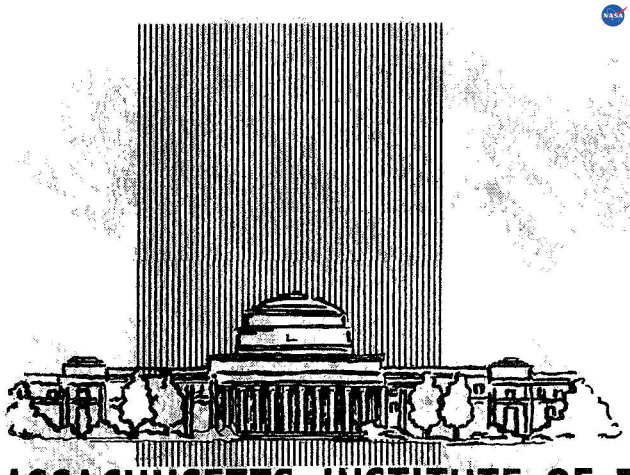

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

IONIZING RADIATION AND MAGNETIC FIELDS: A REVIEW OF THEIR EFFECTS ON THE NERVOUS SYSTEM

by

H. L. Galiana

February 1969

First Report on Research
Projections in Life Support
Under NASA Grant NGR 22-009-312

MAN-VEHICLE LABORATORY
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SUMMARY

Data on the functional sensitivity of the nervous system to ionizing radiation and magnetic fields suggest caution in prolonged human exposure to similar environments. Unfortunately, the conditions investigated are also characteristic of those expected during a space flight. Studies are thus needed to determine the nature and mechanism(s) of the nervous system's reactions to these and other factors, and to investigate the degree to which the astronaut's performance capabilities may be affected. Such knowledge would also prove helpful in determining protection standards for occupationally exposed personnel and in medical research. Proposed areas for continued research are described below.

Area	Problem
Radiobiology	1. Maximum permissible doses to nervous system and mechanism of effects 2. Role of time factor in CNS dose-effect relation 3. Long term effects of chronic low dose irradiation (e.g., on vision, muscular coordination . . .)
Magnetic Fields	1. Further studies on mechanism(s) of effects of strong and weak fields on nervous system 2. Maximum permissible magnetic field intensity exposure and exposure duration 3. Possible use of a magnetic field to induce sensation of gravity via paramagnetic otoliths 4. Investigation of magnetic pretreatment to reduce radiosensitivity

PREFACE

This report is the first of a series on Life Support in Unusual Environments, prepared under NASA grant NGR 22-009-312, under the supervision of Prof. L. R. Young of the Massachusetts Institute of Technology.

It is not intended to be a study in depth, but rather a brief review of the effects of radiation and magnetic fields on the nervous system. Our goal is to point out to NASA and the engineering academic community major problem areas suitable for graduate level research and bring to bear on the biotechnology field the investigative and creative efforts of engineering and medical schools.

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Measurement and Protection	1. Possible effectiveness and mechanism of pharmacological protection of CNS 2. Perfection of solar flare prediction methods 3. Development of pulsed magnetic shielding 4. Development of methods for predicting relative radiosensitivity for team selection 5. Dosimetry techniques for continuous monitoring of dose, dose rate and dose distribution 6. Accurate determination of magnetic environment in the spacecraft 7. Accurate measurement of local magnetic fields at proposed landing sites 8. Simulations of expected radiation and magnetic conditions to study effects on animals

I. INTRODUCTION

In studying the behavior of human or animal organisms in the presence of unusual environmental factors, the reaction of the nervous system is perhaps the most important. Any disturbance in the usual function of the nervous system will result in changes in the other system states, since it is the central controller and coordinator of all systems in the body. It is thus of vital interest to determine and understand the influence of various parameters on the nervous system, in order to distinguish the resulting changes in other systems of the body from those directly caused by the environment.

The nervous system is usually divided, for convenience, into a central nervous system (brain and spinal cord) and a peripheral nervous system (peripheral nerves.) It consists of two types of cells, neurons (or nerve cells) and supporting elements called neuroglia (or glial cells.) In the peripheral nervous system, the nerve fibers run in bundles called nerves; all fibers have supporting neurilemmal sheaths and sometimes also insulating myelin sheaths. In the central nervous system, the fibers may also have myelin sheaths, while the supporting and insulating role about nerve cell bodies is now filled by the neuroglia. The capacity of the nervous system to recover or regenerate after disease or injury is different in its peripheral and central portions. If a peripheral nerve is divided, new fibers may grow out from the central stump only if the two cut surfaces are approximated. On the other hand, in the central nervous system only abortive attempts at recovery are observed and new fibers are never formed. In other words, lesions that kill nerve cell bodies (nicrosis) or transect nerve fibers are permanent , while recovery is possible if there's only partial damage (e.g.

from pressure on a fiber.)

We will consider here the effects of ionizing radiation and magnetic fields on the integrity and functional level of the nervous system. Prophylactic and monitoring measures will be discussed to describe possible means of protecting the nervous system from detrimental variables.

II. IONIZING RADIATION

II.1 Units and Biological Dosage:

In evaluating the biological effects of radiation, the greatest problem lies in the diversity of the reactions exhibited by different systems after exposure to the same dose (in rads) of radiation. Further, the same dose of different types of radiation will produce variant effects on the same sample. To quantify these variant effects, the concept of the relative biological effectiveness (RBE) of a radiation was introduced, where

$$\text{RBE} = \frac{\text{dose (rads) of 250 kV Xrays for a certain effect}}{\text{dose (rads) of other radiation for same effect}}$$

where one rad represents an absorption of 100 ergs of energy per gram. Unfortunately, even the RBE factor may be variant for any given type of radiation (e.g. protons) changing with the dose level, dose rate and depth, linear energy transfer (LET), initial system state and biological effect chosen. The LET value itself is proportional to the square of the charge on the particle and inversely proportional to its velocity (Ref. 33). By necessity, the RBE values of radiations for man must be estimated from measurements on whole body irradiation of cells, plants and animals, or accidental acute human exposures. Such experiments have shown that the RBE of a radiation is directly related to its LET in the system (see Table 1.)

TABLE 1

Typical RBE's in Mammalian Cells

Radiation	LET(keV/μ)	RBE
130-730 MeV protons	0.3-0.7	0.6-0.8(ref.53)
hard γ and X-rays	0.2-0.4	<1 (ref.18,53)
soft γ and X-rays	~3.0	1
910 MeV α particles, β particles, neutrons		~1 (ref. 33) ~1-2 (ref. 33) ~2-5 (ref. 33)
5 MeV α particles	$2-5 \times 10^2$	~5-10(ref. 33)
5.7 MeV ^{40}Ar ions	$\sim 19.4 \times 10^2$	~2 (ref. 33)

The RBE factor is impractical in radiation protection and dose prediction studies. It is always determined experimentally and varies with too many factors. Further, the above results are usually determined using acute high level doses, with less emphasis on low level chronic doses. These last studies now appear to be the most important for the CNS as will be seen in section 2.3.

Here we are concerned with predicting the expected effective dosage to the CNS in various radiation environments. In this case, the expected effective dose or dose equivalent (DE), in rems, is numerically equal to the product of the absorbed dose (D), in rads, with the quality factor (QF), distribution factor (DF) and any other relevant factors of the radiation (Ref. 56).

DE (rems) = D (rads) QF. DF. ...

The abovementioned factors are assigned on the basis of many considerations; the QF depending on the LET, the DF on the geometric distribution of the dose, etc. The DE can thus be made to take into ac-

count the physical characteristics of the radiation, and the rate and spatial distribution of the dose in the body.

For example, in the case of low energy electrons (e.g., in belts) it is sufficient to calcululate their surface dose and consider the effect on skin or eyes; in any case, they are easily shielded. On the other hand, protons form the major portion of galactic, solar and belt radiation, ranging widely in energies and mean free paths (see Table 2).

TABLE 2

Proton Mean Free Paths in Tissue Behind 1 gm/cm^2 (Ref. 22)

Energy (MeV)	Mean Free Path (cm)
10	0.124
20	2.250
200	25.800

Thus in calculating the expected dosage from proton radiation, at low energies it is sufficient to consider the surface dose, but at higher energies, the particles' LET increases as it slows down in the tissue, generating secondary high LET radiation and increasing the required QF. In these cases it may be necessary to consider the average tissue or depth dose (at the end of path), as the case may be, and probably limit exposure according to damage to the hemotopoietic or genetic organs, or the CNS.

It is difficult to extend this dose concept to low flux heavy energetic ionized particles (cosmic rays), which are capable of producing tracks 25μ in diameter, several mm. long. The "dose" is concentrated in the core of the track, and can reach several thousand rads, decreasing to less than 1.5% of this at the perimeter. This type of radiation can be especially dangerous in the CNS, where even a mean free path of a few mm. can cause destruction of vital cells.

The above considerations usually lead to the following maximum permissible dose values, (see Table 3) where the allowed average dose (per man) decreases as the fraction of the population exposed increases. Acceptable emergency dose levels are given together with the currently allowed levels of total integrated dose.

TABLE 3

Proposed Maximum Permissible Dose Levels

(Ref. 18, 32, 40, 42)

Remarks	Organ	Average (rem/yr-man)	Emergency (rem)	Total (rem/man)
population-general	genetic	5/30		
population-individual	genetic	.5		
occupational	genetic	5.0	25	5(N-18)*
astronaut	1) genetic	55.0		200
	2) hemoto-poietic	55.0	200	270
	3) skin	350.0	700	1600
	4) extremities	770.0	980	4000
	5) eyes	54.0	200	270
LD_{50}	whole body		500	

* N = age in years of individual

No value, except for the eyes, can be offered for the CNS since such studies are not yet completed. Many more irradiation experiments are required to accurately measure LET and RBE values of different types of radiation in nervous tissue. Only then can the QF and other factors be assigned properly to define expected and dangerous DE levels for the CNS.

II.2 Sources and Physical Dosage:

During his evolutionary development, man has always bee exposed to both internal and external irradiation. Internal radiation exposure can result from the ingestion of radioactive materials with food, or the inhalation of isotopes in the atmosphere. Natural background radiation exposure is due to cosmic rays filtered by the atmosphere and the presence of radioactive nuclei in the earth's crust. Thus the total dose caused by both internal and external irradiation will vary with altitude, latitude and locality on the earth. However, it is always limited to a few hundreds of millirems and, since man has evolved in its presence, it will not be discussed further, except as a reference to determine acceptable long-term exposure levels from other sources (Ref. 32, 40.)

Other more dangerous sources of radiation exposure are now man-made X-ray machines and nuclear fission equipment, used for industrial, medical and research purposes. Current protective measures usually limit the genetically significant dose to the population from these sources to approximately 50 mrem/year (Ref. 32.) The major natural sources of radiation in this galaxy, to which some men may today be exposed, are solar flares, galactic cosmic rays (beyond the earth's atmosphere) and trapped particles in the earth's (or other planet's) magnetic field.

The galactic cosmic radiation appears to originate outside the solar system and arrives isotropically. It consists mainly of charged atomic nuclei stripped of their planetary electrons, with energies ranging from 10^2-10^{12} MeV. Almost 99% of this radiation consists of protons and alpha particles, at the rate of approximately four particles/cm^2-sec, though they contribute only roughly 60% to the total dose, the remaining part being provided by heavier particles. The lower energy particles are deflected away from the earth during solar

flares, reducing the dosage by almost 50%. Most of this cosmic radiation is filtered out by the Earth's atmosphere, and in space it only contributes 5 - 12 rad/year to the expected physical dose. Physical shielding of even 10 gm/cm^2 does not significantly affect the expected dosage in deep space, due to the large energies involved. (Ref. 18, 22, 25, 33, 57)

In addition to the constant stream of cosmic particles, solar flares eject tremendous amounts of ionizing particles into space. The solar flare particles consist largely of protons and some electrons, sometimes also including alpha particles and rarely heavier nuclei. The protons account for more than 80% of the flux on an energy per nucleon basis, reaching integral fluxes (> 10 MeV) as high as 10^{10} part./cm^2 for the larger flares. The frequency of solar flares tends to follow 11 year cycles, correlated with solar activity: during solar maxima, a dozen or more major flares may be observed, while only a few flares may be observed during the solar minima. The dose rate in space resulting from high intensity flares may be as much as 3 X 10^4 rad/hr with an integrated dose from 500 - 1000 rads. As much as 12 gm/cm^2 of shielding material would be required to reduce this integral dose to ~ 40 rem. (Ref. 20, 25, 26, 51, 57, 58)

Futhermore, the Earth's dipolar magnetic field has trapped ionized particles (mainly protons and electrons) into two high energy zones centered on the magnetic equator, the Van Allen belts. The first inner Van Allen belt lies at altitudes between 500 and 2500 miles above the earth, at latitudes less than 20 deg. It consists mainly of 10^6 - 10^{10} eV protons with a flux of ~10^4 part./cm^2-sec, and 20-60 keV electrons with a flux of roughly 10^9 part./cm^2-sec. The dosage to be expected from

such hard radiation is of the order of 500 rad/sec and is only reduced to 10-100 rad/hr with 4 gm/cm^2 of shielding (Ref. 11, 42). The intensity of this belt is stable with time and is probably due to the decay of neutrons from cosmic-ray induced nuclear disintegrations in the atmosphere, trapping the resulting e^- and p^+ in the geomagnetic field (Ref. 11, 57).

The outer Van Allen belt is almost exclusively composed of low energy high flux electrons, (10^4 - 10^6 eV, 10^8 - 10^{11} part/cm^2-sec). It lies at latitudes between $\pm$ 40°. The depth of this belt can almost double during solar flares and it is thus thought to be the result of solar gas trapped and accelerated in the geomagnetic field. The dose rate which can be received in this belt is as much as 4 x 10^4 rad/sec but the 'soft' nature of this radiation makes it easy to stop: 4 gm/cm^2 of shielding reduces the dose to less than 1 rad/hr (Ref. 11, 20, 25).

The radiation dose below these belts is usually negligible: exceptions are the soft auroral radiation in northern latitudes and the more dangerous levels in the South Atlantic anomaly. Because the magnetic center of the Earth is displaced from its geographic center, the particle fluxes are largest over the South Atlantic Ocean (~ 30 deg. south latitude, 15 deg. west longitude) than anywhere else at the same altitude. The expected dosage at approximately 200 km can be as much as 1/10 rad/hr.

II.3 Effects on the Nervous System

As was seen previously, the maximum permissible body dose is usually limited by the radiation exposure of the genetic or hematopoietic organs. The nervous system has long been considered highly radio-resistant and its exposure was not thought to be a limiting factor. However, as will be discussed below, the nervous system's function is quite radio-sensitive and this might very well be in the future an important consideration in the determination of maximum levels of exposure for astronauts, if

they are to remain mentally alert and efficient.

The integrity of nerve cells in the central nervous system (CNS) and peripheral nervous system (PNS)is highly radio-resistant since several thousands rads of local radiation exposure are required to kill them. A man would be lethally injured long before such levels are reached in the CNS if the irradiation were over the whole body. For example, a 25 micron (~ cosmic ray track) beam of 22 MeV deuterons requires a dose to mouse brain tissue of over 500,000 rads to kill only nerve cell bodies within 24 days; in this case the nerve fibers are not destroyed and there is no permanent vascular damage (Ref. 50, 54, 55).

Morphological studies also indicate that increasing the beam diameter to 1 mm, decreases the required dose for total tissue necrosis to 10,000 - 30,000 rads, depending on the animal (Ref. 54, 55). Again the total necrosis occurs within 24 days, only in the last part of the 1.5 mm track. With further increase of the high energy particle beam diameter, a few thousand rads of radiation are sufficient to selectively cause vascular damage and nerve necrosis at the end of the track in cat brain tissue (Ref. 36). This apparent inverse relationship between CNS radiosensitivity and tissue volume exposed is probably due to the decreased probability of vascular damage as the beam is narrowed: as vascular damage is decreased, the nerve cells must then be killed directly by the radiation, which increases the required dose level.

The peripheral nerve fibers are even more radioresistant than the CNS. Over 10,000 rads of local irradiation are required to produce late degeneration (in approximately 1 year) and more than 50,000 rads for early and irreversible suppression of the action potential (Ref. 19, 50). However, as little as 200 rads irradiation can result in nuclear abnormalities, lasting at least 6 months, and causing impaired repair after any subsequent physical damage (Ref. 14). In all the above mentioned

cases, the dose rate is not an important factor and has no apparent effect, as least at these high doses.

The effects of such high level doses on the CNS and PNS are extremely important since they are used in stereotaxic radiosurgery, for both therapeutic and physiological studies, and may also result from human exposure to high energy cosmic ray particles, solar flares, or accidents with radiation equipment. However, the effect of low dose predictable radiation (e.g., occupational) on human nervous tissue now appears to be also of great importance.

At lower dose levels, (up to a few hundred rads) though there is no killing of nerve cells, there is now evidence of disturbances in the functional activity of the nervous system in animals. Changes in the conditional reflexes and EEG activity of rabbits occur with as little as a few rads irradiation (Ref. 42). Daily local irradiation of malignant tumors in the nasopharynx of human patients with a few hundred rads produces a transient increase in the level of CNS excitability: increased flicker fusion frequency and decreased reaction times (Ref. 16). Though peripheral nerve fibers are highly radio-resistant, the function of synaptic areas is much more sensitive: for example, 10 rads of X-ray exposure to the eye will decrease visual thresholds (Ref. 50). These observations point to the high radio-sensitivity of the <u>functional</u> state of the CNS.

Comparative studies on the effects of low dose whole body irradiation of mice with different types of radiation give interesting results. It appears that an acute dose of as little as 25 rads of Co^{60} gamma rays or 1.25 MeV neutrons significantly affects the conditioned reflex indices of these mice. Attenuation of the stimulation processes (increased latent period and number of extinctions) was observed, the

neutron radiation being most effective. Also, in differential conditioned reflexes, the gamma irradiation caused disinhibition of differentiation (decreased latent period), while the neutron irradiation intensified the differentiation, probably through summation of conditioned and protective inhibition (Ref. 30). Investigations with larger doses produced similar though more intense reactions. Studies with 5 MeV proton irradiation resulted in parallel but weaker results, compared with the gamma radiation. It was concluded that neutron, gamma and proton irradiation, in that order, affect both the excitation and inhibition processes in the CNS of mice: the neutrons, and to a lesser extent the gamma radiation, disrupt mainly the excitation processes while the protons disrupt mainly the inhibition processes. The observed effectiveness of these radiations, pertaining to conditioned reflex studies, correlates well with their LET and therefore with the changes in hematological indices they occasion.

The mechanism(s) of the radiological actions on the CNS is not very well known. Some investigators have shown that radiation exposure immediately decreases the O_2 consumption (Ref. 35) and blood flow (Ref. 29) in rat brains, with normalization in a few days. Furthermore, irradiating the cerebellum of guinea pigs with 8000 - 9000 rads of X-rays decreases the gamma amino butyric acid concentration of the cerebellum, parallel to the increased motor disorders leading to death (Ref. 39). However, there still remains to determine which, if any, of the above observations represent a direct effect of radiation and which are simply secondary to it.

An important question is whether the functional tolerance of nervous tissue to radiation exposure might not be increased if it were administered at low dose rates. Most physiological systems can sustain

safely large doses of radiation if given in a period of days or weeks, where the same dose could be lethal if given in a few minutes; this is the role of the time factor in the QF of a radiation. Unfortunately, such experiments on the CNS of animals show an indifferent or even increased radiosensitivity with decreased dose rate, for low dose levels up to a few hundred rads (Ref. 37). For example, whole body irradiation of dogs with 250-700 rads of 510 MeV protons resulted in the greatest dystrophic changes in the CNS and PNS when the dose was applied over a period of a few weeks as opposed to within a few minutes (Ref. 12). Similarly, gamma irradiation of male guinea pigs in doses up to 500 rads was most effective when administered chronically, according to the resulting change in the indices of the electromyographic characteristics of the vestibular tonic reflex (Ref. 2, 3). Thus at dose levels below 1000 rads, where the hematological damage in the CNS does not dominate, it appears that chronic exposures are more dangerous than acute ones. Lengthening the exposure time enhances the chances of damaging low redundancy functional units, without giving the benefit of an increased repair period (as opposed to highly reproductive genetic or hematological systems.) On the other hand, lethal whole body irradiation with thousands of rads is most effective if administered acutely. Here the damage to the CNS is mainly through the failing hematopoietic system.

Though we are now aware of the high radiosensitivity of the <u>functional state</u> of the CNS in animals, the question arises whether any such changes in man would be important enough to affect his performance at the low permissible doses which do endanger his immediate health and comfort. Further studies of low dose long term effects on his life span, vision, muscular coordination, etc., are required to evaluate the danger.

II.4 Protection and Monitoring Techniques:

The first step in insuring good crew performance in the presence of radiation would be to select those crew members who are expected to be the least radiosensitive. Unfortunately, there are practically no methods for predicting radio-sensitivity, only hypothetical opinions. One method might be to study the reaction to irradiation of an autogenous cell culture of the man in question (Ref. 22). Possibly, through roentgenous copy, we could take advantage of the fact that a small dose of radiation can change the bioelectric activity of the brain. The animals in which this reaction has been observed appear less radio-sensitive (Ref. 44), and further work might be warranted to study its possible extension to human reactions.

Pharmacological means have been investigated for many years and offer the hope of chemically protecting man from harmful irradiation effects, if given prior to exposure. Their mode of action is not always very well understood though they appear to create tissue anoxia or provide free radicals for combination with dangerous ions produced by the irradiation. Many drugs such as serotonin or cystamine have been very successful in animal experiments but unfortunately so far prove toxic to man in the required dosage (Ref. 1, 18, 53). Another drug has a very low toxicity, even to man, when applied topically on the skin: dimethyl sulfoxide (DMSO) has proven up to 70% effective in protecting mice from an LD_{50} of X-rays, if applied topically on the animals' tail prior to irradiation (Ref. 59). The most effective protection may well be a combination of low doses of such drugs. Much work remains to be done to determine the quantitative effects of such chemical agents and the exact dosage and methods of application required. Radioprotection is most important for the CNS where there is no possible replacement of killed cells.

Further protection, or prevention of dangerous irradiation exposure can be obtained by planning trips in periods of relative solar minima, using predictive techniques. So far the available methods only allow for flare prediction within 2 or 3 days with a 75% accuracy (Ref. 51). Good operational forecasting (several days or weeks) needs to be developed to plan flight schedules safely and the short range (several hours) methods perfected to give the astronauts time, in flight to prepare for likely "ionization storms" (Ref. 38, 46). Once good predictive facilities are available, a simulation of the expected radiation conditions on a flight (e.g., to the moon and back) can be effected to study probable dose and dose rate effects on animals (Ref. 41, 51).

The resulting observations can be used as guidelines for the required levels of physical shielding, both standard and emergency, to limit the dosage to the genetic organs to 55 rems/yr in the spacecraft (Ref. 26). A maximum permissible dosage level for the CNS should be evaluated, as it might turn out to be even less than that for the genetic organs. Possibly the only method of determining this level will be to monitor accurately the long term dosage to astronauts and evaluate periodically their cerebral functions with appropriate tests. Intensive observation and experimentation should also be implemented upon their return to Earth. Careful dosimetry and observation of radiation equipment operators should obviously be made as they form an ideal population to study long term, low dose and dose rate effects of radiation on the nervous system.

Many types of radiation dosimetry are available, some physical, others chemical. Among these thermoluminescent and film dosimeters will give an indication of the physical surface dose at their location. The average absorbed body dose can be related to the presence of substances containing deoxyribose in the urine, or to the immunological state of the

organism (skin microflora, phagocytic activity of the neutrophytes, etc.). Whole body counting can be used upon return to Earth. Also the composition of the peripheral blood, if monitored daily, gives an idea of the dose absorbed by the hematological system. In order to determine the dose-effect relations for the CNS, good surface and depth dose measurement and analysis techniques should be provided since the spatial distribution of the radiation dosage on the body greatly affects its system reactions.

Finally, another possible means of extending protection to astronauts would be to envelop the spacecraft with a magnetic field, deflecting any dangerous radiation away from its occupants. However, much work remains to be done to determine the biological effects of such magnetic fields and their required method of operation, that is, continuous or pulsed in emergencies.

II.5 Conclusion and Recommendations:

Animal experiments have shown that the CNS is functionally radiosensitive at doses as low as 25 rads, and that the degree of this sensitivity may even be increased if the dose rate is decreased. Further studies are needed to evaluate the maximum permissible dose to the CNS by

1. Extrapolation from more animal experiments (e.g., monkeys).
2. Accurate dosimetry and observation of radiation personnel and astronauts.

Known protective measures should then be perfected and implemented, including

1. Pharmacological protection of the CNS.
2. Reliable operational (a few hours) flare prediction.

3. Determination of optimum trajectories.

4. Adequate physical and/or magnetic shielding.

Such studies will lead to a better understanding of radiation effects on the CNS and will have a great impact on radiation therapy of patients with malignant tumors, and on the protection required for operators of nuclear equipment.

III Magnetic Fields

III.1 Environmental Levels:

In travelling into outer space, astronauts will leave not only the Earth's gravitational field, but also it's familiar geomagnetic environment. Previous fears concerning the possible detrimental effects of zero-g on humans have now been proven largely unfounded. Where dangers still exist (e.g., cardiovascular deconditioning) protective measures can be taken. However, very little is known about the effect of a change in the magnetic environment on humans. Orbital flights have so far kept astronauts within the Earth's geomagnetic field. Fortunately, unlike the zero-g environment, it is possible to create various magnetic environments in limited volumes on the Earth. With the aid of special coils or shielding materials, such systems can be used to study the possible effects of magnetic conditions along different parts of future space flight trajectories.

Among the various magnetic environmental levels to be encountered are those in the Earth's own field, in interplanetary space, and on or near the planetary destination sites. The Earth's magnetic field is close to that of a dipole for 3 to 7 earth radii (R_e) with a level of roughly 0.5 gauss at the surface. However, at greater distances it becomes grossly distorted by the solar wind as it gradually decreases in intensity. It has a blunt spherical nose at approximately 10 R_e on an

Earth-sun line and a long comet-like tail away from the sun that extends almost halfway to the moon, to more than 20 R_e (Ref. 43, 52). On the other hand, the interplanetary field appears to be less than 10 gamma* and measurements indicate probably less than 100 gamma on approach to moon impact and during flyby of Mars and Venus (Ref. 13, 15, 48, 49).

Furthermore, the immediate magnetic environment of a space crew will depend on the magnetic properties of their craft and its circuitry, on whether strong fields will be generated as radiation protection (Ref. 24, 31, 45), and on possible future uses of magnetohydrodynamic propulsion.

III.2 Effects on the CNS:

Since man has evolved in the Earth's geomagnetic environment, it is plausible to assume that removing him from this environment could have some detrimental effects. Whether the resulting damage would be reversible and/or negligible remains to be seen. Magnetobiologists have long studied the effects of magnetic fields on plant and cellular growth. However, we will limit ourselves here to a review of observed changes in the central nervous system when exposed to either very strong or very weak magnetic fields, as compared with the Earth's field, since these are possible environmental levels during space flight.

Workers in nuclear physics laboratories often reported brief exposures to as much as 20,000 gauss with no ill effects. This led to the conclusion that humans could tolerate brief exposures to high intensity magnetic fields with no apparent cumulative effects (Ref. 7). As early as 1896, it was observed that placing a man's head in a magnetic field could lead to the production of phosphenes (luminous sensations) (Ref. 62). This effect has again been more recently observed, using both d.c. and a.c. magnetic fields with intensities from a few hundred to a few thousand gauss (depending on the frequency). The magnetophosphene

* 1 gamma = 10^{-5} gauss

effect is reversible (at least for the short exposure times studied) and is probably a result of electric currents induced in the retina by the magnetic field (Ref. 61).

Unfortunately, the results of such brief exposures are not sufficient. If magnetic fields are used to shield spacecraft from ionizing radiation, the exposure times will be more of the order of several hours, not minutes. Apparently small animals can be exposed to fields as high as 140,000 Oe for as long as 1 hour and survive with no changes in neutrophyl, lymphocyte or monocyte counts. Furthermore, magnetic gradients of as much as 500 Oe/cm do not seem to be detrimental (Ref. 8). But such observations do not give any indication of possible changes in the central nervous system of these animals during the exposure periods.

Studies have been undertaken to investigate the development of conditioned reflexes and the characteristics of EEG's of animals and primates while exposed to strong magnetic fields. In the case of fish and birds, conditioned reflexes to magnetic fields from 1 - 800 Oe were either very weak or non-existent when compared with light or sound. However, magnetic fields of 100 - 200 Oe were strong inhibitors of previously developed conditioned reflexes (e.g., magnet and light), with the inhibitory effect often persisting for several minutes after magnet turn-off (Ref. 27, 28). In terms of conditioning and performance, a magnetic field thus appears to have mainly a "corrective" or inhibitory effect, often persisting after turn-off. Experiments on "cerveau isolé" further show this to be the result of a direct interaction of static magnetic fields on the structures of the forebrain and diencephalon.

The results of EEG experiments on rabbits and monkeys are confusing and contradicting. Kholodov (Ref. 28) usually observed an inhibitory state in the EEG of rabbits exposed to a static magnetic field of 800 Oe for several hours. That is, there was a significant increase in the

number of spindles and slow high-amplitude waves, and a decline in the excitability of the cortical end of the visual analyzer. However, depending on the initial state of the CNS, an opposite excitatory reaction could sometimes be observed. On the other hand, Beischer (Ref. 9) exposed monkeys to fields as high as 91, 250 Oe and always observed a shift in the EEG toward high amplitudes and higher frequencies. Though this might indicate an excitatory state in the CNS, the animals' performance in a visual discriminatory task progressively decreased as the field intensity increased. At a field strength of 90,000 Oe, they ceased to perform their task. There is thus agreement in that high intensity magnetic fields have mainly an inhibitory effect on the performance and conditioned reflexes of animals, appearing after a significant latent period (seconds or tens of seconds), and exhibiting a prolonged aftereffect. However, the character of the EEG does not always agree with this conclusion. Either artifacts are sometimes picked up on the electrodes during recording, or the magnetic field does not act directly on the neurons but rather on the surrounding glial cells and chemical processes.

Glia are assumed to be intermediaries between nerve and circulatory elements, their high metabolism keeping the activity of neurons at a sufficient level. Any activation of the glia causes inhibition in the brain (Ref. 21). To test the presence of a glial factor in the CNS reaction to magnetic fields, rabbits, cats and rats were exposed up to 70 hours to a magnetic field of 200-300 Oe. Histological studies of the sensorimotor cortex showed initially (1 hr. exposure) a sharp productive reaction (hyperplasia and hypertrophy) in the glial elements, while the neurons remained intact. As the exposure period was extended (10-12 hours), the glia remained productive and the neurons underwent reversible

swelling. Longer exposure periods (60-70 hours) caused productive dystrophic damage to the neuroglia and dystrophy in the nerve cells (Ref. 28, Chapter 9).

It would thus appear that the effect of a high intensity magnetic field on the brain is realized primarily through changes in the metabolism of glial cells. Many of the observed effects of a magnetic field on the CNS can be explained by this increased metabolism in the neuroglia. The observed long latent period of the reaction to a magnetic field indicates that the neurons cannot be directly affected since their latent period is in the order of milliseconds. However, inhibition of the neurons via changes in the metabolism of the neuroglia would exhibit the required latent periods and after effect. This is supported by the fact that the glia are the first to show morphological changes during exposure to magnetic fields of the order of hundreds of oersteds. In the case of magnetic fields of tens of thousands of oersteds , more experimental work is required to verify that the EEG is truly synchronized at high frequencies and if so whether another mechanism from that above would be responsible for such a reaction at these higher field intensities.

The effects of the near-absence of a magnetic field on the CNS are relatively unknown, though this is the environment astronauts will most likely spend most of their time in during interplanetary space flights. Beischer exposed men in an 8' x 8' x 8' room to a field less than 50 gamma (Ref. 5, 10). The confinement of the subjects began 6 days prior to exposure (itself 10 days) and ended 5 days after magnet turn-off. Except for the normal trends expected during a 21 day confinement period, all physiological measurements remained normal (EEG, EKG, blood pressure, etc.). Similarly, visual and psychophysiological tests showed in general no unusual effects of the null field. The critical flicker

fusion frequency (CFF) of the subjects was the only measure that changed in correlation with the magnetic field change. In fact, the CFF was observed to decrease gradually and continuously after the null field was generated, and to revert abruptly to its pre-exposure value upon the return of the normal geomagnetic environment. However, the exact seat of this magnetic effect in the visual pathways is unknown. The null field might induce the formation of defective protein in the photoreceptor cells, or cause inhibition anywhere else along the visual pathway or cortex.

III.3 Conclusions and Recommendations:

Present available data suggests caution in prolonged human exposure to either low field or high field environments. Further long-term experiments, especially with primates, are required to determine

1. The mechanism of the magnetic effect.
2. Maximum permissible field intensities and exposure durations, if warranted.

Accurate measurements are also needed of

1. Magnetic environment in the spacecraft.
2. Magnetic field levels at proposed planetary landing sites.

Further research on synergistic effects should also be of interest, such as

1. Magnetic pretreatment to reduce radiosensitivity (Ref. 4) or increase lifespan of tumour bearing mice (Ref. 23).
2. Possible application of magnetic field to induce sensation of gravity via paramegnetic oboliths (Ref. 5).

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