RADIATION PROBLEMS RELATED TO SPACE FLIGHT

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Man's history is a chronicle of adventure, of daring probings into the unknown or the unexplored. Each of these steps has necessitated the acquisition of new knowledge, the development of new devices or methods in order that newly found forces or environments might be harnessed in such a manner that they would become stepping stones along the path toward even greater advances in our civilization. The development of these new devices or methods marks in many instances the early beginnings of our present day concept of industrial or environmental medicine.

Not long ago I read an article in an old magazine published when automobiles were first making their appearance. The writer portrayed with genuine alarm the disaster certain to befall any individual who rode in one of these conveyances, and permitted air to be forced into his lungs by propelling him at the unheard of speed of 15 miles per hour. Of course, we did not give up the automobile. We developed a windshield and set our sights on higher speeds. More recently our invasion of the air brought about history's greatest conquest of the elements.

Many are the lessons we have learned as a result of our determination to adapt man to this new environment in such a way that he might perform effectively, and at the same time safely. The everyday use of modern aircraft as an integral part of our vast transportation system provides mute testimony of the success of our endeavors. It is not necessary now to be a carefully selected individual safely to take advantage of the many benefits of this mode of travel. So successful have our efforts been that the average citizen can travel in this way today with less physical discomfort than that encountered in crossing the Rockies in the family car. But we can not stop here and rest on our laurels. An even greater conquest beckons. We stand on the threshold of man's greatest adventure: The conquest of space.

Up until now we have in each case engaged in a further exploration of an environment with whose basic makeup we were familiar. We were forced to learn to live with either more or less of certain things about which we knew a great deal. In most cases the response of the body could be predicted with some degree of certainty based on our familiarity with the factors making up this new environment. In preparing to introduce man to space we find ourselves faced with many situations about which we know virtually nothing. True, we can make many predictions with considerable assurance, but we still must await the real thing for confirmation of these predictions. Such things as weightlessness, extreme acceleration, radiation unfiltered by a friendly atmosphere all present challenges which must be met. To survive in space man must be able to withstand the effects of these new environmental factors or be isolated from them. In some cases we are not going to be able to isolate man from these new forces. As an example it would appear that the state of weightlessness must be endured by the occupants of our space vehicle. Our capability to explore this situation beforehand is severely limited. To date we have not been able to reproduce this state for periods in excess of something under two minutes. Such short periods of exposure provide little information on the chronic effects which might be produced as a result of the prolonged exposures which will be a part of sustained flight in outer space.

The problem of radiation effects poses many similar situations which must be faced. Precedent offers little help in predicting the effect of this new environment of the physical economy of man once he leaves behind him the friendly and protective cloak of our atmosphere which shields him from many of these forces here in his natural habitat. Of great concern is the total array of radiations we may encounter. These could pose a considerable obstacle to the safety of man in space, particularly as regards hazardous ionizing radiation. It is with this problem that we will concern ourselves this evening. At the present time it is possible to estimate some of the biological effects which will result from exposures at the top of the atmosphere. However a thorough

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knowledge of the effects of exposure patterns to be encountered in interstellar space must await the initiation of new research projects made possible by the availability of a research space vehicle. Pending the acquisition of such data by way of this research space vehicle certain predictions can be made with a fairly high index of reliability.

It would seem desirable at this point to review some of the pertinent aspects of the behavior of cosmic radiation as compared with the more orthodox forms of radiation. It must be borne in mind that the biological effects of different ionizing radiations depend on the dose, the distribution and the specific ionization of the particles of that form of radiation under consideration. For example, x-ray dosage in air is measured in the conventional roentgen unit, for other media the REP or *roentgen equivalent physical* unit is used. Specific ionization may be defined as the number of ION pairs formed along the track of a single particle in a unit thickness of tissue. This is proportional to the LET or *linear energy transfer* which in turn may be described as the energy absorbed from a single particle in a unit thickness of tissue. Different kinds of particles such as mesons or protons have, as far as is known, the same biological effect if their LET is the same. On the other hand the LET of a particle is a function of its velocity, so that the same sort of particle can have quantitatively different biological effects in the high and low LET regions. Thus, to assay the probable biological effects of cosmic radiation the dose in REP and the distribution of LET among the cosmic ray particles encountered must be considered. Of course, this information is not at present available to us from direct physical measurements, but it is felt that it can be approximated with satisfactory results.

Many studies have been carried out which establish the dependence of biological effects on the LET of the particles in question. To apply this information we use the value RBE or the *relative biological effectiveness*, which is the x-ray dose at, for example, the 200 KV level required to produce a measurable effect, divided by the dose required at the LET of the particles under evaluation. In order to compare the biological effect of a given radiation with that of the more familiar x-rays we find it desirable to employ a correlating value such as the REM or the *roentgen equivalent man.* This unit describes the dose of 200 KV x-rays that would be required to produce quantitatively the same biological effect as the dose under study. For our purpose here it follows then, that if the daily dose of cosmic radiation is known in REM units we can approach the problem of the hazards of cosmic radiation by directly applying the safety standards known for x-radiation.

The ionization measurements of Bowen, Millikan, and Neher (1) suggest that at medium geomagnetic latitudes, at sea level, the daily dose from cosmic radiation may be established at about 0.1 MR in 24 hours. It must be borne in mind that this dose can be expected to vary with geomagnetic latitude. Near the equator cosmic ray ionization is low since particles with low energies can not approach the surface of the earth closely because of the influence of the magnetic field of the earth. It follows that near the magnetic poles of the earth it can be predicted that both high and low energy particles can probably penetrate to the earth. At high altitudes and near the north and south poles it is entirely possible that the 24 hour dose might increase to as much as 30 MR.

Next we must consider the mean rate of energy loss per particle since the magnitude of any biological effect of exposure to this energy will depend on this value. Using the data of Van Allen and Tatel (2) who measured the number of cosmic ray particles encountered using rockets, and the average value for the ionization of these particles, the mean specific ionization per particle may be obtained.

It might be interesting at this point to look back a bit at the historical development of our understanding of the basic problem here. Early in our investigation of cosmic ray physics extensive measurements were made of the ionization produced by cosmic radiation in enclosed ionization chambers borne aloft by balloons. It was soon realized that these ionization data were quantitative and not qualitative, that they gave the rate of production of IONS, but provided virtually no clue as to the nature of the radiation which caused the production of these IONS. The pioneering ionization chamber measurements of Hess and Kolhorster (3) led to the suggestion that radiation of extra-terrestrial origin was entering the earth's atmosphere. This ionization was for some time felt to be radiation of a very high energy, gamma ray character. Later it was found that the rate of ionization varied with geomagnetic latitude thus establishing the fact that a considerable portion of the primary energy was coming to earth in the form of charged particles. Electrons then came to be regarded as the principal component of the primary cosmic ray beam. This concept held sway until the pioneering high altitude experiments of Schein, Jesse, and Wollan (4) first gave direct evidence of the fallacy of this view. Time does not permit tracing the many astute attacks on this problem which have culminated in our present day state of understanding of this form of radiation. It is enough to say that identifying technics have been worked out which are appropriate to the energy range involved, and which take into account the perplexities of the experimental situations. It is not easy to distinguish among these various radiations when the measuring apparatus must be sent unattended to high altitudes by means of a rocket or a balloon. Electrons and gamma rays have been shown to comprise only a negligible portion of the primary cosmic ray beam. Rather the major part of the primary cosmic beam is known now to consist of protons.

An interesting observation might be made at this point. It appears that the relative composition of cosmic radiation bears a striking resemblance to the relative abundance of the chemical elements in universal matter as such elements have been estimated by astrophysical studies on the spectra of stars and by the analysis of meteorites. It follows then that cosmic radiation might be thought of as a representative sample of universal matter which has, however, been stripped of all electrons and accelerated to a high energy. I hasten to add that the source of cosmic radiation and these mechanisms of stripping and acceleration are at present not understood. They promise to remain for some time the subject of theoretical speculation.

Recognizing this, we turn our attention to a consideration of the probable biological effects of this energy in the light of the exposure data developed in the course of the studies already referred to. By way of these studies we arrive at certain conclusions. The primary effect of cosmic nuclei is almost entirely confined to the cell through which the nuclei pass. True, there may be some cells, off the track of cosmic ray nuclei, that are also inactivated by intermediate chemical action, but it is not anticipated that such cells will be found in biologically significant numbers. From our experimental data, we obtain an estimated total dose of 0.07 REM per 24 hour day (5). This must be evaluated in terms of total hours spent in this environment, by an individual, in a time unit, such as a year. It is not at the moment anticipated that our man in space will initially exceed 1000 hours of such exposure per year. For this reason, we might safely expect that this 0.07 REM will in truth represent the weekly exposure rate of this individual. It can be seen then that this anticipated exposure is considerably lower than the permissible weekly dose of 0.3 REM established by the National Committee on Radiation Protection, as well as the more recently proposed 0.1 REM.

Let's explore this matter of the death of cells along the track of a nucleus a bit further by assuming an unfavorable case in which each heavy nucleus kills all of the cells through which it passes. Assuming a cell diameter of ten microns and considering only heavy nuclei, the daily dose of 0.07 REM would then mean destruction of only 0.0035 per cent of all body cells in one day. Except in the case of nerve cells, this figure is much lower than the rate of growth and death of cells in normal tissue. Along the heaviest tracks many cells might be destroyed, yet because of the rare incidence of these tracks we would not expect the total number of body cells involved to be biologically significant. The site of such a track would in many ways resemble the situation resulting from piercing body tissue with a fine needle.

I have selected a few of the areas in which concern has been expressed regarding the results of exposure to cosmic radiation and attempted to evaluate them in the light of our knowledge of radiation effects, applying to this knowledge our meager data on cosmic radiation. First the probable effect of cosmic radiation on longevity. Here the difficulty inherent in attempting to extrapolate the results of animal experiments to obtain reliable values in man have resulted in conflicting reports from various investigators (6). While advances are being made in this field (7) the problem is still complicated by the differences in body mass, in life span, and in radiosensitivity. Based on such data as are available, it would appear that our expected exposure of 0.07 REM per week might result in decreasing the life span of man by not more than a fraction a year (8). Of course the difficulty in establishing this statistically is readily apparent.

Carcinogenesis is frequently speculated upon as an attribute of heavy cosmic ray nuclei possibly because of the established effects of alpha particles as carcinogenic agents. There is much dispute as to the mechanism of carcinogenesis as a result of irradiation, while virtually nothing is known about the effectiveness of heavy nuclei. It seems certain, however, that the number of cellular interactions at the same energy dose will be much smaller than in the case of alphas and that many of the cells through which heavy nuclei pass will die as a result of a single such interaction. It is my opinion that we might expect to encounter this cellular death, rather than any abnormal response leading to the development of a tumor.

The problem of fertility occupies a position of some importance in our thinking because of the age group with whom we will be concerned in our "Man in Space" effort. There seems to be no very valid reason to view this situation with alarm. The results of animal experimentation point to a wide species variation in the sensitivity of the gonads to repeated doses of radiation. Mice, rats, and rabbits appear to be relatively resistant to such exposures, while, on the other hand, the dog displays a more marked susceptibility to repeated low doses of radiation. Boche (9) found an observable reduction in sperm counts to result from such exposure, but of signal importance is the fact that these animals recovered in four weeks after exposure. It is not felt that any lasting effect on fertility is to be anticipated as a result of exposure to cosmic radiation.

The question of long range genetic effects of cosmic ray exposures is an extremely difficult one to approach. I do not think the authorities in this field agree at all on this question even in relation to forms of radiation about which we know a great deal (10–12). The solution of this problem in man may not be known for a long time. Many of the defects are recessive and may not show for several generations. At any rate the very nature of this problem dictates that studies, to be reliable, would have to be carried out on large numbers of animals over a considerable period of time. This in itself poses a considerable problem in relation to the use of a research space vehicle to conduct the necessary large scale exposures. I think we can safely say that the effectiveness of high specific ionization in producing mutations is less than that of x-rays. Data available today indicate that there is a greater possibility of causing increased lethal effects by exposure to primary cosmic radiation. Effects on the brain, nervous system, retina, and crystalline lens are of particular interest, but it is my opinion that sufficient data are not available in relation to any of these structures to make it possible to speculate intelligently on the possible effects of their exposure to cosmic radiation.

In concluding our discussion of the possible hazards to health resulting from exposure to cosmic radiation it would appear that the weight of evidence seems to point to this type of radiation as posing less of a problem than the low energy radiations, so much a part of our terrestrial environment. I would be the last to say that we have no problem in this area; but I firmly believe that the possible harmful effects of such exposures do not appear to be of sufficient magnitude as to be allowed to interfere with our effort to introduce man into this new and challenging space environment. To shield man from this energy seems virtually impossible within the weight limits certain to prevail in the design of space vehicles. This energy has been measured as far as 1968 feet below the surface of the earth in a salt mine. It has been suggested that should our investigations determine that shielding is required, perhaps that part of the shell of the vehicle which surrounds its human occupant might be converted to use as a fuel tank. This would offer some degree of shielding without adding to the essential weight of the vehicle. We sincerely hope our speculations are borne out by data collected on our early research probings of space and that such heroic design innovations will prove unnecessary.

Other forms of radiation which are certain to be encountered in interstellar space include solar radiations in the ultraviolet and soft x-ray regions. Based on present data these radiations would not constitute a direct hazard to passengers in space vehicles. The mechanical requirement for a reasonably thick wall in this pressurized hull should provide adequate protection from radiations of this type detected so far.

The effort in the direction of manned space vehicles has brought with it many related problems. Significant here is the impact this effort has had on the development of electronic equipment to track and detect such vehicles. The trend toward increasing power in, for instance, our radar systems has been greatly accelerated by the imminent requirement to accomplish such monitoring over previously unrealistic distances. The electronic engineer finds himself faced with the problem of developing hardware in the form of extremely long range radar systems, to accomplish this task. This has in turn brought about the development of new power tubes capable of producing fantastic levels of power in the radio frequency portion of the electromagnetic spectrum. We will discuss this problem in some detail in a moment, but first let me say a word about spurious x-radiation produced by these high power tubes. We have tubes in operation capable of producing as much as 500 R of high energy x-radiation per minute. This x-radiation is in the order of 500 KEV of energy. In addition it has been filtered of all of its low energy component by passage through the metal wall of the tube. The extremely high energy of this radiation results in the production of significant levels of secondary radiation in the shielding placed around the tube. Some of these tubes require as much as 4 inches of lead shielding to protect operating personnel from the primary radiation. This radiation problem has made necessary some radical changes in our laboratory operating procedures and has forced the establishment of a rigid program of personnel monitoring. This situation is cited to call attention to the scope of the radiation problem incident of the effort in support of space flight.

The final aspect of radiation as related to space flight concerns the possible biological effects of exposure to microwave energy. Until recently this was not considered an urgent problem since the highest power radars in operation did not produce enough power to appear to be significant biologically. With the advent of long range missiles and the related interest in probing interstellar space came the development of radars of extremely high power output. Up until recently the highest power radar we had could not produce more than 60,000 W or 70,000 W of average power. Almost overnight this power level has been jumped up to 600,000 W. Immediately ahead of us we can see this level being raised to as much as 1,000,000 W. This magnitude of power makes the investigation of possible biological effects an urgent consideration.

Then too we have been stimulated to some extent in this connection by a growing interest in this problem on the part of the general public. This problem has no doubt been exaggerated in the mind of the average citizen by a tendency to consider all radiation as being similar in nature and biological effect. His peace of mind has not been aided any either by the scare stories which from time to time appear in the press describing the death or injury of an individual as a result of a short duration exposure to the beam of a radar set. It is not remarkable that when he next sees a sign along the highway advising him that his speed is being checked by keeping him in the beam of a traffic control radar, he is prone to picture himself as the next victim of this "Invisible Death Ray." Of course, he asks questions. We feel that as the principal producers and users of this form of energy, we have a moral obligation to provide the answers to his questions. Unfortunately we find ourselves without the factual data required to give these answers. As a result it has been decided to expedite a program of biological investigation designed to acquire these urgently needed data.

Since this constitutes what might be considered the first comprehensive attack on this problem, and since in many ways it involves new approaches in biological study it might be well to discuss this effort in order to provide background information which will enable one to better evaluate the product of this research as it develops. There are certain basic things to be borne in mind about radio frequency energy as related to biological processes. First, the ability of this energy to penetrate living tissue is a function of the frequency of the incident beam. In general the lower frequency, longer waves penetrate more deeply than do the higher frequency shorter waves. Next, each tissue has a specific coefficient of absorption for this energy which in turn is frequency-dependent. Next, as a beam of this energy passes from a tissue of one dielectric constant to a tissue of another dielectric constant standing waves are produced in the space between these tissues. These waves may be several times as great in amplitude as those making up the primary beam. Then too, there is reason to believe that all matter has its own resonant frequency peculiar unto itself, and that at this frequency an effect might be produced whch would be relatively independent of the power applied.

Bearing these things in mind it becomes immediately apparent that the selection of a research approach to this problem was difficult. It was obviously impossible to explore all of the frequencies we have in use. Availability of funds and availability of research groups to undertake the work dictated that we adopt a sampling approach. It was decided to begin with five representative frequencies spread across the frequency spectrum of interest. These five frequencies were selected based on widespread use in existing or contemplated equipment and on areas in the spectrum where the development of extremely high power is planned. Since an intelligent evaluation of this problem involves the most exacting as well as imaginative application of both biological and engineering principles, it was decided to put the investigation of each frequency in the hands of a composite group representing all of disciplines concerned. These teams have been asked to screen animals for gross effects after whole body exposures to biologically significant levels of power. More refined investigations are developed as a consequence of the results observed after these gross exposures. The power level at which these whole body exposures would be carried out was arrived at after a thorough study of the work that had been done in this field. While most of the reports in the literature on this subject are isolated in nature and many are actually case histories of individuals exposed to a greater or lesser amount of this energy, it was possible to come to the conclusion that based on these reports 0.2 w/cm^2 was the power level at which biological effects might be anticipated (13). When we studied the methods used to accomplish these experimental exposures and evaluated the instrumentation used, it became apparent that some of the results reported might conceivably have been produced by as little as 0.1 w/cm^2 of the energy under study (14). With this in mind we have asked our investigators to conduct their whole body exposures at power levels between 1.0 w/cm^2 and 0.01 w/cm^2 to insure identifying any possible effect. Exposures are being conducted under both acute and chronic conditions. These studies are progressing nicely and we hope to have some concrete data in the very near future.

The urgency of this problem has made mandatory an accelerated effort in certain isolated areas of specific biological concern. These areas are the eye, the brain, and hollow viscera as related to the production of standing waves as described above. To date only the studies of the eye have been productive of significant results. Here the investigations so far completed, point directly toward the production of an accumulative effect as a result of repeated exposures to subthreshold doses of this energy. While these experiments are far from completed the data thus far obtained appear to be fairly reliable. In any event the very fact that repeated doses of this energy, applied with adequate time for cooling between doses, produce a lenticular opacity characteristic of a larger single dose is in itself a challenging development. The scientific appetites of all of our investigators have been whetted by this report. While we all are still of the opinion that the basic effect resulting from exposure to this energy is a thermal one, the suggestion here of an intermediate effect merits careful and thorough investigation.

This work is concerned with the effects on the crystalline lens of the eye using rabbits as the experimental animals. Many more animals will have to be exposed under varying circumstances before these results can be finally accepted. At no time have we been able to discern any cellular response in any of our investigations which cannot be related directly to the production of heat. Certainly, we have not unearthed any data which would support the claim that this energy is an "Invisible Death Ray" as was charged in one recent story in the press. To date the results of our investigations which are being carried out by seven competent university groups are in the main encouraging, insofar as our ability to live with this energy safely is concerned.

As our understanding of the behavior of this energy in living tissue is expanded, it seems certain that two results are inevitable. First, at certain frequencies we feel that we will be able to liberalize to some extent our present maximum safe exposure level. Second, it seems most likely that this increased knowledge will find application in other fields of biological research. We sense that new doors may be opened for those individuals engaged in the exploration of cellular life.

Of course, as the power output of our new equipment is increased we realize that the risk to man increases. We accept this fact, however, for we feel that our people must learn to respect this energy, not fear it. This appears to be true, too, of the problem of exposure to cosmic radiation. For some years the mysterious lethal capability of this energy has been whispered about and speculated upon. As I am sure all of you know, and most certainly those of you with a small boy in your family, the popular appeal of this concept has resulted in the introduction of quite an array of fantastic ray guns to the armament of certain comic book characters. There is even a movie going the rounds in which the adult appetite for the bizarre is stimulated by a sequence in which an individual exposed to the beam of one of these exotic rays is so reduced in size that he ultimately fights a duel with an insect using a straight pin as a weapon. Such tales can only endure until such time as we are able to combat them with factual data. I feel that this applies equally well to our plan to send a manned vehicle into space. Each bit of data we are able to develop appears to dispel, or certainly question the validity of, the air of mystery which at present surrounds the capability of man to engage in interplanetary travel. We will look back, in your time and mine, and wonder at our concern over an environmental situation with which we will have learned to cope on a completely routine basis, much as we today engage in high altitude passenger flights in pressurized aircraft.

REFERENCES

1. Bowen, L. S., Milliken, R. A. and Neher, H. W.: New evidence as to the nature of the incoming cosmic rays, their absorbed ability in the atmosphere, and the secondary character of the penetrating rays found in such abundance at sea level and below. Physiol. Rev., **53:** 217, 1938.
2. Van Allen, J. A. and Tatel, H. E.: The cosmic ray counting rate of a single geiger counter from ground level to 161 kilometers altitude. Physiol. Rev., **73:** 245, 1948.
3. Hess, V. F.: Über Beobachtungen Der Durchdringenden Strahlung Bei Sieben Freiballonfahrten. Physikalis. Ztschr., **13:** 1084, 1912.
4. Schein, M., Jesse, W. P. and Wollam, E. O.: The nature of the primary radiation and the origin of the mesotron. Physiol. Rev., **59:** 615, 1941.
5. Tobias, C. A.: Radiation hazards in high altitude aviation, Wright Air Development Center Tech. Rep., **52:** 119, 1952.
6. NEPA Medical Advisory Panel, A. H. Dowdy, Chairman: Tabulation of available data relative to radiation biology. NEPA, 1254, 1949.
7. Spargo, D., Bloomfield, J. R., Glotzer, D. J., Gordon, E. L. and Nichols, O.: Histological effects of long-continued whole-body gamma-irradiation of mice. J. Nat. Cancer Inst., **12:** 615, 1951.
8. Boche, R. D.: Observations on populations of animals exposed to chronic roentgen radiation. A.E.C. Document, MDDC, 204, 1946.
9. Muller, H. J.: Our load of mutations. Am. J. Human Genetics, **2:** 111, 1950.
10. Stern, C.: Human Genetics, W. H. Freeman and Co., San Francisco, 1950.
11. Evans, R. D.: Quantitative inferences concerning the genetic effects of radiation on human beings. Science, **109:** 299, 1949.
12. Schwan, H. P. and Li, K.: Hazards due to total body irradiation by radar. Proc. Inst. Radio Engineers **44:** 1572, 1956.
13. Knauf, G. M.: Biological effects of microwave radiation on Air Force personnel. A.M.A. Arch. Ind. Health, **17:** 48, 1958.
14. Carpenter, R.: Informal progress report, Tufts University, 15 June 1957, USAF Contract, AF 41 (657) 86.