STRESS REVIEWS
RADIATION

S. B. Sells, Marcia J. Duke, and Nurhan Findikyan

Contract No. Nonr 3436(00)
Dimension of Stimulus Situations
which Account for Behavior Variance
Group Psychology Branch
Office of Naval Research

Technical Report No. 9

August, 1966

TEXAS CHRISTIAN UNIVERSITY
INSTITUTE OF BEHAVIORAL RESEARCH

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FOREWORD

As one task related to the understanding of environmental variables accounting for behavior variance, our staff has undertaken extensive study of a variety of literatures related under the general topic of stress. A series of working papers was prepared, summarizing these reviews of the literature. These have been edited and will be reproduced for the use of colleagues who may find the compilations of value. The Stress Reviews completed to date cover extremes of the physical environment, involving cold, heat, radiation, and atmospheric extremes.

S. B. Sells, Ph.D.
Principal Investigator

RADIATION

Bands of intense cosmic and other ionizing radiation have been identified in space and present an additional major hazard to space crews. Radiation associated with nuclear weapons and with nuclear reactors has also received much recognition and study, as has microwave radiation generated by radar and other electronic equipment. Other important sources of exposure to radiation by military and civilian personnel include: industrial radiography, static eliminators, luminescent markers, diagnostic and therapeutic medical uses, industrial tracer and measurement procedures, calibration of disaster control and post-attack survival instruments and disaster operations (Meyer, 1962).

Unlike other stress sources, radiation is silent and invisible and has genetic effects as well as effects on physiological function and performance. The reviews by Hekhuis (1961) and Hanks (1961, p. 266 and 277) discuss the medical and biological problems of ionizing the microwave radiation comprehensively. Tobias (1960) and Furchtgott (1956) have reviewed behavioral studies.

EFFECTS OF IONIZING RADIATION

The symptoms of radiation sickness, which develop with varying speed and severity in relation to dosage factors, individual and species differences, and other stresses affecting the individual at the time, include (1) decrease in circulating lymphocytes, hemorrhagic manifestations, and vascular changes associated with brain pathology; (2) disturbance of water metabolism; (3) anorexia, nausea, and vomiting, depression of food intake and loss of body weight; and (4) with severe disturbance of the organism, the pituitary-adrenocortical stress syndrome.

Ionizing radiation may be applied to the whole body, as in a space ship going through a zone of intense radioactivity, or to an exposed part of the body. Dosage effects depend on total dosage, rate of irradiation, the part of the body exposed, and the area affected (Air Force Nuclear Radiation Guide. 1962). This Guide mentions 250 rem or less as a tolerable total dose, 300 to 550 rem as a sub-lethal dose, and 650 rem as lethal. Saylor et al. (1962) have estimated that with an acute dose of 180 to 220 r the expected effect on human subjects would be vomiting and nausea for about one day, followed by other symptoms of radiation sickness in about 50 per cent of personnel exposed. For 400 to 500 r they estimated that all exposed persons would

experience vomiting and nausea the first day, followed by radiation sickness, with about 50 per cent dying within a month and the survivors convalescent for about six months. Very few survivors would be expected at the dosage level of 550 to 750 r; symptoms would occur rapidly, within one or two hours, at 1000 r; and at 5000 r, incapacitation would occur almost immediately and all personnel would be fatalities within a week.

VISUAL EFFECTS

Buchanan et al. (1961), on the basis of a literature survey, reported that ionizing radiations produce deleterious ocular effects, the most prominent being the development of cataracts. Retinal damage has been reported although thresholds for damage have not been established. However, a single large dose has been found more harmful to the lens than an equivalent cumulative dose administered in small amounts. Brown and McDowell (1958) and McDowell and Brown (1958) have reported data on the effects of radiation on visual acuity in monkeys. In the first study, visual impairment noted in a high-irradiation group (616 rep) during the first year after irradiation was still manifested three years after exposure. Monkeys in the intermediate dosage group (308 rep), who had shown no impairment in the first post-irradiation year, did show impairment of visual acuity after three years. These results were

evaluated by the authors as not explainable in terms of learning ability deficit. In the other study, visual acuity was compared in normal and chronic focal-head irradiated monkeys. The most efficient performance was that of the control group. Of two irradiated groups, those with irradiation of posterior association areas performed better than those whose focal irradiation was in the frontal association areas.

EFFECTS ON NERVOUS SYSTEM

A Russian investigator, Domashlak, cited by Tobias (1960), reported that persons systematically exposed to doses of ionizing radiation of 0.05 r to 0.65 r showed more functional than pathological disturbances of the nervous system.

BEHAVIORAL EFFECTS

Furchtgott (1956) mentioned the following variables as relevant to the evaluation of radiation effects on behavior: 1. quantity (total dose); 2. rate of delivery or dosage; 3. type of radiation; 4. manner of exposure; 5. time after exposure that observations are made; 6. species differences; 7. sex differences and individual differences within the species; 8. condition of the organism (other stresses usually enhance radiation effects;) 9. concomitant drug administration and hypoxia (depressants); 10. site of exposure, with particular reference to reproductive activity of the tissues

(the most proliferating are usually most sensitive).

In summarizing learning effects, he concluded that the available research, mostly on rats and monkeys, indicates that radiation produces a certain amount of depression in activity which is most apparent when motivation is low or when a task requires considerable effort. In general, effects on learning, retention, and transfer were slight. Gross muscular activity appears more subject to impairment over longer periods (following exposure) and general malaise resulting from radiation sickness may cause reduction in performance. Furchtgott concluded that there is some evidence of effects on hearing and vision.

Tobias (1960) referred to the work of Morazov and others in Russia who found changes in human behavior following near-maximum permissable doses. They used speech-motor conditioning as a means of detection, with such measures as delayed formation of temporary bonds, prolonged latent period of conditioned reflexes, and difficulties in alternation of reflexes. Payne (1958) found no more than a faint influence on psychomotor performance, in one study, and no indication of radiation impairment, in a second, in his investigations of adult male patients in advanced stages of neoplastic disease who performed psychomotor tasks after exposures as high as 50 r and 200 r.

Several recent studies have been reported on smaller mammals. Neller (1960) found that audiogenic seizure susceptibility of mice was increased by increases in atmospheric or experimentally administered radiation. Blair and Arnold (1956) found moderate impairment of maze retention (measured in terms of errors) in rats exposed to cranial radi tion doses of 2500r using hunger as a drive. Blair (1958) later tried a dose level of 5000 r with 34 rats and found significant decrease in both maze time and maze errors. In the earlier experiments motivational factors were believed to play a major role in accounting for the results, particularly hunger and decrease in exploratory behavior.

Kaplan et al. (1951) trained four groups of rats (one trial daily for 15 days) on a Lashley, Type III maze, and then exposed them to 600, 360, 180, and 90 r respectively. After 18 hours following radiation, they tested for retention of the partially learned maze habit. No significant differences were observed on pre-radiation training trials. During the 5-day period immediately following radiation, both time and error scores of the 600 r group were significantly greater than those of the controls, with most worked impairment on the second

to fourth days, when physiological symptoms were most acute.

A high percentage of deaths occurred on the sixth to twenty-fifth post-radiation days, but no significant maze retention differences were found between the 600 r and 90 r groups. The 360 r group made significantly more errors than the controls during the five post-radiation days. Other results showed that results were related to severity of dosage, but were less marked among survivors during the 6 to 25 post-radiation trials.

Brown et al. (1960) gave six groups of rats 0, 25, 50, 75, 100, and 125 r respectively for one hour each day, after prior training to respond to a 20 to 1 reinforcement ratio in a Skinner Box. The largest source of variance in response rate during the course of daily irradiation was cumulative total dose received. It was reported that 86 per cent of the variance in response rate could be accounted for by a simple linear function relating the square root of response rate to cumulative total dose.

The animal of choice in biological and behavioral research on radiation effects has been the monkey and both rhesus and maccata mulatta monkey have been experimentally irradiated more than any other species. These studies confirm the effects of radiation on appetite, activity, manipulative behavior and strength. Harlow and Moon (1956) trained 23 monkeys on a

series of standard laboratory tasks and then exposed them to 100 r of X-radiation every 35 days until death. All irradiated animals died; the LD50 was estimated to be 950 r, and the LD100, 1200 r. The irradiated group lost weight, while the control group gained. Radiation resulted in a significant decrease in activity and appetite, proportional to total dose received, but caused no impairment of any learning task. On two of these, oddity and delayed response tests, an enhancement of the performance of experimental animals was found, which was attributed to decreased general activity and distractibility. An effect of 400 r on activity and manipulative ability, as compared with a control group, was reported by Leary and Ruch (1955). However, these authors concluded that the effects of radiation are most pronounced on low motivated behavior. McDowell and Brown (1958) obtained results in agreement with Harlow and Moon on an oddity-reversal problem on which a high-irradiated group showed a statistically significant superiority in negative saving scores.

Kaplan and Gentry (1953) and McDowell and Brown(1958) studied the effects of radiation on transfer of learning. The former investigators, using a 400 r dose found no differences among controls, monkeys whose CNS was shielded from the

dose, and those not shielded. Similar results were reported in the later study.

Gentry, Brown, and Overall (1958) tested 33 monkeys on transposition problems to determine the extent to which subjects receiving different radiation doses utilized relationships between stimuli as a basis of problem solution. Relational learning was found to decrease as a linear function of radiation dosage. Riopelle, Grodsky, and Ades (1956), using these groups of monkeys who received a 350 r dose once, 10 doses of 100 r, and 10 doses of 200r, respectively, with hunger as the drive, found a significant increase in discrimination learning in the irradiated groups, along with a reduction of activity.

Kaplan and Gentry (1954) and Kaplan et al. (1954) reported results on the effect of radiation on retention of learned responses. The results indicated that a lethal dose of radiation did not destroy entirely a monkey's memory for a learned task. In monkeys who survived as long as 151 to 168 hours post-radiation, retention was demonstrated between 8 hours post-radiation and 21 hours preceding death. Similar results were reported on hand and orally manipulated puzzles and object discrimination tasks by Davis et al. (1956). These authors interpreted their data as supporting a hypothesis that the

X-radiation behavioral syndrome affects non-food motivation primarily, rather than learning.

In summary, the results of behavioral investigations on radiation effects indicate that the most significant effects are tied to physical impairment. There is little doubt that the threat of physical impairment in human subjects would probably be greater than the secondary behavioral effects observed in the research reviewed. In addition to the effects discussed, there are genetic effects, such as those studied by Tait et al. (1952) and reviewed by Hanks (1961) and Hekhuis (1961). In view of the evidence on genetic mutations produced by radiation exposure, there are implications for personnel of an entirely different type which merit consideration in the exposure of personnel to radiation environments. There appears to be no threat of sterility, which was at one time questioned, but the effects on offspring, even in cases where no overt symptoms of bodily injury or malaise are experienced, cannot be ruled out.

TOLERANCE LIMITS

According to Buchheim (1963) the average accumulated dosage of radiation of people living on the earth at sea level

would be 10 r in 30 years, under normal conditions. An accumulated dosage of 30 r in 30 years was recommended as a limit for the world population by the National Academy of Sciences. The AEC has recommended the following conservative exposure limits, largely for genetic reasons: 0.3 r per week, 5 r per year, and 15 r in a peak year. Buchheim added that up to 50 r in 20 days, as an acute dose can be tolerated without any noticeable non-genetic effects; 450 r for humans is considered a 50 per cent lethal dose (LD50) and 650 r, a 100 per cent lethal dose (LD100), both when administered over a short period of time (acute dose).

PROTECTION AND THERAPY

According to Hart (1961), in order to remain within the Van Allen belts for longer than a few minutes, mass shielding will be mandatory to reduce the dose rate within the space vehicle to a tolerable level. Malfunctions possibly resulting from manned space flight through or within the radiation belts would result in radiation sickness to one or more crew members, the remote possibility of death, and resulting inefficiency which could lead to mission failure. Carpenter (1963) has reported that the radiation levels at the Mercury orbital altitudes are insufficient to be considered of great importance. However, at present it does

seem feasible to eliminate the possibility of genetic effects at these levels. The only protection for personnel so exposed is abstinence from procreation unless they are willing to accept the possibility of mutants in their own offspring.

Buchheim has reported that radiations from the sun other than the occasional radiation from solar flares can be adequately handled within today's technology. The effects of thermal radiation can be controlled by adjusting the absorptivity and emissivity of the outer skin of the space vehicle. As far as solar radiation in the visible, ultraviolet, and soft X-ray regions are concerned, present data indicate that these do not constitute a direct hazard to crews of space vehicles, as they can be stopped easily or weakened by the layers of almost any structural material covering the walls of the craft. At present, there is no satisfactory way of shielding space crews against cosmic radiation, which remains a major hazard. The relative biological effectiveness of cosmic rays, as compared with other known forms of radiation, is still unknown, but the seriousness of this problem is recognized. Mayo (1961) stated that it has been determined that high-molecular-weight materials (such as lead) cause much greater secondary emission when subjected to high-energy ionizing radiation than do the low-molecular-materials (such as hydrogen). However, no practical configuration of a

sufficient amount of hydrogen to attenuate certain high-energy particles has yet been reported.

Since adequate shielding materials against cosmic radiation are unabailable for the immediately forseeable space flights, the principal protective strategy at this time appears to lie in planning of flight trajectories to avoid heavy density radiation areas. Exit and reentry via routes over the Earth's polar regions have been suggested as a means of avoiding the intense radiation belts entirely (Buchheim, 1963). Weybrew (1960) has restated the often mentioned fact that shielding of personnel against radiation from reactors in nuclear submarines has been good and the hazards very slight. It is possible that adequate shielding may be developed for nuclear-powered aircraft and for space vehicles, but the solution of these problems is not yet available.

Melville, Harrison, et al. (1962) have reported that post-irradiation symptomatic therapy of the radiation syndrome has been utilized to provide significant extension of survival time, compared to irradiated controls, of monkeys X-irradiated to a total dose of 900r. Further, the therapeutic regimen has been successfully combined with chemical radioprotectants to enhance survival time in a third group of animals. The combined treatment is more effective than therapy alone. The overall clinical condition of these animals is

far superior to that of untreated irradiated animals.

It must be recognized that ionizing radiation as a major stress is relatively new to man and that his experience with it is recent. To quote Hekhuis (1961, p. 59):

> The evaluation of the radiation hazard to an individual or a population cannot be valid in terms of considering radiation as a sole source of hazard or injury. It must be realized that radiation has been present in certain amounts in our environment for a long period of time and that the increase in radiation is not providing a new hazard, but a new degree of hazard. This degree of hazard must be evaluated not only in its own right but in comparison with other hazards that are involved in the life situation and the operational requirements. The resulting effect or damage from radiation in most cases can be fairly well estimated as it progresses, and this time relationship allows effective, corrective, and therapeutic action to be taken if the dose effect is significant. As compared with other damaging effects, this treatment of radiation provides a greater advantage to the individual in that time is provided for evaluation and effective action.
>
> The viewpoint of persons concerned with the control and interpretation of radiation exposure must be based on education, knowledge and experience. The hazard that can be accomplished by premature and inaccurate interpretation and publicizing of incomplete observations is often far greater than the determined effect of the radiation in itself. In many simulated cases the damage produced by the panic of the individuals believing themselves exposed to radiation far surpasses any expected effect of the radiation itself on the biological system.

MICROWAVE RADIATION

Microwaves affect man adversely in at least four ways (McLaughlin, 1962): 1. by raising tissue temperatures to intolerable levels and causing cellular damage or death; 2. by emanation of X-rays from microwave equipment; 3. by molecular absorption by tissues; and 4. directly, as heat or in some other manner, setting off stress reactions. Microwave radiation is a term used for electromagnetic frequencies used in radar equipment and also in medical procedures (e.g. diathermy) to heat body tissues. The microwave region covers the frequency range from 300 megacycles to about 150,000 to 200,000 megacycles (Hanks, 1961, p. 277). Frequencies can be converted to wave lengths by the equation FL=C, where F=frequency, L=wave length, and C=velocity of light, expressed as 3×10^{10} cm/sec. Frequency is expressed in megacycles and wave length in centimeters. Since different investigators report in different terms, this simple conversion formula is useful. For example, W or 3 cm. is equivalent to 10,000 megacycles (the X-band in airborne radar equipment),5 cm.-5,000 megacycles (c-band), 10 cm.-3,000 megacycles (s-band); medical diathermy apparatus uses a

12.2 cm.-2450 megacycle frequency band. Another variable of biological (as well as technical) importance is power, in watts. Many current radar systems are limited to 250,000 w, but ground installations and some airborne radar exceed that by a factor of 10 or 20, and research is in progress on power sources in excess of 100,000,000 w (Hanks, 1961).

Hanks has quoted Schwan and Li (1956) to the effect that:

> 1. The percentage of absorbed energy (by the tissues) is near 40 per cent at frequencies much smaller than 1,000 and higher than 3,000 megacycles. In the range from about 1,000 to 3,000 megacycles, the coefficient of absorption may vary from 20 to 100 per cent.
> 2. Radiation from a frequency below 1,000 megacycles will cause deep heating, not well indicated by the sensory elements in the skin and, therefore, considered especially dangerous. Radiation whose frequency exceeds 3,000 megacycles will be absorbed by the skin. Radiation of a frequency between 1,000 and 3,000 megacycles will be absorbed both in body surface and in the deeper tissues, the ratio being dependent on the parameters involved.

Hanks generalized from these conclusions that much of the present radar equipment is operating at frequencies that are largely reflected or absorbed in the very first few millimeters of body tissue. The conversion of this energy to heat in the skin layer and activation of the heat-sensitive receptors also serves to notify the individual of the presence of radiation. However, the effects

vary with the tissues affected. Vascularized tissues, provided with a blood supply, can absorb more radiation than nonvascularized tissues, such as the lens of the eye. The lens, intraocular fluid, urine held in the bladder, intestinal contents, surgically implanted metal plates, cartilage, and certain bones gain heat rapidly and, if heated excessively, can be damaged or cause damage to adjoining tissues. The same applies to poorly vascularized and heat-sensitive tissue, such as the testes.

When the entire body is exposed to radiant heat, the problem is more complicated. Each part has a thermal burden that it cannot share with any other and total body temperature may rise if the thermoregulatory system is unable to dissipate the accumulating increment. With direct exposure to intense energies it is conceivable that an intolerable rise in body temperature could occur without sufficient warning, particularly when the thermal conditions of the surrounds contribute to the process.

Hanks has calculated tolerances to whole-body microwave radiation as .143 large calories per minute, equivalent to 0.1 kw/m^2, the assumed area of the exposed surface. This conservative figure is equal to about one tenth of the metabolic heat produced by the average body in a quiet, standing position. The

heat added by the microwave radiation would then be equivalent to that added by the initiation of light handwork by the person standing. Hanks pointed out that it would be necessary to increase the radiant flux ten times in order to double the total heat gain of the body due to metabolism alone, and 50 times as much radiation, or 0.5 w/m^2, to create a total body heat from basal metabolism plus the heat from radiation, to equal that produced by metabolism alone in the effort of felling trees or climbing steps. This provides a large safety factor under ordinary circumstances, but, as he noted in discussion of several studies, allowance for high air temperature, high humidity, and other conditions conducive to raising body temperature should be made. Further, local tissue exposure, particularly of the eyes, which are susceptible to the phenomenon called "denaturation of protein," may be more important in relation to microwave radiation than whole-body exposure. A temperature of $45^{o}C$, which is 2^{o} lower than the level at which lenticular opacities have been produced in the eyes of experimental animals, has been suggested as an upper limit for the human eye, to avoid damage.

Turner (1961) reported clinical observations by the USSR Academy of Medical Sciences, of 525 persons who had been exposed to microwave radiations of various intensities and durations. The results

of these examinations prompted the establishment of the Russian permissable limits of exposure of 0.01 mw/cm^2 per entire working day.

Despite the concern with microwave radiation hazards, Hanks has asserted that "no single case of fully verified injury to radar personnel has been discovered as a result of their work to date as far as this writer is aware," and he cited a study of 335 persons exposed to radar over a 14 year period as confirming his own observations. Nevertheless, the electrons that produce microwave radiations are capable of producing X-rays in their interaction with materials in the generating devices used, provided that their energies are high enough. Although no special protection, other than control of exposure by positioning of personnel, shielding, and control of work-rest cycles, is presently indicated, the potential hazards of new equipment should be monitored. As voltages rise, shielding becomes more difficult because of the more intense X-radiation produced, which, uncontrolled, could prove more hazardous than the microwave radiation itself.

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13. ABSTRACT

Sources of radiation and the effects of radiation on the human organism are reviewed.

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