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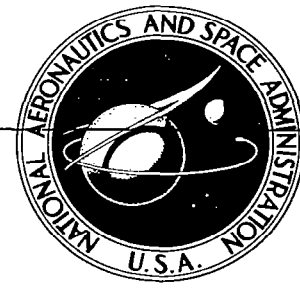

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BIOMAGNETICS

Considerations Relevant to Manned Space Flight

by Douglas E. Busby, M.D.

Prepared by
LOVELACE FOUNDATION FOR MEDICAL EDUCATION AND RESEARCH
Albuquerque, N. M.
for

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D. E. B.

ABSTRACT

Astronauts venturing out on the lunar surface and the surfaces of our neighboring planets will be exposed for a few hours in duration to magnetic field intensities which are markedly less than that of the Earth's field. The intensities of magnetic fields to which they will be exposed inside spacecraft cabins can be stated only after completing a detailed survey of the contribution made to these fields by the functioning electronic components of spacecraft. Assessment of individuals regularly working in and exposed continuously for 10 days to magnetic fields less than 100 gammas in intensity indicate that extremely low-intensity magnetic fields encountered during a nominal Apollo Moon mission should not affect astronaut health or performance. Careful physiological and psychological observations first on higher primates, then on man exposed to such fields for more prolonged periods of time must be carried out before this conclusion can be drawn for longer exposures.

Recent technological advances in propulsion and radiation protection have made it possible that astronauts might also be exposed intermittently to high-intensity, relatively low-gradient magnetic fields during space missions. The duration of such exposures could range from less than an hour while servicing a magnetohydrodynamic propulsion engine, to several days if pure magnetic or plasma radiation shielding is used for protection of astronauts from solar flare radiation. From past experience with personnel who enter high-intensity magnetic fields for brief periods of time in their work, magnetic field exposures while servicing magnetohydrodynamic engines should not be hazardous to astronauts. On the other hand, past exposures of man and sub-human systems to high-intensity magnetic fields do not indicate whether astronauts exposed for up to several days to currently estimated magnetic field intensities associated with pure magnetic or plasma radiation shielding could suffer impairment of their health or performance. This answer can be obtained only by carefully conducted experiments which closely simulate such exposures, and look closely for physiological, psychological and pathological changes, especially in exposed higher primates, before assessing the response of man to such exposures.

TABLE OF CONTENTS

	Page
Acknowledgements	ii
Abstract	iii
List of Figures	vi
List of Tables	vi
Introduction	1
Magnetic Field Exposures in Space	2
Effects of Low-Intensity Magnetic Fields	7
Effects of High-Intensity Magnetic Fields	15
References	46

LIST OF FIGURES

Figure No.		Page
1	Measured and postulated magnetic fields in the planetary system.	2
2	Comparative weights for various radiation shielding systems.	5
3	Scotopic critical flicker-fusion frequencies in 4 subjects before, during and after exposure to a magnetic field less than 50 gammas in intensity, in a Helmholtz coil system.	8
4	Scotopic critical flicker-fusion frequencies in 2 subjects before, during and after exposure to a magnetic field less than 50 gammas in intensity, in a magnetically-shielded room.	9

LIST OF TABLES

Table		Page
1	Exposure of biological systems to high magnetic fields.	17

"Magnetic force is animate or imitates life; and in many things surpasses human life, while this is bound up in the organick body."

William Gilbert, 1600

INTRODUCTION

During lunar and planetary missions, astronauts will be exposed to magnetic fields which are much less in intensity than the magnetic field on the surface of the Earth. As well, recent technological advances in radiation protection and propulsion have made it possible that astronauts might also be subjected to fields of much greater intensity than the Earth's field. This brief review defines the characteristics of possible magnetic field exposures in space and examines the biomagnetic literature in an attempt to determine whether or not such exposures could affect astronaut performance and health. Directions for "space-oriented" research in this area are suggested.

MAGNETIC FIELD EXPOSURES IN SPACE

Intensities of measured and postulated magnetic fields in the planetary system are depicted in spectrum form in Figure 1. The Earth's magnetic field, which varies in time and place from about 0.3 to 0.6 gauss* at ground level, decreases in intensity as the inverse cube of the distance from Earth [24, 50, 75]. Due to the so-called solar wind, composed of low energy charged particles which emanate continually from the sun's outer corona, the outer boundary of this field is compressed down to a magnetically-turbulent stagnation zone between about 8 to 14 Earth radii on the Earth's sunlit side; on the Earth's darkened side, this boundary extends out into a long tail, at least half-way to the Moon (about 31 Earth radii [41, 42, 110, 111, 133].

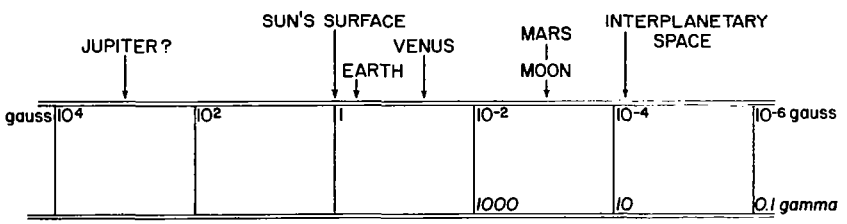

Figure 1 Measured and postulated magnetic fields in the planetary system.

(Revised from Beischer [25]).

Magnetic fields in interplanetary space, beyond the outer boundary of the Earth's magnetic field, have been measured by a number of satellites in the past few years. Except during high intensity solar flares, the level of these fields should vary from about 2 to 12 gammas [41, 42, 50, 145]. Data from the magnetometer on the Lunik II satellite indicated that the magnetic field on the Moon's surface is less than 100 gammas in intensity [41, 43, 51]. Mariner II satellite data indicated that the magnetic field intensity on Venus is at least an order of magnitude less

*The "gauss" is the unit of magnetic induction, or flux density. The "oersted", to be used in other sections of this report, is the unit of magnetic field strength. In a vacuum and for all practical purposes in air, magnetic induction is numerically equal to field strength. For historical reasons, the strength of the geomagnetic field is always given in gauss which, prior to 1930, was defined as the unit of magnetic field strength. A field strength of 1 oersted exerts a force of 1 dyne on a unit magnetic pole in a vacuum.

than the Earth's field intensity [130], so confirming earlier predictions [51, 80]. Although it had been thought that Mars might have a magnetic field similar to that on Earth [24, 80], the Mariner IV magnetometer indicated that the Martian magnetic field intensity is about 3×10^{-4} that of the Earth's field, or about 100 gammas [131]. Jupiter is thought to possess a magnetic field which is considerably stronger than the Earth's field [24, 50].

Although it can be assumed that astronauts will be exposed to extremely low-intensity magnetic fields during extravehicular operations beyond the geomagnetic field and on the surfaces of Mars and Venus, the magnetic field intensities in the immediate vicinity of or within spacecraft cabins in these regions have not been measured. On the one hand, magnetic fields associated with activated electronic components and ferromagnetic materials in spacecraft might make a significant contribution to the ambient magnetic environment of astronauts, possibly as great as the intensity of the surface field on Earth [147]. As indicated in the Gemini mission, spacecraft fields would add to the field of the ambient environment, which apparently passes through a spacecraft wall with insignificant attenuation [105].

On the other hand, these fields could in effect cancel each other out. It is considered likely that similar cabin magnetic fields will be associated with electronic component functioning in the Apollo command and lunar excursion modules, and perhaps other future spacecraft [95, 130]. Hence, if such fields exist at a near-zero level due to a cancelling phenomenon, field intensities in spacecraft cabins will essentially be the same as those of ambient space and lunar environments. Astronauts would then be exposed to magnetic field levels of less than 100 gammas for prolonged periods of time during lunar and planetary missions.

It is possible that artificial magnetic fields of high intensity might be created in and around future spacecraft. The recent discovery of materials which maintain their superconductivity in the presence of strong magnetic fields has prompted consideration of the use of magnetic shielding to deflect hazardous charged particles, especially from high-grade solar flares, away from manned compartments of spacecraft [36, 79, 95, 99, 137, 138].

Superconductive materials, such as an intermetallic compound of niobium and tin,and two metallic alloys, niobium-zirconium and niobium-titanium, lose their electrical resistance when cooled to very low (e. g. liquid helium) temperatures [125]. Hence, the electrical power requirements are kept at a minimum, since negligible power is required to sustain a peak magnetic field once the current is started. Even with the added weight of cryogenic materials and other system components, magnetic shielding remains feasible, since the cross section of wire required to transmit a given current is much less than that of an ordinary conductor. It has been stated that the problem of secondary radiation due to the impact of incoming particles on components of a space vehicle can be reduced to negligible levels, especially if uncontained field designs are used in solenoid construction [79]. However, current models of predicted solar flares do not indicate that such radiation would create a significant hazard [90].

An even more practical scheme for deflecting harmful particulate radiations in space is plasma radiation shielding [97, 98]. To deflect high energy incident protons, a spacecraft is maintained at a potential of several hundred million volts above its surroundings. The key to maintaining this potential is the control of otherwise attracted electrons by a magnetic field. The magnetic field strength required to control these electrons is far less than the strength required in a pure magnetic shield to control energetic protons. As a result, engineering estimates of the weight of this device, assuming superconductors, show that it, as a whole, is far lighter in weight than the pure magnetic shield [97, 98]. A preliminary comparison of weights of radiation shielding systems, including presently used solid shielding and a possible locally-shielded area, or so-called "storm cellar", is given in Figure 2.

As to whether or not pure magnetic or plasma radiation shielding will be utilized in the future will depend on a number of factors, such as the further assessment of space radiation hazards and the solution of a great number of problems in hardware development. Militating against such systems might be the effectiveness of creating an adequately shielded area in the spacecraft by suitable placement of equipment and stores.

Magnetic field intensities of proposed pure magnetic and plasma radiation

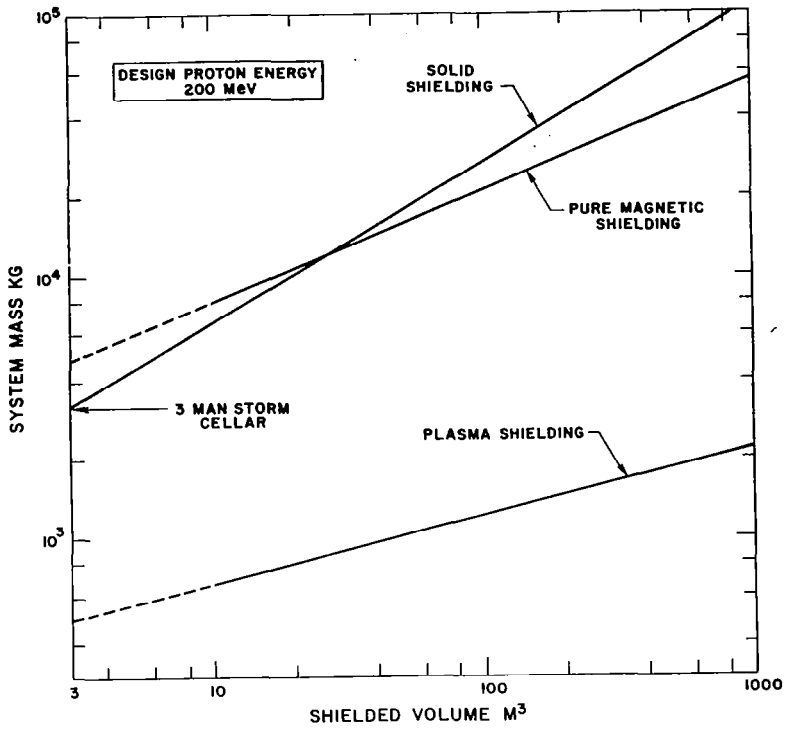

Figure 2 Comparative weights for various radiation shielding systems.

(After Levy and Janes [98]).

shields have been estimated [36, 79, 95, 96, 97, 98, 99, 137, 138]. It should be noted that such shields will be poorly designed if stray fields extend very far from the desired interaction region [96]. Thus none of them should involve substantial exposure of astronauts to main fields. An adequate field strength produced by pure magnetic shields will probably not exceed 10,000 gauss [96]. This level would be sufficient to deflect protons of energies of up to 200 to 500 Mev. [36, 96]. Since it would be possible to direct most of a magnetic shield away from a spacecraft interior, the field intensity within its cabin might be expected to vary from less than 100 to 1,000 gauss [96]. Such a field would be of relatively low gradient. If plasma radiation shielding is used, much lower magnetic fields, possibly in the range of 2,000 gauss will be utilized [96, 97, 98]. The magnetic field strength inside a spacecraft cabin might then be substantially less than

100 gauss [96].

Magnetic fields used for directing plasma ion flow from magnetohydrodynamic propulsion engines will probably be well enough contained and directed that the magnetic field intensity inside a spacecraft will not be raised to significant levels above the engine shut-off level [96]. Servicing procedures on these engines would take place with essentially no magnetic field, or at the most, a small seed field possibly of about 1,000 gauss used for starting an engine [96]. This field might extend outside the engine about a plasma channel diameter, which might be about a foot or so [96].

In conclusion, one can at the present time be certain that astronauts venturing out on the lunar surface and the surfaces of our neighboring planets will be exposed to magnetic field intensities which are markedly less than that of the Earth's field for periods of a few hours in duration. The intensities of magnetic fields to which astronauts will be exposed inside spacecraft cabins can be stated only after completing a detailed survey of the contribution made to these fields by the functioning electronic components and ferromagnetic materials in spacecraft. If pure magnetic or plasma radiation shielding, and magnetohydrodynamic propulsion are used in space travel, astronauts might be exposed intermittently to increased, relatively low-gradient magnetic fields for periods of less than an hour while servicing a propulsion engine, to the several days over which a radiation hazard from a solar flare might exist [55, 56].

EFFECTS OF LOW-INTENSITY MAGNETIC FIELDS

Since astronauts will soon be exposed to magnetic fields which are much less in intensity than the Earth's magnetic field, the question arises as to whether the human body has during its evolution become dependent on the presence of the Earth's magnetic field for the maintenance of its normal functional integrity. Accordingly, it has become most important to ascertain whether a low-intensity magnetic field exposure could possibly lead to an impairment of health or performance of an individual. The very few reported studies in which man, sub-human species, cell cultures and biochemical systems have been exposed to extremely low-intensity magnetic fields are briefly discussed below.

Over periods of several years, personnel working in magnetically quiet areas of geodetic stations and degaussing facilities have been exposed for most of their working day to magnetic fields as low as 100 gammas in intensity [24, 25]. A survey of these individuals yielded no obvious detrimental effects attributable to their unusual occupational environment [21, 24].

Beischer [25, 27, 28, 34] has apparently carried out the only human experiments to date in this area. In an early investigation, male subjects were continuously exposed to magnetic fields of less than 50 gammas in intensity for 10 days in duration. A modified Helmholtz coil system was used to obtain this magnetic environment within their comfortable living area. In a preliminary study, two subjects did not, during the exposure period, demonstrate any abnormal variation in their weight, body temperature (oral), respiratory rate, blood pressure, electrocardiogram, electroencephalogram and blood analyses, which included white blood count, differential white blood count, hemoglobin concentration, hematocrit and protein-bound iodine concentration [25, 34]. Their psychophysiological and psychological assessments included tests of space perception, hand-eye coordination, visual spatial memory, body image, visual fields, visual digit span, critical flicker-fusion, reproduction of time intervals, Graybiel-Fregly posture, visual auditory conflict and conceptual reasoning. The Zuckerman adjective check list, a questionnaire, the Minnesota clerical

and Wonderlic personnel tests, and neuropsychological assessments were also carried out. All the above tests were described as failing to demonstrate any remarkable changes during exposure [25]. However, there was an indication that the absence of the Earth's magnetic field caused a decrease in the scotopic critical flicker-fusion frequency. In the post-exposure control period, the subjects living outside of the coil system, frequency values returned toward pre-exposure levels over a period of several days.

Four subjects were then exposed in a similar formal experiment, but with reference behavior in the Earth's magnetic field being established by a five day control period living in the coil system before and after the exposure [28]. As in the preliminary study, all physiological tests yielded negative results. The scotopic critical flicker-fusion frequency, as shown in Figure 3, again showed a tendency, in three of the four subjects studied, to diminish gradually during the exposure period, and then recover rapidly to baseline levels in the post-exposure period.

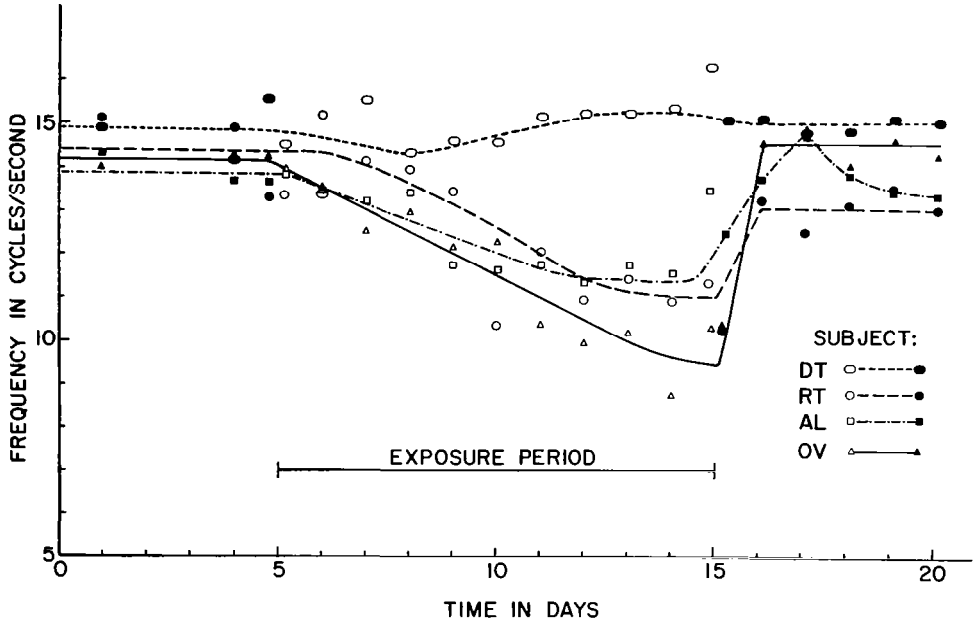

Figure 3 Scotopic critical flicker-fusion frequencies in 4 subjects before, during and after exposure to a magnetic field less than 50 gammas in intensity, in a Helmholtz coil system.

(After Beischer [29]).

Recently, Beischer [33] has exposed two healthy normal subjects for a period of 5 days to a magnetic field below 50 gammas in a magnetically-shielded room. These individuals lived in a similar, unshielded room during the 3 day pre- and post-exposure control periods. As has been illustrated in Figure 4, the flicker-fusion threshold in the scotopic range of vision again decreased during exposure, returning to control values over 2 to 3 days post-exposure.

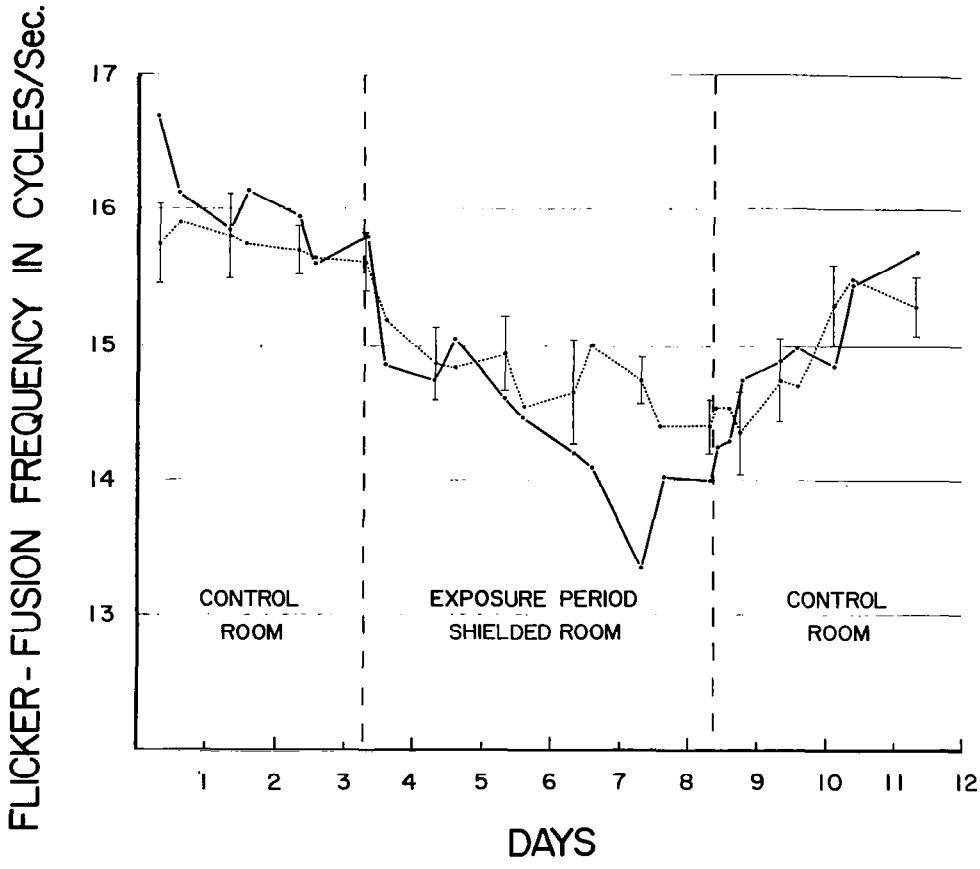

Figure 4 Scotopic critical flicker-fusion frequencies in 2 subjects before, during and after exposure to a magnetic field less than 50 gammas in intensity, in a magnetically-shielded room. (After Beischer [33]).

The cause of this apparent effect of a low magnetic field, and possibly a decrease in visual acuity observed in some exposed individuals in these experiments, remains to be established. It is noted that the scotopic critical

flicker-fusion frequency is very difficult to measure [136] and, if comparable to the central critical flicker-fusion frequency test, could be highly variable [88, 89]. Beischer [33] has postulated that a substance or factor essential in the visual process might be formed during exposure to low magnetic fields, being gradually depleted as exposure proceeds and replaced again slowly during the recovery period in the geomagnetic field. Further studies are indicated in this area to establish definitely whether such a phenomenon does occur and if so, whether it could have a significant effect on visual functioning.

There have been few exposures of animals to extremely low-intensity magnetic fields reported in the literature. Tchijevsky was cited by Becker [19] as having probably produced a decrease in magnetic field intensity while attempting to study the effects of air ionization and cosmic radiation on living organisms. Apparently the experimental conditions produced rather rapid onset of inanition and death in rats.

Tchijevsky's observation is interesting in the light of findings in an experiment being conducted by Halpern and Van Dyke [70, 72, 142, 143]. During the past 18 months, these investigators have kept Swiss/Webster white mice and their progeny in mu-metal cylinders 8 inches in internal diameter and 24 inches in length, oriented in the East-West direction. Mu-metal is an austentitic, nickel-iron-chromium-copper alloy of high magnetic permeability and low corrosion resistance. The magnetic field intensity in the cylinders apparently remained well below the 100 gamma level. Control mice have lived in similar aluminum cylinders, which do not have an appreciable attenuating effect on the Earth's magnetic field. The floors and end enclosures (inset one inch from the ends) of all cylinders consisted of non-magnetic, stainless steel, hardware cloth. The cylinders and cages were intermixed and adequate temperature, humidity and ventilation of them insured. The adult population of each cylinder was kept under 8 mice.

As pointed out in a preliminary, unpublished report [143], an unspecified number of originally four-month-old male and female mice were maintained continuously in mu-metal cylinders for periods of 4 to 12 months.

Each shield originally contained a single mouse family of one male and three females (Group I). Data is not available on the number of mouse families this experiment was started with. First generation (F_1) mice litters were equally divided at weaning time (21 days), one-half (Group II) being retained in the mu-metal cylinders and the other half (Group III) being placed in the aluminum cylinders. Group I females were continuously re-mated with their original males.

In contrast to the normally-thriving control mice in the aluminum cylinders, the mice in the mu-metal cylinders have presented a characteristic, rather bizarre picture. Premature mating and frequent pregnancies have produced somewhat larger but apparently normal litters [70, 143]. By the F_4 generation, reproduction has usually ceased [70]. Unanticipated cannibalism and abortions of newborn mice has been encountered to a greater degree in the F_2 generation (and subsequent F_1 generations of the original animals) than in the F_3 and F_4 generations [143]. At an early age, large numbers of mu-metal mice have become docile and inactive. Many mice have exhibited the highly unusual behavior of lying on their backs for prolonged periods of time [70]. About 14 per cent of the adult population has developed a characteristic and uniformly progressive alopecia over the top of the head to at least half way down the back. Interestingly, there are no known mice which have the genetic trait of developing hair loss as adults. Coarse hair, characteristic of aged mice, has also appeared at an early age. Death has occurred prematurely, often as early as 6 months of age.

Histopathological observations have been made on selected organs from 36 Group I mice. Although the same manifestations were not always present in the same organs of all mice at the time of sacrifice, positive alterations, either grossly or microscopically, were apparent in most of the animals studied [143]. Connective tissue and epithelial tumors, which have frequently been found in various loci, remain to be studied further microscopically [70].

The skin has been found to be hyperplastic, but only in areas of alopecia, and characteristically has an undisturbed basement membrane, excessive mitotic activity in the basal layer, columnar-shaped granulosa cells, a

hyperkeratotic stratum corneum, and hair follicle plugging with hyperplastic squamous epithelium [70, 142]. The livers of all experimental mice studied have shown the presence of hemosiderin crystals in the Küpfer cells to a variable degree [70, 143]. In addition, liver tissue from these animals has clearly exhibited nuclear changes characterized by increased numbers and noticeable enlargement of their nucleoli, suggesting perhaps some alteration in the metabolism of ribonucleoproteins [143]. Peripheral blood smears showed very noticeable deposits of hemosiderin within polymorphonuclear leucocytes, and a very high incidence of reticulocytosis.

Most kidneys studied were polycystic to some degree, the cysts often markedly compressing adjacent cortical parenchyma [143]. Many experimental mice, especially those examined after spontaneous death, had their urinary bladders distended with urine and apparently a white precipitate. In at least a third of these mice, the bladder mucosa was markedly hyperplastic, forming trabeculae and polypi [70]. The combined findings of polycystic kidneys and bladder precipitate suggested that certain of these animals might have succumbed from uremic poisoning. Notably, no bladder parasites have been found in either the experimental or control mice.

The ovaries had numerous large, persisting corpus lutea, which often entirely encapsulated this organ [143]. Few follicles were in evidence, in spite of the high incidence of pregnancy in these animals [70, 72]. In many mice, the uterus has been somewhat enlarged having numerous epithelial cyst formations in the endometrium.

Van Dyke and Halpern have pointed out that what they are observing in the mu-metal mice is a diffuse, hyperplastic condition [70, 72, 142, 143]. They cannot forsee any possible cause of this condition other than the chronic exposure to the extremely low-intensity magnetic field [70, 142]. It is suggested that a detailed evaluation of the protocols and conditions of this experiment should be made for the possibility of infectious, genetic or other factors being responsible for these unusual results. At present, none of these protocols have been made available to other investigators

or this reviewer.

A few cell cultures have been placed in extremely low-intensity magnetic fields. Becker exposed cultures of Staphylococcus aureus to an average magnetic field strength which was estimated to be approximately one-tenth that of the Earth's magnetic field [19]. He reported that as compared to control cultures which were not exposed, experimental cultures in all dilutions showed a fifteen-fold reduction in the number of colonies, as well as some reduction in colony size. In other cell culture experiments, Green and Halpern found that the growth of HeLa, KB, WI-38, Chinese hamster and chick embryo cultures was unaffected by a four day exposure to a magnetic field intensity of about 50 gammas [60].

Finally, the acid phosphatase activity of serosal macrophages in mice exposed to a magnetic field of less than 80 gammas in intensity has been studied by Conley and co-workers [46]. These macrophages were stimulated by injecting a standard amount of the liposaccharide of Escherichia coli intraperitoneally. The low magnetic field level was produced with a modified Helmholtz coil system. As compared to similarly-injected, but unexposed control groups, the total acid phosphatase activity of the serosal macrophages was significantly decreased in all low-field groups studied. While unidentified environmental factors produced differences in activity at least as great as those seemingly related to field differences, no correlation with day-to-day temperature variations, or the small fluctuations in the local intensity of the Earth's magnetic field were found.

Beischer has been the only one to attempt a theoretical explanation for biological phenomena observed during exposure to low-intensity magnetic fields [24]. He pointed out that hydrogen nuclei and other cell constituents briefly precess with frequencies according to their mechanical and magnetic moments when the body turns about in the Earth's magnetic field. It was suggested that such an interaction may provide living matter with spatial cues.

Whether this concept explains the various aforementioned phenomena which have been attributed to extremely low-intensity magnetic fields remains to be determined, however. It might be possible that the observed directional influence of magnetic fields on lower forms of life, such as mud snails and planaria [18], may be due to an integrated sensation-reaction effect of molecular or atomic precessions. One cannot even venture to say whether such interactions have, during evolution, become a necessity for maintaining normal functional integrity of higher organisms such as man. Nor can it be attempted to relate this concept to the view of Van Dyke and Halpern [143] that removal of the Earth's magnetic field may result in the release of some governing force that controls the rate of cellular growth and proliferation.

In conclusion, it is readily apparent that one cannot ascertain from past studies in which man and sub-human organisms have been exposed to extremely low-intensity magnetic fields whether prolonged exposure of an astronaut to such fields could possibly lead to an impairment of his health or performance. Assessment of individuals regularly working in and exposed continuously for 10 days to magnetic fields less than 100 gammas in intensity indicate that physiological, psychological, or pathological effects of exposure to extremely low-intensity magnetic fields would not be expected to occur during a nominal Apollo Moon mission. However, careful physiological and psychological observations first on higher primates, then on man exposed to such fields for more prolonged periods of time, must be carried out before this conclusion can be drawn for longer exposures.

EFFECTS OF HIGH-INTENSITY MAGNETIC FIELDS

As was pointed out above, astronauts could be exposed intermittently to high-intensity, relatively low-gradient magnetic fields for periods of from less than an hour while servicing a magnetohydrodynamic propulsion engine, up to several days if pure magnetic or plasma radiation shielding is used for protection from solar flare radiation. Maximum field intensities in both situations are currently expected to be less than 1000 gauss and may, especially if plasma radiation shielding is utilized, be substantially less than 100 gauss. This chapter examines pertinent biomagnetic research carried out to date in an attempt to determine whether or not such field intensities could possibly affect health or performance of astronauts.

Other than the recent need for space-oriented information [7, 21, 23, 31, 32, 84], most biomagnetic research has been stimulated by discoveries that magnetic fields inhibited tumor and other cell growth [3, 9, 40, 64, 76, 115], slowed aging [14], conferred radiation protection [4, 16], altered plant growth and development [52, 104], affected spatial orientation [18, 38], reduced mutation rates [108], and could be used to characterize biologically-active radicals and study basic biological mechanisms [15, 49, 61, 67, 68, 74, 113, 146]. The results of most of these experiments considered pertinent to this report are summarized in Table 1. Studies on plants are referenced in the biomagnetic bibliographies prepared by Gross [63], Davis and co-workers [48], and other authors [52, 104].

In general, it is readily apparent that Table 1 provides very little information that specifically applies to possible exposures of astronauts to magnetic fields. Most experiments have been carried out on low animal forms. Application of inordinately high fields, often for very short durations, militates against the extrapolation of results of experiments with larger mammals to a possible astronaut situation. Moreover, fixation of body parts in fields might not simulate magnetic exposure of an astronaut, who would presumably not be restricted to one plane of movement in a magnetic field, except perhaps while sleeping. Inconsistent findings in similar experiments conducted by different investigators have made it difficult to establish

TABLE 1

EXPOSURE OF BIOLOGICAL SYSTEMS TO HIGH MAGNETIC FIELDS

EFFECTS STUDIED	BIOLOGICAL SYSTEM	FIELD STRENGTH	FIELD GRADIENT	FIELD DIRECTION*	DURATION OF EXPOSURE	EFFECTS OBSERVED	REF.
General effects	Man (head only exposed)	2,500 Oe	- - - - -	Side-to-side (head fixed in field)	- - - - - - - - - -	No apparent effect on respiration, pulse rate, patellar tendon reflex or sensorium.	117
General effects	Man (occupational exposures)	Up to 5,000 Oe	Essentially homogeneous	Random	Accumulated exposure time up to 3 days/year/man	No deleterious effects.	21
General effects	Man (occupational exposures)	Up to 20,000 Oe	Essentially homogeneous	Random	Up to 15 minutes at a time	No deleterious effects; usually only a part of the body exposed (entire body in one instance); one case experienced pain in filled teeth.	21
General effects	Man	- - - -	- - - - -	- - - - -	- - - - - - - - - -	Modification of visual images induced by hypnosis or mescalin intoxication.	82
Motor activity	Dog	1,000 to 2,000 Oe	- - - - -	Random - horizontal field	5 hours	No apparent effect.	117
Motor activity Food consumption Appearance	Mouse (70 days of age)	4,200 Oe	Homogeneous	Random - vertical field	4 weeks	Increased activity and lower food consumption from 361 to 509 days of age, thereafter activity decreased; appeared to age less rapidly.	5
Motor activity Food consumption Appearance	Mouse (200 days of age)	4,200 Oe	Homogeneous	Random - vertical field	4 weeks	No apparent effect.	5

*With respect to exposed biological system.

TABLE 1 (continued)

EXPOSURE OF BIOLOGICAL SYSTEMS TO HIGH MAGNETIC FIELDS

EFFECTS STUDIED	BIOLOGICAL SYSTEM	FIELD STRENGTH	FIELD GRADIENT	FIELD DIRECTION	DURATION OF EXPOSURE	EFFECTS OBSERVED	REF.
Cardiac and respiratory activities	Squirrel monkey	62,500 Oe at heart (70,000 Oe at head)	2,400 Oe/cm at heart (200 Oe/cm at head)	Head-to-foot (body fixed in field)	3 hours	No change in breathing rate; gradual decrease in heart rate and increase in T wave amplitude, which recovered slowly after exposure; increase in degree of sinus arrhythmia; recent studies indicate T wave change was artifact.	29, 30, 31
Cardiac and brain electrical activities	Squirrel monkey	100,000 Oe Oe	Homogeneous	Head-to-foot (body fixed in field)	24 hours	Electrocardiographic changes similar to above monkey experiment; electroencephalographic pattern apparently increased in amplitude and frequency; monkey stopped lever punching for food above 60,000 Oe; no gross pathology in one of two exposed monkeys being examined.	29,33
Brain electrical activity	Rabbit (head only exposed)	500 Oe	- - - -	Side-to-side (head fixed in field)	1 minute	Rise in number of spindles and slow waves in all recorded areas of brain; latency reaction 5-100 seconds, latency recovery 15 seconds; in order of decreasing responsiveness were hypothalamus, sensorimotor cortex, optic cortex, specific nuclei of thalamus, nonspecific nuclei of thalamus, caudate nucleus and reticular formation of midbrain; response, especially in reticular formation, enhanced by adrenaline and caffeine, and diminished by nembutal and aminasine.	83, 85

TABLE 1 (continued)

EXPOSURE OF BIOLOGICAL SYSTEMS TO HIGH MAGNETIC FIELDS

EFFECTS STUDIED	BIOLOGICAL SYSTEM	FIELD STRENGTH	FIELD GRADIENT	FIELD DIRECTION	DURATION OF EXPOSURE	EFFECTS OBSERVED	REF.
Brain electrical activity	Rabbit (head only exposed)	800 Oe	- - -	Side-to-side (head fixed in field)	- - - - - - - -	Increased number of spindles in frontal region and of slow high-amplitude oscillations in the occipital region; decline in cortical responsiveness to light flashes.	81
Brain electrical activity	Squirrel monkey	To 40,000 Oe, then to 72,450 Oe	Homogeneous	Head-to-foot (body fixed in field)	45 minutes each step	Increase in frequency from prevailing frequencies of 8 to 12 cps to 14 to 50 cps; increase in voltage from peak-to-peak amplitude of 25 to 50 microvolts to 50 to 400 microvolts; no polarity or homogeneous-inhomogeneous field differences.	32, 86
		To 20,000 Oe, then to 40,000 Oe, then to 60,000 Oe	Homogeneous	Head-to-foot (body fixed in field)	3 minutes each step		
		To 22,540 Oe, then to 45,472 Oe, then to 68,414 Oe, then to 91,258 Oe	Strongly inhomogeneous	Head-to-foot (body fixed in field)	1 minute each step		
Brain electrical activity	"Animal" (head only exposed)	2,500 Oe or "more"	- - -	Side-to-side (head fixed in field)	- - - - - - - -	Pattern changed from moderate amplitude alpha to high amplitude delta, which is typical of moderate to deep anesthesia; animal remained immobilized in field of magnet.	19

TABLE 1 (continued)

EXPOSURE OF BIOLOGICAL SYSTEMS TO HIGH MAGNETIC FIELDS

EFFECTS STUDIED	BIOLOGICAL SYSTEM	FIELD STRENGTH	FIELD GRADIENT	FIELD DIRECTION	DURATION OF EXPOSURE	EFFECTS OBSERVED	REF.
Brain electrical activity	Pigeon (head only exposed)	Up to 3,000 Oe	Homogeneous	Side-to-side (head fixed in field)	- - - - - - - -	D. C. shift, indicating polarization, at sharp threshold between 100 to 300 Oe; shift originates from Purkinje layer of cerebral cortex, and its amplitude and latent period of onset are roughly proportional to magnetic field intensity; post-rotatory responses markedly increased in amplitude and decreased in frequency.	66
Body metabolism	Mouse	4,200 Oe	Homogeneous	- - -	1 hour	No change of oxygen uptake.	127
Body temperature restoration	Mouse	4,500 Oe	500 Oe/cm	- - -	1 hour	Delay of body temperature restoration after hypothermia.	128
Body temperature	Mouse	4,200 Oe	Homogeneous	Random - vertical field	4 weeks	Decrease of rectal temperature by about 0.8° C during exposure; recovered over several weeks after exposure.	6, 11
Organ effects (spleen, liver, adrenal glands and bone marrow)	Mouse	4,200 Oe	Homogeneous	Random - vertical field	35 days	Spleens showed reactive reticulocytosis with increased number of megakaryocytes, liver cells were regenerating, adrenals showed narrowed and missing zona fasciculata and bone marrow megakaryocytes were decreased in number.	134

TABLE 1 (continued)

EXPOSURE OF BIOLOGICAL SYSTEMS TO HIGH MAGNETIC FIELDS

EFFECTS STUDIED	BIOLOGICAL SYSTEM	FIELD STRENGTH	FIELD GRADIENT	FIELD DIRECTION	DURATION OF EXPOSURE	EFFECTS OBSERVED	REF.
Organ effects (spleen, liver, adrenal glands, bone marrow, lymph nodes and jejunum)	Mouse	4,000 Oe	500 Oe/in	Random - horizontal field	30 days	No apparent effects.	65
Organ effects (liver and adrenal glands)	Mouse	4,200 Oe	Homogeneous	Random - vertical field	35 days	Livers showed centrolobular necrosis and pyknosis; adrenal glands unaffected.	134
Organ effects (spleen, liver)	Mouse	13,500 Oe	400 Oe/cm	Random - horizontal field	25 days	No liver or spleen weight changes.	53
Organ effects (adrenal glands)	Mouse	2,500 Oe	Homogeneous	Random - vertical field	Two female generations (80 days)	Adrenals had very little zona fasciculata in first generation mice, no zona fasciculata in second generation mice.	135
Organ effects (adrenal glands)	Mouse	4,200 Oe	Homogeneous	Random - vertical field	10 days	Narrowing or complete disappearance of zona fasciculata of adrenal glands.	135
Organ effects (brain)	Rabbit and cat (heads only exposed), and rat	200-300 Oe	- - -	Side-to-side (heads of rabbit and cat, and body of rat fixed in field)	1 hour, 10 hours, and 60 to 70 hours for 3 to 7 hours daily	After one hour, glial hyperplasia and hypertrophy in rabbits; after ten hours, same, associated with cloudy swelling of neurons in rabbits and cats; after sixty to seventy hours, glial hyperplasia, hypertrophy and atrophy, and dystrophic nerve lesions in all animals.	85

TABLE 1 (continued)

EXPOSURE OF BIOLOGICAL SYSTEMS TO HIGH MAGNETIC FIELDS

EFFECTS STUDIED	BIOLOGICAL SYSTEM	FIELD STRENGTH	FIELD GRADIENT	FIELD DIRECTION	DURATION OF EXPOSURE	EFFECTS OBSERVED	REF.
Blood parameters Liver and spleen weights	Mouse	13,500 Oe	400 Oe/cm near ends of magnet core	Random - horizontal field	25 days	No total or differential white blood cell count, red cell count, hematocrit, or liver or spleen weight changes found in animals sacrificed after 16, 17, 20, 23, and 25 days of exposure.	53
Blood leucocyte response	Mouse	4,200 Oe	Homogeneous	Random - vertical field	35 days	Decrease (20 to 40%) of circulating leucocytes to minimum about 12 to 16 days, then temporary rise to near baseline about 18 to 21 days followed by second decrease to minimum about 30 days; minima and maxima reached earlier in younger animals; removal of mouse from field at times of reaching minima results in rise of leucocytes to 20% above baseline levels within two weeks; leucocyte changes mainly in polynuclear component.	13,15
Effect of magnetic-withdrawal leucocytosis on mortality from 800r total body radiation	Mouse	4,200 Oe	Homogeneous	Random - vertical field	35 days (radiation given when ceased magnetic field exposure)	21% decrease in death rate.	13,16
Red blood cell response	Mouse	13,000 Oe	450 Oe/cm	Random - vertical field	1 week	Increase in red blood cell count.	11

TABLE 1 (continued)

EXPOSURE OF BIOLOGICAL SYSTEMS TO HIGH MAGNETIC FIELDS

EFFECTS STUDIED	BIOLOGICAL SYSTEM	FIELD STRENGTH	FIELD GRADIENT	FIELD DIRECTION	DURATION OF EXPOSURE	EFFECTS OBSERVED	REF.
Blood coagulation response	Mouse	13,000 Oe	450 Oe/cm	Random - vertical field	2 days	Increase in blood coagulation time.	11
Antibody production	Mouse injected with sheep red blood cells	4,000 Oe	500 Oe/in	Random - horizontal field	6 days	Decrease in antibody production as noted by titer of 1:50 in control, and 1:36 in exposed animals on seventh day.	61
Body growth	Mouse (38-day female)	9,400 Oe	Homogeneous	Random - vertical field	96 hours every 14 days, for 5 cycles	Weight decrease to minimum on second day of exposure in first cycle only; weight lag recovered within four days after each exposure period.	8
Body growth	Mouse (30-day female)	4,200 Oe 3,600 Oe	80 Oe/cm 650 Oe/cm	Random - vertical field Random - vertical field	30 days 30 days	Weight decrease to minimum on second day in both field groups; subsequent weight gain poorer for the more homogeneous field group.	8
Body growth	Mouse (young)	5,900 Oe	100 Oe/cm	Random - vertical field	4 weeks	Weight decrease to minimum on third day of exposure; females became pregnant and bore normal offspring after exposure.	8
Body growth	Mouse (3-week male)	Between 13,500 and 14,400 Oe	400 Oe/cm near ends of magnet core	Random - horizontal field	11 days	No weight change.	53
Wound healing	Mouse	4,000 Oe	500 Oe/in	Random - horizontal field	Up to two months	Slowed skin wound healing due to marked delays in fibroblast proliferation and fibrosis.	65

TABLE 1 (continued)

EXPOSURE OF BIOLOGICAL SYSTEMS TO HIGH MAGNETIC FIELDS

EFFECTS STUDIED	BIOLOGICAL SYSTEM	FIELD STRENGTH	FIELD GRADIENT	FIELD DIRECTION	DURATION OF EXPOSURE	EFFECTS OBSERVED	REF.
Pregnancy	Mouse (mated in magnetic field)	2,500 Oe	Homogeneous	Random - vertical field	Duration of pregnancy (20 days)	All mice became pregnant, but either fetus re-absorption, stillbirths, or weak litters which died within 1 to 2 days.	12
Pregnancy	Mouse (pregnant)	4,200 Oe	Homogeneous	Random - vertical field	Duration of pregnancy	Fetus re-absorbed if placed in field before tenth gestational day; homogeneous vertical field of 8,000 Oe exposure after eighteenth gestational day had no effect.	12
Pregnancy	Mouse (pregnant)	4,200 Oe	Homogeneous	Random - vertical field	From fifteenth day of, to end of pregnancy	Smaller litters and stunting of offspring which carried on to successive generations.	12
Tumor growth	T2146 adeno-carcinoma in mouse	3,000 Oe	600 Oe/cm	Random - vertical field	From 5 days after tumor implant	Sudden rejection of tumor in 5 of 6 animals studied.	9
Tumor growth	C4461 pulmonary adeno-carcinoma in mouse	4,000 Oe	200 Oe/cm	Random - horizontal field	From time of tumor implant	No apparent effect.	64

TABLE 1 (continued)

EXPOSURE OF BIOLOGICAL SYSTEMS TO HIGH MAGNETIC FIELDS

EFFECTS STUDIED	BIOLOGICAL SYSTEM	FIELD STRENGTH	FIELD GRADIENT	FIELD DIRECTION	DURATION OF EXPOSURE	EFFECTS OBSERVED	REF.
Tumor growth (effect of magnetic pretreatment)	dbrB mammary adenocarcinoma, sarcoma I, H2712 mammary adenocarcinoma, C4461 pulmonary adenocarcinoma, L1210S lymphoid leukemia and Erlich's ascites adenocarcinoma in mouse	4,000 Oe	200 Oe/cm	Random - horizontal field	30-day pre-treatment; tumors injected 7 to 10 days after exposure	Lengthened survival time of dbrB mammary adenocarcinoma-bearing mice only.	64
Tumor growth	C3HBA and H2712 mammary gland carcinomas in mouse	4,200 Oe	50 Oe/cm	Random - vertical field	From time of tumor implant	Lengthened lifespan of tumor-bearing mice by 44%; no metastatic spread.	9
Tumor growth	Erlich's ascites adenocarcinoma in mouse	Between 13,500 14,400 Oe	400 Oe/cm near ends of magnet core	Random - horizontal field	From time of tumor implant	No apparent effect.	53
Cell culture growth	12 genera of bacteria, 4 genera of yeasts, and 4 genera of molds	3,000 Oe	Homogeneous	Random	48 hours	No effect on size or morphology of colony, size and shape of individual cells, cellular reaction to Gram's stain, or cellular pigment or spore production.	78

TABLE 1 (continued)

EXPOSURE OF BIOLOGICAL SYSTEMS TO HIGH MAGNETIC FIELDS

EFFECTS STUDIED	BIOLOGICAL SYSTEM	FIELD STRENGTH	FIELD GRADIENT	FIELD DIRECTION	DURATION OF EXPOSURE	EFFECTS OBSERVED	REF.
Cell culture growth	Escherichia coli and Staphylococcus aureus	3,000 Oe	- - -	Random	48 hours	No apparent effect.	92
Cell culture growth	Staphylococcus aureus, Sarcina lutea and Escherichia	14,000 Oe	Homogeneous	Random	24 hours	Only growth rate of Staphylococcus aureus affected, being decreased beyond the sixteenth hour (didn't occur if culture taken out of field hourly for 3 seconds).	76
Cell culture growth	Escherichia coli	4,250 Oe	1,750 Oe/cm	Random	9 hours	No apparent effect.	76
Cell culture growth	Serratia marcescens	15,000 Oe	2,300 Oe/cm	Random	10 hours	Decreased growth rate from 8 to 10 hours, but control growth cell number recovered by 10 hours.	59
Cell culture growth	Staphylococcus aureus	15,000 Oe	5,200 Oe/cm	Random	10 hours	Increased growth rate from 3 to 6 hours; growth inhibition from 7 to 9 hours, the control growth cell number being recovered by 9 hours.	59
Cell culture growth	Chick heart fibroblasts	200 to 490 Oe	- - -	Random	68 hours	Stimulated growth by 26%.	115
Cell culture growth	Chick heart cell culture	1,000 Oe	- - -	Random	- - - - - - - - - -	Growth retardation; presence of abnormal giant cells.	91
Cell culture growth	Embryonic heart tissue	5,000 Oe	- - -	Random	3 to 6 hours	No effect.	114

TABLE 1 (continued)

EXPOSURE OF BIOLOGICAL SYSTEMS TO HIGH MAGNETIC FIELDS

EFFECTS STUDIED	BIOLOGICAL SYSTEM	FIELD STRENGTH	FIELD GRADIENT	FIELD DIRECTION	DURATION OF EXPOSURE	EFFECTS OBSERVED	REF.
Cell culture growth	Mouse lung fibroblast cells	7,000 Oe	- - -	Random	- - - - - - - - - -	Growth retardation.	118
Cell culture growth	Guinea pig macrophages	2,000 to 8,000 Oe	Homogeneous	Random	4 hours	Increased number of viable cells, especially around 4,000 Oe.	141
Cell culture growth	Rabbit myocardium	14,600 Oe	5,000 Oe/cm	Random	3 to 7 days	Growth enhancement.	118
Cell culture growth	HeLa, KB, WI-38, Chinese hamster and chick embryo cells	400 Oe	20 Oe/cm	Random	4 days	No effect on growth.	71
Cell culture growth	KB cells	4,000 Oe	Homogeneous	Random	3 days	Decreased growth rate.	40
Cell culture growth	HeLa cells	5,000 Oe	Homogeneous	Random	10 days	No apparent effect.	69
		27,000 Oe	Homogeneous	Random	10 days	No apparent effect.	
		77,000 Oe	Homogeneous	Random	10 days	No apparent effect.	
Cell culture growth	KB, Chang's liver and sarcoma-180 cells	12,000 Oe	Homogeneous	Random	3 and 4 days	No apparent effect.	107

TABLE 1 (continued)

EXPOSURE OF BIOLOGICAL SYSTEMS TO HIGH MAGNETIC FIELDS

EFFECTS STUDIED	BIOLOGICAL SYSTEM	FIELD STRENGTH	FIELD GRADIENT	FIELD DIRECTION	DURATION OF EXPOSURE	EFFECTS OBSERVED	REF.
Cell culture growth	Mouse sarcoma-37 ascites tumor cells	4,400 to 8,800 Oe	Up to 1,000 Oe/cm	Random	18 hours	Some degeneration of cells.	108
	Mouse sarcoma-37 solid tumor cells	4,400 to 8,800 Oe	Up to 1,000 Oe/cm	Random	18 hours	No effect.	
Cell culture oxygen uptake	Embryo and adult mouse kidney, mouse ascites sarcoma-37 cells and yeast	40 to 10,000 Oe	Homogeneous	Random	10 minutes on, 10 minutes off	Oxygen uptakes of embryo kidney decreased 27 per cent above 85 Oe, adult kidney unaffected, sarcoma-37 decreased 28 per cent above 80 Oe and yeast increased 40 per cent above 85 Oe; changes prompt and reversible; no further depression or stimulation of respiration above these field levels; continuous exposure for 3 to 4 hours yielded similar results.	116, 123
Cell culture oxygen uptake	Guinea pig kidney	2,900 Oe	1,040 Oe/cm	Random	42 hours	No apparent effect.	102
Cell culture oxygen uptake	Chlorella pyrenoidosa	100,000 Oe	- - -	Random	17 to 25 minutes	No apparent effect.	73
Cell culture oxygen production (photosynthesis)	Chlorella pyrenoidosa	10,000 Oe	- - -	Random	40 minutes	No apparent effect.	73

TABLE 1 (continued)

EXPOSURE OF BIOLOGICAL SYSTEMS TO HIGH MAGNETIC FIELDS

EFFECTS STUDIED	BIOLOGICAL SYSTEM	FIELD STRENGTH	FIELD GRADIENT	FIELD DIRECTION	DURATION OF EXPOSURE	EFFECTS OBSERVED	REF.
Cell division	Sea urchin	70,000 to 140,000 Oe	Homogeneous to 4,500 Oe/cm	Random	From time of fertilization	Over 100,000 Oe, division retarded regardless of gradient; between 80,000 and 100,000 Oe, division delay more pronounced in high gradient fields; below 80,000 Oe, delay related more directly to gradient than field strength; about 70,000 Oe and a gradient of 4,200 Oe/cm, effect on cell division negligible; mitotic apparatus appeared unaffected in this study.	121
Cell division	Sea urchin	100,000 to 140,000 Oe	Homogeneous and inhomogeneous	Random	From time of fertilization	Early cleavage retarded.	26
Genetic effects	Drosophila melanogaster	6,000 Oe	Homogeneous	Random	60 minutes (newly hatched eggs)	No change in hatching ratio or time necessary for eggs to develop into flies; enhanced mortality when 165 r x-irradiation given with magnetic exposure.	54
Genetic effects	Drosophila melanogaster	100 to 4,400 Oe	- - -	Random	From one to three generations	Frequency of deformities increased above 3,000 Oe.	108
Genetic effects	Drosophila melanogaster	10,000 Oe	Homogeneous	Random	30 minutes (adult fly)	No subsequent effects.	26, 45
		100,000 Oe	Homogeneous	Random	2 hours (adult fly)	No subsequent effects.	
		18,000, 21,000 and 22,000 Oe	Homogeneous	Random	From egg to newly-hatched fly	No apparent effect.	
		11,000 Oe	1,500 Oe/cm	Random	From egg to newly-hatched fly	No apparent effect.	

TABLE 1 (continued)

EXPOSURE OF BIOLOGICAL SYSTEMS TO HIGH MAGNETIC FIELDS

EFFECTS STUDIED	BIOLOGICAL SYSTEM	FIELD STRENGTH	FIELD GRADIENT	FIELD DIRECTION	DURATION OF EXPOSURE	EFFECTS OBSERVED	REF.
Genetic effects	Drosophila melanogaster	Several thousand Oe	Several hundred Oe/cm	Random	24 hours - eggs	Induced visible wing and lethal mutations.	44
Genetic effects	Tribolium confusum eggs	3,600 Oe	Homogeneous	Random	7 days after irradiation	Decreased induction of wing abnormality by 1,200 r, 250 Kvp x-rays; most effective where synergism between temperature and x-ray.	4
Genetic effects	Mouse (70-day female)	4,200 Oe	Homogeneous	Random	4 weeks	Decreased incidence of mammary gland carcinoma.	14
Enzyme activity	Succinic dehydrogenase, glutamic dehydrogenase, lactic dehydrogenase and glucose-6-phosphate dehydrogenase in liver of exposed mouse	5,000 Oe	500 Oe/cm	Random	24 and 72 hours	As noted by histochemical techniques, increase in succinic dehydrogenase, malic dehydrogenase and glutamic dehydrogenase; other enzymes unaffected.	129
Enzyme activity	Trypsin *in vitro*	8,000 Oe	220 Oe/cm	Random	up to 3 hours	5 to 23% activating effect on enzyme during first two hours, leveling off during third hour.	47
Enzyme activity	Trypsin and chymotrypsin *in vitro*	13,000 Oe	Homogeneous	Random	up to 4 hours	Activating effect on trypsin at pH3, inactivating effect at pH8; activating effect on chymotrypsin.	132

TABLE 1 (continued)

EXPOSURE OF BIOLOGICAL SYSTEMS TO HIGH MAGNETIC FIELDS

EFFECTS STUDIED	BIOLOGICAL SYSTEM	FIELD STRENGTH	FIELD GRADIENT	FIELD DIRECTION	DURATION OF EXPOSURE	EFFECTS OBSERVED	REF.
Enzyme activity	Carboxy-dimutase in vitro	20,000 Oe	Homogeneous	Random	6 days	14 to 20% activating effect on enzyme.	1
Enzyme activity	Ribonuclease and succinate-cytochrome c reductase in vitro	0 to 48,000 Oe	Homogeneous	Random	5 and 6 minutes	No effect.	103
Enzyme activity	Ribonuclease, polyphenol oxidase, peroxidase and aldolase in vitro	up to 170,000 Oe	Homogeneous	Random	up to 20 min	No effect.	119
Enzyme reactivation	Trypsin inhibited by egg white	5,000 Oe	Homogeneous	Random	17 hours	Partial reactivation at pH 3.0.	146
Enzyme reactivation	Partially inhibited trypsin by ultraviolet	5,000 Oe	Homogeneous	Random	up to 18 hours	Reactivation.	47
Chromatographic migration rate	Catalase, cytochrome C and hemoglobin	1,220 Oe	Homogeneous	- -	- - - - - - - - - -	No apparent effect.	107

TABLE 1 (continued)

EXPOSURE OF BIOLOGICAL SYSTEMS TO HIGH MAGNETIC FIELDS

EFFECTS STUDIED	BIOLOGICAL SYSTEM	FIELD STRENGTH	FIELD GRADIENT	FIELD DIRECTION	DURATION OF EXPOSURE	EFFECTS OBSERVED	REF.
Response of isolated denervated heart	Turtle heart preparation	3,400 to 15,600 Oe	Homogeneous	Side-to-side	- - - - - - - - - -	Potential spikes, indicating abrupt depolarization, appeared at varying time intervals after exposure onset and either continued indefinitely or disappeared shortly after exposure cessation; amplitude and frequency of spikes were irregular but correlated roughly with field strength; complete recovery of baseline electrical cardiac activity seldom occurred after exposure cessation; decrease of contraction amplitude and incomplete relaxation during diastole appeared at varying time intervals after exposure onset.	122
Response of isolated vagal heart	Frog heart preparation	4,000 Oe 15,000 Oe	830 Oe 3,700 Oe	Side-to-side Side-to-side	- - - - - - - - - - - - - - - - - - - -	Increased rate of acetylcholine hydrolysis, as noted by a consistent decrease in duration of vagal inhibition and proven with deuterated acetylcholine; contractility unaltered after 10-minute exposure to lower field, diminished within one minute-exposure to higher field; delayed onset of arrhythmic contractions after ceasing higher field exposure, these contractions lasting for up to several days after exposure; rate of acetylcholine hydrolysis and myocardial contractility recovered over periods of up to several hours after exposure cessation.	148

TABLE 1 (continued)

EXPOSURE OF BIOLOGICAL SYSTEMS TO HIGH MAGNETIC FIELDS

EFFECTS STUDIED	BIOLOGICAL SYSTEM	FIELD STRENGTH	FIELD GRADIENT	FIELD DIRECTION	DURATION OF EXPOSURE	EFFECTS OBSERVED	REF.
Transmembrane sodium transport	Frog skin	250 to 650 Oe	Homogeneous	Across skin	- - - - - - - - - -	Reduction of sodium influx and efflux by 10 to 30 per cent within one second of applying field; ouabain prevented this effect.	37
Transmembrane sodium transport	Frog skin	Up to 10,000 Oe	- - -	Across skin	- - - - - - - - - -	Reduction of skin polarization at thresholds between 800 to 8,000 Oe (mode 5,000 gauss); effect disappears by blocking sodium pump with asphyxiation, cyanide and ouabain.	67
Transmembrane sodium transport	Frog skin	3,500 Oe	- - -	- - -	- - - - - - - - - -	No apparent effect.	107
Urinary electrolyte excretion	Mouse	14,000 Oe	Homogeneous	Random - horizontal field	5 days	Significant increase in sodium and potassium excretion; calcium excretion unchanged.	74
Estrus cycle	Mouse	4,200 Oe	Homogeneous	Random - vertical field	2 weeks	Estrus cycle "disappeared".	6
Red blood cell agglutination	Human red cells with type specific antisera	20 to 50,000 Oe 16,000 Oe	"Moderately Homogeneous" 1,500 Oe/cm	Random Random	5 minutes to 2 hours	Enhanced agglutination for D-positive genotypes against Anti-D serum; same for C and E systems; no enhancement for A, B, and O, and M and N systems; no further enhancement in inhomogeneous field.	68
Orientation of red blood cells	Sickled erythrocytes	3,500 Oe	Homogeneous	Random	- - - - - - - - - -	Sickled erythrocytes oriented perpendicular to long axis of field.	109

TABLE 1 (continued)

EXPOSURE OF BIOLOGICAL SYSTEMS TO HIGH MAGNETIC FIELDS

EFFECTS STUDIED	BIOLOGICAL SYSTEM	FIELD STRENGTH	FIELD DIRECTION	FIELD DIRECTION	DURATION OF EXPOSURE	EFFECTS OBSERVED	REF.
Survival	Mouse	43,000 Oe	Homogeneous	Random - horizontal field	1 hour	Survived.	
		100,000 Oe	Homogeneous	Random - horizontal field	2 hours	Survived.	21, 22, 30
		120,000 Oe	Homogeneous	Random - horizontal field	1 hour	Survived.	

definite effects of magnetic fields, especially on sub-mammalian systems. Finally, so vital for assessing magnetic field effects, the strength, gradient and directional characteristics of fields used in experiments have often not been cited by biomagnetic investigators.

In his search for data on human exposures to magnetic fields, Beischer asked a number of nuclear physics laboratories to comment on the experiences of their personnel who enter high-intensity fields in their work [21]. Such random observations, summarized in Table 1, are to date apparently the only specifically useful information for judging whether or not possible magnetic fields in space could affect astronaut health or performance. From the results of his survey, Beischer concluded that "magnetic fields up to 20,000 oersteds can be tolerated by man without sensation in part- or total-body exposure for short periods of time, and that there seems to be no effect of cumulative exposure to fields of 5000 oersteds for a total of three days per year per man". The need to undertake careful physiological and psychological testing of subjects during and after exposure to simulated space magnetic field conditions was emphasized.

Not presented in Table 1, but considered important to take into consideration here, are observations made on the human population during its exposure to changes in the Earth's magnetic field intensity [19, 57, 58]. The question must again arise as to whether the Earth's magnetic field has, during the evolution of man and other organisms, become an environmental factor to which physiological processes are adjusted. This field undergoes rhythmic circadian (about 24 hours) and longer-period (approximately one lunar month) variations in intensity. Moreover, there are random fluctuations, or magnetic storms, of larger magnitude and more rapid rate of change than the rhythmic variations produced by solar flare activity. The fact that living organisms demonstrate cyclic phenomena with periods closely approximating the major geophysical cycles (circadian and lunar month), even in the total absence of environmental cues such as light, temperature and barometric pressure, suggests that biological rhythms may be dependent for their timing on these subtle

rhythmic changes in the Earth's magnetic field intensity. Becker [19] pointed out that the cyclic behavior of organisms can be viewed as a rhythmic variation in their level of irritability. Accordingly, he postulated that a magnetic storm might produce a demonstrable variation in level of irritability, possibly through a galvanomagnetic effect, as magnetic fields interact with electric current flow in the brain stem [19]. Two studies with his co-workers have demonstrated a highly significant relationship between the average daily magnetic field variations and the incidence of psychiatric hospital admissions for treatment of schizophrenia [57, 58]. Becker pointed out that the Earth's magnetic field is subject to continuous pulsations of low magnitude, with frequencies ranging from 0.1 to 100 cycles per second [19]. Since the majority of these pulsations center around 8 to 16 cycles per second, he has suggested that they might have had some influence on the average frequencies of the human electroencephalographic pattern. This may, of course, be a fortuitous finding. Finally, he went on to demonstrate in animal experiments that application of magnetic fields of over 2500 oersteds in intensity perpendicular to the brain stem could reduce consciousness and alter the electroencephalographic pattern to one ressembling moderate to deep anesthesia, presumably due to a diversion of current flow in the brain by the field. This finding compares to that of the Russian biomagnetic researcher, Kholodov [82], who exposed squirrels to high magnetic fields. Taking this and other observations noted above into account, Becker [19] predicted that alterations in biological cycles, levels of consciousness, and efficiency in performing complex tasks will be discernable in astronauts exposed to magnetic fields much different to that on Earth, especially if such fields are of high intensity and pulsating at a low frequency. Since schizophrenics are known to have a functionally more labile nervous system, he suggests that due to possible variations in sensitivities of otherwise normal individuals to the neurological effects of magnetic fields, there might be some variability of space crew responsiveness to the magnetic fields to which they might be exposed in space [20]. Becker's postulates, which have been supported in the Russian literature [144], remain to be proven by experiment.

It should be mentioned here that under certain conditions, man can sense the presence of a magnetic field. As Alexander [2] pointed out in his review of this area, phosphenes, or flashes of light may be seen when the head is placed in a fluctuating magnetic field. This phenomenon should not occur if an astronaut and a static magnetic field are in a stable relationship to each other. However, if an astronaut moves in the field, it is conceivable that he might experience phosphenes. Also of interest is the fact that in a number of carefully controlled experiments, Rocard [124] has found evidence that the reflex of the dowser is started by movement through an anomaly in the Earth's magnetic field. He attributes this reflex to unexplained alterations in muscle tone. It was reported that dowsers can sense field changes of from 0.3 to 0.5 millioersteds per meter or 0.3 millioersteds per second, can have the response if many small anomalies are present within a few meters distance, and can be "saturated" if the rate of field increase is constant. He also demonstrated that most individuals are sensitive to these magnetic field changes once they learn how to hold a divining rod. Whether such a phenomenon could actually occur and possibly affect the performance of a highly skilled manual task by an astronaut exposed to a magnetic field in space is conjectural.

In biomagnetic studies with mammals, the enormous hardware and power requirements for producing high magnetic field intensities in cages of adequate size, and with adequate ventilation, lighting and temperature control, have made the mouse the popular experimental subject. Hence, in most experiments using larger animals, the entire body or part of the body has had to be held fixed in the field, so limiting the duration of exposure. As noted above, the latter type of experiment is not considered to simulate possible exposures of astronauts to magnetic fields in space, unless an astronaut is sleeping during his exposure to a magnetic field. It should be noted, however, that the advent of superconducting coils will make exposure of larger, unrestrained animals and even man to high-intensity magnetic fields possible.

The pertinent data from mammalian experiments summarized in Table 1

brings out several points for discussion. Although recordings of motor activity, food consumption and appearance indicated that the mouse is unaffected by several weeks' exposure to vertical, homogeneous magnetic fields in the range of 4000 oersteds [5], autopsy studies showed that the mouse could experience liver damage, bone marrow suppression and alterations of adrenal cortical structure during such an exposure [134, 135]. Since the adrenal glands were unaltered in mice exposed to horizontal fields of up to 13,500 oersteds in strength with a gradient of 400 oersteds per centimeter [53], it has been considered possible that the directional nature of a magnetic field exposure may be a factor causing adrenal and other reported biomagnetic effects [11]. J. M. Barnothy [8] has postulated that a change in the direction of the field or gradient vector relative to the co-ordinate system of the exposed system, be it an organ, cell or molecule, should entail a change in the direction, or a reversal in the sign of the physical effect, which is the precursor of the biological effect. Therefore, to determine the role played by magnetic field direction in producing biomagnetic effects, experiments in which the vector direction of the field (or gradient) is periodically changed relative to the exposed specimen appear indicated.

It is indeed remarkable that when squirrel monkeys were fixed in position in a highly inhomogeneous, 70,000 oersted magnetic field for 3 hours, or in a homogeneous, 100,000 oersted field for 24 hours, respiratory rate was unaltered and only a small decrease in heart rate and increase in sinus arrhythmia occurred [29, 30, 31, 33]. This should not lead to the assumption that psychomotor task performance would not be affected in such a field, however. In similar experiments, marked changes in brain electrical activity, characterized by increases in prevailing frequencies and voltage, were recorded [32, 86]. Above a 60,000 oersted homogeneous field level, the monkeys stopped punching a lever for food [29, 33]. An effect on the electroencephalographic trace of a rabbit, thought due to either a synchronization or enhancement of neuronal activity, has been produced by fields as low as 800 oersteds in intensity [81, 85]. The enhancement concept appears to be supported by the finding that a direct current shift in the brain of a pigeon occurred at a rather sharp threshold

of 100 to 300 oersteds [66]. It is interesting to note that an electroencephalographic picture typical of deep anesthesia, and apparently associated with immobilization of the exposed "animal", was produced by a 2500 oersted field [19]. Since this field was directed at right angles to the brain stem, the orientation of the brain in a magnetic field, as well as the strength and gradient characteristics of the field, may play a vital role in determining the effect of a magnetic field on the brain. Finally, there is the evidence from experiments with rabbits, cats, and rats, that the application of magnetic fields as low as 200 oersteds in intensity to their heads can produce reversible glial changes within one hour, and for more prolonged exposures, permanently damage both glial and neural brain cells [83, 84, 85]. The remarkable sensitivity of glial cells to magnetic fields may be due to their high metabolic activity necessary for their function in transferring metabolites to and from nerve cells [85, 102]. Hence, from magnetic field effects observed on brain electrical activity and structure to date, it is apparent that close attention must be given to determining whether magnetic fields to which an astronaut might be exposed in space could affect neurological functioning. The importance of simulating possible exposure situations, especially with head fixation to represent sleep periods, is emphasized. Since brain damage has been produced in animals with fields as low as those which could be used in space, it will be necessary to carry out intensive animal experimentation, especially with primates trained in task performance, before exposing man to such fields.

The biphasic blood leucocyte decrease observed in mice exposed to a vertical, homogeneous, 4200 oersted magnetic field has been attributed to an initial lifespan shortening of circulating granulocytic and lymphocytic leucocytes, followed by a stimulation of maturation and release of these elements from their sites of manufacture, and finally by inhibition of leucocyte production, especially of lymphocytic leucocytes [15]. Relevant to the possibility that the directional nature of the magnetic field may be a factor in causing biomagnetic effects is the finding that this leucocyte response was not observed in mice exposed to horizontal magnetic fields [53]. It does not appear that the vertical magnetic fields produced a general bone

marrow suppression, for the red blood cell count actually increased in mice exposed to a vertical field of 13,000 oersteds in strength with a gradient of 450 oersteds per centimeter [11]. Whether suppression of leucocyte activity by a magnetic field could alter susceptibility to infection remains to be determined. The observation that a 4000 oersted horizontal, homogeneous magnetic field altered antibody production in a mouse injected with sheep red blood cells [61] may reflect impaired lymphocytic leucocyte activity. It is interesting to note that after removing the mouse from a magnetic field, the temporary overproduction of leucocytes was sufficient to confer some protection from the lethal effects of total body irradiation which would, at the radiation dosage used, have caused death by suppressing leucocyte manufacture [13, 16]. Finally, another magnetically-induced alteration of a blood parameter observed is the increase in blood coagulation time observed in mice exposed to a vertical field of 13,000 oersteds in strength with a gradient of 450 oersteds per centimeter [11]. Whether this is caused by platelet suppression, diminished prothrombin production due to liver damage, a release of heparin by stimulated mast cells, a depletion of fibrinogen due to microvascular clotting or some other factor remains to be determined experimentally. The above findings again emphasize the need for intensive physiological studies on animals exposed to magnetic fields which might be used in space, before exposing man, experimentally or operationally, to such fields.

Studies of the effects of magnetic fields on a great variety of growing entities was initially stimulated by the observation that the argyrophil fiber system of a chick heart tissue culture exposed to a magnetic field was retarded in development [91]. This fiber system was thought to be the path along which tumor cells migrated from malignant tissues into healthy tissues [9]. Since exposure of mice to several thousand oersteds had an inhibitory effect on pregnancy [12], body growth rate [8] and fibroblast proliferation in healing tissue [65], mitosis was also thought to be retarded by magnetic fields [9]. Accordingly, it was postulated that magnetic field treatment of tumor-bearing animals would diminish both

tumor growth and spread, while at the same time would not be harmful to healthy tissues [9]. This seemed supported by observations that certain tumors injected into mice exposed to vertical homogeneous and heterogeneous magnetic fields were either rejected [9] or obviously limited in spread, so lengthening survival time [9, 64]. On the other hand, horizontal fields of similar intensities failed to alter growth of any one of a variety of tumors injected into mice [53, 64]. This again suggests that the directional nature of a magnetic field exposure may be an important factor in determining biomagnetic effects.

Various cell cultures exposed to magnetic fields have increased [115, 118, 141], unaltered [60, 69, 71, 73, 78, 92, 106, 107, 108, 114] or decreased [40, 59, 76, 91, 118] their growth rates. Such has also been the case in various studies of cell culture oxygen uptake [106, 116, 123]. Pertinent to the possible use of algae for life support during prolonged space missions is the observation that oxygen uptake (in the dark) and oxygen production (photosynthesis) of algae were unaltered during brief exposure to a 10,000 oersted field [73]. Divergent results in cell culture studies cannot be explained on the basis of field strength or gradient used, or the type of cell exposed. Only in one cell growth experiment, in which division of sea urchin eggs was retarded by various fields above 70,000 oersteds, have field strength and gradient been related to the degree of biomagnetic effect observed [26, 121]. However, whether this relationship was primarily due to a direct effect on cell structure or to an alteration of dissolved gas concentrations around the eggs by the magnetic field remains to be determined [121]. Other studies of biomagnetic effects on growth [4, 14, 26, 44, 54, 108] have indicated that prolonged magnetic field exposures can increase the mutation rate of Drosophila [44, 108], counteract radiation-induced mutations in Tribolium [4] and decrease the incidence of mammary gland carcinoma in the mouse [14]. These and other experiments mentioned above emphasize the need for further study of magnetic effects on body tissues, especially the mitotically-active tissues of adult animals exposed for prolonged periods of time to magnetic fields which might be used in space.

The effect of magnetic fields on enzyme activity has been studied by

several investigators [1, 47, 103, 119, 129 132, 146]. In livers of mice exposed for 24 and 72 hours to a field of 5000 oersteds with a gradient of 500 oersteds per centimeter, the activity of certain metabolic enzymes located in mitochondria was found to increase whereas the activity of those in the cytoplasm remained unaltered [129]. It was postulated that the magnetic field altered mitochondrial membrane permeability rather than affecting the enzymes directly. The resulting impairment of metabolic processes might then account for the observed decrease of oxygen uptake by various tissue cultures in a magnetic field [116, 123], the decrease of body temperature of mice exposed to magnetic fields for prolonged periods of time [127], and the delay of body temperature restoration of a hypothermic mouse by a magnetic field [128]. It is considered possible that these findings might be due to alterations of active transmembrane transport mechanisms. The impairment of electrolyte transport across a frog skin placed in a magnetic field [37, 67] may also explain the increased urinary sodium and potassium excretion of a mouse placed in a magnetic field [74] and the abnormal electrical activity which slowly began with and disappeared after an isolated, denervated, turtle heart preparation was exposed to a magnetic field [122]. On the other hand, in support of a direct effect of magnetic fields on enzymes are reports that a variety of enzymes in vitro have been activated by magnetic fields [1, 47, 132, 146], and that increased acetylcholine hydrolysis, possibly due to acetylcholinesterase activation, occurred in an isolated, vagal frog heart preparation exposed to a magnetic field [148]. It is apparent that interactions of biological systems and magnetic fields at the biochemical level, especially in intact organisms exposed to magnetic fields which might be used in space, have only begun to be investigated.

Finally, the results of a few other diversified biomagnetic studies listed in Table 1 deserve comment here. One wonders whether the disappearance of the estrus cycle in mice exposed to a vertical, homogeneous, 14, 200 oersted magnetic field may be related to adrenal gland structural, and no doubt functional changes noted previously [6]. It is interesting that

the chromatographic migration rate of catalase, cytochrome C and hemoglobin, which are thought to be paramagnetic biomolecules, was unaltered by a homogeneous magnetic field of 1220 oersteds [107]. Reports that magnetic fields enhanced red blood cell agglutination [68] and oriented sickled erythrocytes [109] have led investigators to speculate that the form of hemoglobin in red blood cells may possess remarkable paramagnetic properties [109, 113]. The last experiment recorded points out that mice survive exposures to 100,000 and 120,000 oersted fields for 2 and 1 hour durations, respectively [21, 22, 30]. This experiment, as well as a recent one in which two squirrel monkeys were exposed to a homogeneous, 100,000 oersted field for 24 hours [29, 33], serves to demonstrate not only the remarkable tolerance of the mammal to magnetic fields but also, as repeatedly pointed out above, the need to simulate possible magnetic field exposures which might face astronauts in space.

Biomagnetic investigators have advanced numerous theories in attempting to explain and predict effects of magnetic fields on biological systems. It is important to note, however, that to date no one theory has been supported by concrete empirical evidence. As well, the possibility exists that many of the effects of magnetic fields observed, especially in experiments in which the exposed biological entity is moving in relation to the field, may be attributable to electromagnetic rather than pure magnetic phenomena [126].

On a physiological basis, J. M. Barnothy [11] has suggested that many of the reported biological effects of magnetic fields on mice may be due to an excessive stimulation of adrenal cortical activity, probably by adrenocorticotrophic hormone (ACTH) released in excess from the pituitary gland. The major piece of evidence for this "physiological stress" type of reaction is considered to be the lipid depletion and atrophy of the zona fasciculata of adrenals in mice exposed to magnetic fields [134, 135]. Accordingly, Barnothy has pointed out that elevated blood corticosteroid levels may be directly responsible for a number of other phenomena observed in mice exposed to magnetic fields [11], such as retardation of body growth [8, 12] and wound healing [65], diminished antibody formation [61],

depression of the leucocyte count [13, 15], and rejection and limitation of spread of transplanted tumors [9, 64]. There was no basic mechanism proposed for this possible reaction to magnetic fields. However, as repeatedly pointed out above, it is possible that the unidirectional nature of a magnetic field exposure may play a causative role, for many changes observed in mice exposed to vertical magnetic fields have not been seen in mice exposed to horizontal magnetic fields. Therefore studies of adrenal function should be carried out on animals exposed to horizontal fields and vertical fields which remain both unidirectional and periodically reverse polarity.

Other theoretical discussions of biomagnetic effects have centered on postulating possible interactions of magnetic fields and biological systems at molecular and sub-molecular levels. Some theories have been mentioned above; others deserve mentioning here, if only to acquaint the reader with this highly complex area and provide references.

Many investigators have stated that biomagnetic effects from interactions of magnetic fields with paramagnetic molecules, or molecules with unpaired electrons, are unlikely to occur, since at the field strengths used in past experiments, magnetic ordering energies were extremely small as compared to normal thermal disordering energies [10, 23, 25, 26, 61, 120, 139]. It has been pointed out, however, that biological actions are frequently rate dependent, where small changes in energy may be important [40, 107]. As well, associated molecules are known to exist in biological systems, and especially if in the liquid-crystalline, or mesomorphic state, would be more likely to be oriented by magnetic fields than unassociated molecules [68, 87, 107]. In line with this reasoning, Gross [61, 62] has suggested that by distorting bond angles of paramagnetic molecules, magnetic fields can alter the closeness of fit between enzymes and substrates, and so reduce the rates of synthesis of large molecules. He noted that since thermal molecular agitation would tend to erase the orienting effect of a magnetic field on these molecules, larger molecular aggregations would be most susceptible to magnetic field effects. Valentinuzzi [139, 140] stated that Brownian rotation, or rotational diffusion, may be important with respect to chemically effective collisions

when the molecules involved possess specific reactive sites. Thus it was thought that magnetic fields could decrease biochemical reaction rates, and so biological growth, by slowing or stopping rotation, especially of paramagnetic, free-radical intermediates [24]. Reno [121] postulated that gases might migrate differentially in a magnetic field - paramagnetic oxygen towards the geometrical center of a field, and nitrogen, which is diamagnetic and hence contains no unpaired electrons, away from the field center. It has also been suggested that certain biological macromolecules, such as catalase, cytochrome C, myoglobin, hemoglobin, and cyanocobalomine might be expected to exhibit paramagnetic effects by virtue of the transition-metal ions complexed in their structure [107].

Deaver and co-workers [49], and others [139] have been concerned with the role of diamagnetic organic molecules in the interaction of biological systems with magnetic fields. Diamagnetism is exhibited by all biological materials, and simply results from changes in the orbits of electrons when a magnetic field is applied. These orbital changes produce small magnetic fields which oppose the applied field. Although for many molecules the diamagnetism of the entire molecule is simply the sum of the diamagnetic atomic components, greater diamagnetism can occur under certain circumstances, because of the motion of delocalized π, or outer atomic orbiting electrons, in larger orbits throughout the entire molecule. This could conceivably result in anomalous behavior of large molecules in biochemical reactions.

Biomagnetic effects have frequently been attributed to alterations of ion movement by magnetic fields. The forces involved have been outlined by Neurath [113]. Gualtierotti [66] and many others [30, 37, 93, 94, 100, 101, 120, 122, 129] have focused their attention on possible magnetic effects on ion transport across cell membranes, citing experimental evidence to support their hypotheses. Ambrose and co-workers [3] pointed out that consistent with the electro-osmotic theory of protoplasmic movements, it should be possible to affect protoplasmic movements, active transport, and mitosis with strong magnetic fields, since these fields will distort the ionic currents associated with such cellular activity.

Possible magnetic effects on the genetic apparatus of cells have been discussed by a few investigators. M. F. Barnothy [14, 17] suggested that a magnetic field might alter the occurrence of spontaneous mutations by affecting the rate of shift of proton positions (proton tunnelling) in desoxyribonucleic acid (DNA) molecules. Reno [121] has postulated that the rotational unwinding of the double DNA helix prior to mitosis might be retarded by a magnetic field. Butler and Dean [40] have speculated that if some type of intracellular magnetic arrangement is important in chromosome division and attraction to centrosomes, an externally-applied magnetic field might be expected to disturb this control.

Finally, two other theories also deserve mention here. Ragle [120] and Belousova [35] have pointed out that since blood is a conductive fluid, eddy currents will be induced in blood flowing in a direction perpendicular to a constant magnetic field. These currents will slow blood flow. The possible pathophysiological significance of this phenomenon was not speculated, however. Smith and Cook [1, 47] have attributed the activation of various enzymes by magnetic fields in their experiments to an increase in hydrogen bonding and consequently in helicity of the polypeptide backbone of the enzyme. This was presumed to stabilize an enzyme against denaturation, so that after prolonged exposure to a magnetic field, it would not have denatured as fast as an unexposed enzyme.

In conclusion, one can say that from past experience with personnel who enter high-intensity magnetic fields for brief periods of time in their work, magnetic field exposures while servicing magnetohydrodynamic engines should not be hazardous to astronauts. On the other hand, it is readily apparent from the above discussion that past exposures of man and sub-human systems to high-intensity magnetic fields do not indicate whether astronauts exposed for up to several days to currently estimated magnetic field intensities associated with pure magnetic or plasma radiation shielding could suffer impairment of their health or performance. This answer can only be obtained by carefully conducted experiments which closely simulate such exposures, and look closely for physiological, psychological and pathological changes, especially in exposed high primates, before assessing the response of man to such exposures.

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