes. All personnel involved in actual or suspected incidents and those whose jobs have reasonable probability of hazardous exposure to microwave radiation are given a periodic eye examination. The frequency of follow-up examination and administrative control actions taken are dictated by the findings.

Employees are assigned to world-wide duty stations and may be on vacation or temporary duty. Therefore, sufficient time must be allocated in planning to permit notification and assembly of personnel who are to be examined. Normally, examinations are conducted each year.

The microwave-producing systems on the Eastern Test Range, capable of producing hazardous levels of microwave radiation, have been surveyed and action has been taken to prevent personnel exposure. In addition to training and orientation of system operators, engineers, and others closely associated with these systems, signs and barriers, transmitter electrical lockout systems, mechanical antenna stops, and warning lights are employed to protect personnel. In addition, Pan American's Environmental Health section is consulted on the design and installation of each new radar or communications system capable of producing hazardous levels of microwave radiation.

Particular attention is given to areas not controlled by the air force, since it may be necessary either to impose restrictions on use or arrange for restricting access. This latter action can be both difficult and expensive. Exposure control is further complicated by the operation of high-powered radar systems on a number of tracking ships throughout the world.

Resurveys of existing systems are performed when significant changes are made in power or antenna; new facilities are constructed within the hazard perimeter; or leakage around transmitters or waveguide is suspected.

Prior to survey, the following system-operating parameters are examined:

1. Peak power.
2. Pulse width.
3. Pulse repetition frequency.
4. Pulse codes available.
5. Maximum rated duty cycle.
6. Type and size of antenna.
7. Antenna gain and illumination.
8. Beam width and beam skew.
9. Operating frequency (megahertz).
10. Loss in power between transmitter and antenna.
11. Polarization of transmitted wave.

Using these data, theoretical values[4,5] are computed for maximum power densities in the near field; distance at which the far field begins; power density at the beginning of far field; and distance at which the power density is reduced to 10 milliwatts/sq cm.

The team must make a visual inspection of the area to determine the potential radio frequency hazard areas. If the system is located at sites other than the Florida mainland, map inspections are substituted. The possibility of power-density buildup due to reflection is also considered.

The following equipment is used in survey: power density meter or meters; ionizing radiation instruments (hazardous levels of ionizing radiation are generated in the klystrons and magnetrons, modular tubes, and from other high voltage generating tubes); portable two-way radios; and personnel protective clothing or equipment or both.

Survey team members maintain constant radio communication with the operator of the microwave system. In this way, the team is able to control the orientation of the antenna in order to locate the beam and minimize personnel exposure. Power density readings are plotted on a map for interpretation later. These data must be interpreted to determine if personnel exposure can exceed 10 milliwatts/sq cm.

If total exposure from all radiating sources in the area can exceed 10 milliwatts/sq cm during routine operations, action is taken to protect personnel by reducing average power outputs, limiting antenna orientation, or restricting personnel. Although some sources have advocated that the permissible level of exposure may exceed 10 milliwatts/sq cm for brief periods of time, no data is available in support of such a position. Indeed, the results listed in this report demonstrate that, from a clinical point of view it would be unsound to permit exposure exceeding 10 milliwatts/sq cm until more is known concerning injury thresholds.

Portable RF radiation-detecting instruments have been assigned to all range bases and ships which have systems capable of producing hazardous microwaves. Range operating instructions require system logs and periodic surveys of transmitter areas. Also, these instruments are used to perform spot surveys in the vicinity of the radiating system.

Clinical Examination

Clinical examination of employees by a consulting ophthalmologist includes stereoscopic photographs of each lens. The films are used for further evaluation and then filed for comparison with subsequent films.

Examinations are conducted yearly where prior examinations were positive. New suspect groups are added to replace those with negative findings on prior examinations.

Since evidence of lens injury may be delayed several years following exposure, all personnel involved in exposure incidents are given an initial examination with a follow-up one year later. If both examinations are negative, the next follow-up will be approximately five years from the initial examination and repeated every five years.

In addition, consultation is available at all times and is sought following accidents, incidents, or the discovery of conditions which have probably resulted in exposure. In these cases, measurements can frequently be made which permit a reasonable estimate of the level of exposure. In all cases, accident exposures were a result of personnel violation of published safety procedures.

The cases of microwave injury described below were identified by ophthalmologic examination; however, since preemployment examinations do not normally include examination specifically for microwave injury, there is either limited or no information available concerning the prior condition of the lens.

From 1963 to 1968, 35 individuals involved in incidents and 135 individuals selected due to their work assignments received ophthalmologic examinations for microwave injury. Positive findings were exhibited by 12 individuals in the incident group and 21 in the nonincident group. Statistical analysis based on the following data would not be valid for system technicians and the general public.

Table 1.—*Clinical Results, Case 1*

Employee	1963	1964	1965	1966	1967	1968
1	Pos*	Prog†	N-Prog‡	N-Prog	Prog	N-Prog
2	Pos	Prog	N-Prog	N-Exam§	Prog	Prog
3	Pos	Prog	Prog	N-Prog	N-Exam	N-Prog
4	Pos	Prog	Term‖	...	...	...

* Pos, positive findings (minimal).
† Prog, progression since prior exam.
‡ N-Prog, no progression since prior exam.
§ N-Exam, not examined (unavailable).
‖ Term, terminated employment.

Report of Microwave Injury Cases

CASE 1.—This case involves exposure of communication system operators to microwave radiation which leaked from an improperly connected waveguide inside a transmitter panel and escaped into the operating area through an 8 × 12-inch access port in the panel. The normally closed port can be opened to permit access to amplifier controls. The system was operated at 790 megahertz.

After attempting to repair a leak at the waveguide connection, operators brought the system to full power and adjusted controls through the open port. At some time during this operation, they noted an off-scale reading (greater than 20 milliwatts/sq cm) on a portable power density survey meter nearby. The transmitter continued operating at full power for several minutes while the meter was checked for accuracy and a survey of the room was made. Off-scale readings were obtained at all points checked in the operating area regardless of meter orientation.

The exposure time for this incident was less than 15 minutes, and the maximum power density could have been considerably greater than 100 milliwatts/sq cm. The operating log indicated that similar incidents could have occurred previously.

Microwave injury to the eyes was positively revealed in four of the 14 persons available and known to have been potentially involved. Two of these four were present at the time of the described incident. Clinical results of initial and subsequent examinations are shown in Table 1.

CASE 2.—This case involves the exposure of operators to microwave radiation from a system operating in the 400 to 450 megahertz range at a continuous power output of 10 kw.

Patchboards mounted side by side are provided to permit the transmitter output to be connected to various antennas, and "caps" are provided for the open end of the microwave transmission lines which are terminated at the front face of the patchboard. In this instance, the cap had not been installed on one of the patchboards and a malfunction of the switch, which prevented it from closing completely, resulted in leakage of microwave radiation from the uncapped line. An electrical arc discharge at the open line drew attention to the condition. With the switch in a closed position, a power density in excess of 20 milliwatts/sq cm was detected 15 inches from the open line on a patchboard. Personnel frequently worked at one patchboard while the system output was being fed to an antenna connected through the adjacent patchboard. No accurate determination could be made on the microwave power density, the total exposure time, or the number of times similar incidents may have occurred with a malfunctioning switch.

Positive findings were found in five of the 17 currently available personnel. Clinical results of the initial and subsequent examinations are shown in Table 2.

CASE 3.—In this instance, two employees were exposed to microwave radiation emitted from the feed horn of an 84-foot diameter parabolic dish antenna on an ultrahigh frequency radar system when they opened the entry hatch in the center area of the antenna to make physical measurements. The system operates in the 400 to 450 megahertz range with an average power output of 128 kw.

The antenna was oriented vertically with the

Table 2.—*Clinical Results, Case 2*

Employee	1964	1965	1966	1967	1968
5	Pos	Prog	N-Prog	N-Exam	N-Exam
6	Pos	N-Prog	N-Prog	Prog	N-Prog
7	Pos	N-Prog	N-Exam	N-Exam	N-Prog
8	Pos	N-Prog	Prog	N-Prog	N-Prog
9	N-Exam	Pos	Prog	N-Prog	Prog*

* Clinical diagnosis is incipient, microwave cataracts, both eyes.

Table 3.—*Clinical Results, Case 3*

Employee	1966	1967	1968
10	Pos	Prog	Prog
11	Neg*	N-Exam	Pos

* Neg, negative finding.

entry hatch opening downward toward the service platform about 8 feet below. One employee climbed into the open hatch with about one third of his body inside the antenna; the second employee remained on the platform. An electrical arc from the antenna to the measuring device being used alerted the employees to the fact that the radar system was operating, and they immediately evacuated their positions. Employee 10 was on the platform for about six minutes. Employee 11 was inside the antenna for about one minute and on the platform for about five minutes.

The microwave radiation power-density level could have been as high as 280 milliwatts/sq cm at the hatch opening in the antenna. At time of the incident, neither employee could recall looking directly at the feed horn. Power density levels which may have existed on the platform due to direct or reflected radiation were probably less than 200 milliwatts/sq cm, and the total exposure time was estimated at six minutes.

Clinical results of initial and subsequent examinations are shown in Table 3.

Case 4.—In this instance, two employees (12 and 13) were exposed to microwave radiation when they walked by a radiating antenna while inspecting a rooftop. The system was operating at an average power of 1.2 kw in the frequency range of 7,800 to 8,000 megahertz. The employees could have been exposed to a power density of 170 milliwatts/sq cm for about one minute.

Immediate examinations by a local ophthalmologist following the incident revealed no pathology. About six months after the incident, positive evidence of microwave injury to the eye was noted in one case (employee 13) when the employees were examined by the consulting ophthalmologist.

Table 4.—*Clinical Results, Survey Personnel*

Employee	1964	1965	1966	1967	1968
14	Pos	N-Prog	N-Prog	N-Prog	N-Prog
15	Pos	Ref*	Ref	Ref	Ref
16	Pos	N-Prog	Term	...	...
17	Neg	Pos	Ref	Ref	Ref
18	Neg	Neg	Pos	N-Prog	N-Prog
19	...	...	...	Neg	Pos

* Ref, refused examination.

Table 5.—*Clinical Results, Surveillance Personnel*

Employee	1967	1968
20	Pos	N-Prog
21	Pos	N-Prog
22	Pos	N-Prog
23	Pos	N-Prog
24	Pos	N-Prog
25	Pos	N-Prog
26	Pos	N-Prog
27	Pos	N-Prog
28	N-Exam	Pos
29	Neg	Pos

Nonincident Group

The largest number of persons in the eye examination program is not known to have been definitely involved in an incident of the types described; however, their work assignments are such that they could have been exposed to microwave power densities greater than permissible levels.

Included in this group are microwave survey teams personnel who perform surveillance at shipyards where tracking ships are built or modified and engineers who work directly on range systems which are installed or modified. The shipyard surveillance personnel were included in the program when power-density calculations, surveys, and a review of vendors' safety procedures indicated that microwave exposures could have occurred.

Results.—Twenty-eight people who participated as members of microwave survey teams were examined. Clinical results for those with positive findings are shown in Table 4.

Seventy personnel who performed surveillance at shipyards during installation or modification of radar and communication systems aboard tracking ships were examined. Clinical results for those with positive findings are shown in Table 5.

In 1968, a suspect group consisting of 37 engineers who work directly with systems which are installed or modified was examined. Five exhibited positive findings. Follow-up examinations will be administered.

Summary

Since ophthalmological examinations for evidence of microwave effects are not a routine part of the preemployment physical examination and, since almost all of the persons hired as radar or communication system operators or engineers have had previous experience with systems in the armed forces or industry, it is not certain if those persons showing evidence of microwave injury on first examination actually received the exposure while working on the Air Force Eastern Test Range.

Many instances of known exposure were followed by the development of typical microwave lens changes. Characteristically, these begin as thickening and opacification of the lens capsule at the posterior surface of the lens. Once formed, there is no regression. Although there may be long dormant periods, the changes in the capsule eventually progress until the capsular opacification is extensive.

Shortly after the capsular opacification has become extensive, opacification begins to occur in the lens substance itself. This stage, exemplified by Employee 9, is known as "incipient cataract." Subsequently, the cataract matures, thereby resulting in major visual loss.

The cases reported demonstrate the latency and slow evolution of microwave cataractogenesis in man. Following irradiation, it is not unusual for the appearance of pathology in the capsule to be delayed for several years. Further, the process can lie dormant for many years before visual acuity begins to fail. However, acute exposure to high-power densities greater than 500 milliwatts/sq cm can result in the formation of cataracts within weeks.

A prolonged course results from exposures to power densities less than 500 milliwatts/sq cm and the accumulation of exposure data indicates that exposures approximating 100 milliwatts/sq cm might have a causal relationship to cataractogenesis. Therefore, it is not, in our opinion, clinically credible to permit access to environments exceeding 10 milliwatts/sq cm, no matter how briefly, and consider it "safe."

This program points out the need for at least two types of specialists who are not ordinarily found in an occupational medicine program. The first is the engineer who must be skilled in microwave engineering. He must be familiar with computations for the prediction of hazard potential based on operating factors. He must be able to apply the results of computations to real situations in the field. He must be able to go into the field, analyze hazardous situations, and obtain accurate physical measurements. At Pan American, personnel trained and skilled in health physics are assigned to this part of the program; likewise, an ophthalmologist with experience in microwave effects is essential.

The orientation of management concerning the hazards involved is of great importance. Safety operating instructions must be disseminated to the employees working with or in the vicinity of systems capable of producing hazardous levels of microwave radiation.

Pan American Aerospace Services Division is the prime contractor to the US Air Force for the operation and maintenance of the Air Force Eastern Test Range.

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