# SPACE BIOMAGNETICS*

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**Abstract.** Astronauts who venture from their spacecraft onto 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 while inside their spacecraft 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 if an activated magnetohydrodynamic engine must be serviced, to several days if pure magnetic or plasma-radiation shielding is used for astronaut protection 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 or not astronauts who are 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.

> "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)

## 1. Introduction

During lunar and planetary missions, astronauts will be exposed to static 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 they 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 possibly affect astronaut performance and health. Directions for 'space-oriented' research in this area are suggested.

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## 2. 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, appears to decrease in intensity as the inverse cube of the distance from earth (BEISCHER, 1963; DIEMINGER, 1961; HART, 1961). Due to the so-called solar wind, which is 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, apparently extending at least half-way to the moon (about 31 Earth radii) (CAHILL, 1962, 1965; NAS-NRC, 1962; NESS, 1966; SONNETT, 1962).

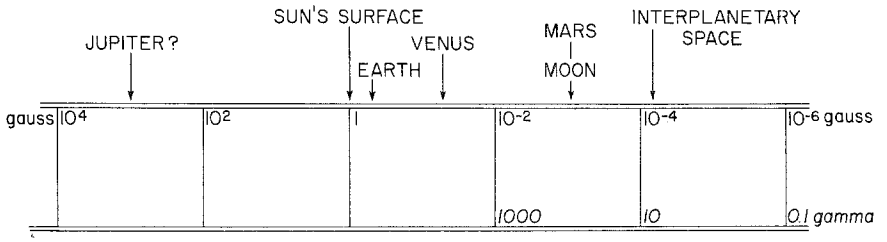


Fig. 1. Measured and postulated magnetic fields in the planetary system. (Revised from BEISCHER, 1963b.)

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 appear to vary from about 2 to 12 gammas (CAHILL, 1962, 1965; DIEMINGER, 1961; WILCOX, 1966). 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 (CAHILL, 1962; CANTARANO and MARIANI, 1966; DOLGINOV and PUSHKOV, 1963). Mariner-II satellite data suggested that the magnetic-field intensity on Venus is at least an order of magnitude less than the earth's field intensity (SMITH *et al.*, 1965), so confirming earlier predictions DOLGINOV and PUSHKOV, 1963; KERN and VESTINE, 1963). Although it had been postulated that Mars might have a magnetic field similar to that on earth (BEISCHER, 1963; KERN and VESTINE, 1963), the Mariner-IV magnetometer indicated that the Martian magnetic-field intensity is about $3 \times 10^{-4}$ that of the earth's field, or about 100 gammas (SMITH *et al.*, 1965). Jupiter is thought to possess a magnetic field which is considerably stronger than the earth's field (BEISCHER, 1963; DIEMINGER, 1961).

Although it can be assumed that astronauts will be exposed to extremely low-

* 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.

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 (WOMACK, 1966). As indicated in the Gemini program, spacecraft fields could add to the field of the ambient environment, which apparently passes through a spacecraft wall with insignificant attenuation (MODISETTE, 1966). On the other hand, magnetic fields generated in spacecraft 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 (LEVY, 1961; SMITH *et al.*, 1965). If such fields exist at a near-zero level due to a cancelling phenomenon, field intensities in spacecraft cabins will therefore essentially be the same as those of ambient space, lunar, and planetary 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 (BERNERT and STEKLY, 1964; KASH and TOOPER, 1962; LEVY, 1961; LEVY and STEKLY, 1964; TOOPER, 1963; TOOPER and DAVIES, 1962). 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 (SAMPSON *et al.*, 1967). 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 secondary radiation resulting from the impact of incoming solar flare particles on components of a space vehicle can be reduced to negligible levels, especially if uncontained field designs are used in solenoid construction (KASH and TOOPER, 1962). However, current models of predicted solar flares do not indicate that such radiation would create a significant hazard in present spacecraft (LANGHAM *et al.*, 1965).

An even more practical scheme for deflecting harmful particulate radiations in space is plasma-radiation shielding (LEVY and JANES, 1964a, b). 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 (LEVY and JANES, 1964a, b). 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.

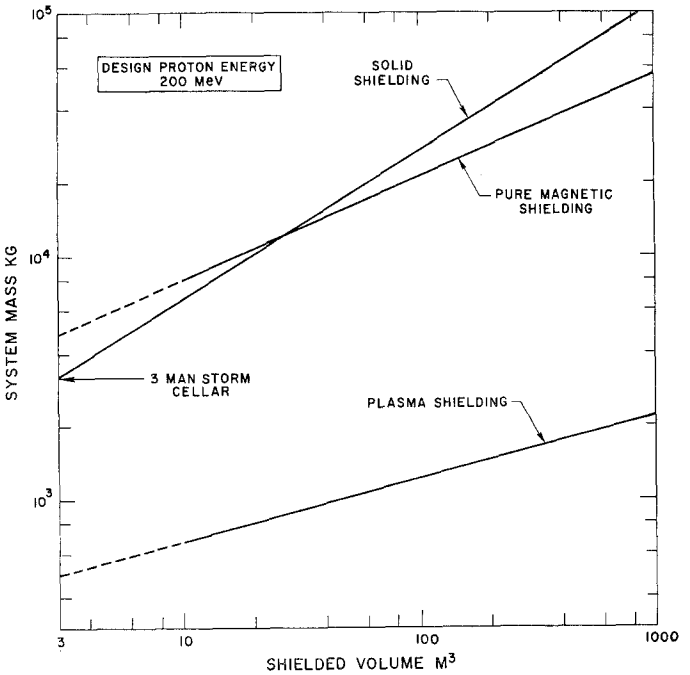


Fig. 2. Comparative weights for various radiation shielding systems. (After LEVY and JANES, 1964b.)

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 spacecraft by suitable placement of equipment and stores.

Magnetic-field intensities of proposed pure magnetic and plasma-radiation shields have been estimated (BERNERT and STEKLY, 1964; KASH and TOOPER, 1962; LEVY, 1961, 1966; LEVY and JANES, 1964a, b; LEVY and STEKLY, 1964; TOOPER, 1963; TOOPER and DAVIES, 1962). It should be noted that such shields will be poorly designed if stray fields extend very far from the desired interaction region (LEVY, 1966). 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 10000 gauss (LEVY, 1966). This level would be sufficient to deflect protons of energies

of up to 200 to 500 MeV (BERNERT and STEKLY, 1964; LEVY, 1966). Since it would be possible to direct most of a magnetic shield away from the spacecraft interior, the field intensity within the spacecraft cabin might be expected to vary from less than 100 to 1000 gauss (LEVY, 1966). Such a field would be of relatively low gradient. If plasma-radiation shielding is used, much lower magnetic fields, possibly in the range of 2000 gauss will be utilized (LEVY, 1966; LEVY and JANES, 1964a, b). The magnetic-field strength inside the spacecraft cabin might then be substantially less than 100 gauss (LEVY, 1966).

Magnetic fields used for directing plasma-ion flow from magnetohydrodynamic propulsion engines will probably be so well contained and directed that the magnetic-field intensity inside a spacecraft will not be raised to significant levels above the engine shut-off level (LEVY, 1966). Servicing procedures on these engines would take place with essentially no magnetic field, or with at most a small seed field possibly of about 1000 gauss which might be used for starting an engine (LEVY, 1966). This field might extend outside the engine about a plasma-channel diameter, which might be about a foot or so (LEVY, 1966).

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 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 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 an activated propulsion engine, to the several days over which a radiation hazard from a solar flare might exist (FREIER and WEBBER, 1963a, b).

## 3. 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 or not 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 determine if 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 (BEISCHER, 1962a, 1963a, b).

A survey of these individuals yielded no obvious detrimental effects attributable to their unusual occupational environment (BEISCHER, 1962a, 1963a).

BEISCHER (1963b; 1965; 1966a; BEISCHER and MILLER, 1962) 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 (BEISCHER, 1963b; BEISCHER and MILLER, 1962). 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 (BEISCHER, 1963b). 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 experiment, but with reference behavior in the earth's magnetic field being established by a 5-day control period living in the coil system before and after the exposure (BEISCHER, 1966a). 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.

Recently, Beischer (BEISCHER *et al.*, 1967) 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 is 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.

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 (SZAFRAN, 1966) and, if comparable to the central critical flicker-fusion frequency test, could be highly variable (LANDIS, 1954; LANDIS and HAMWI, 1954). Beischer (BEISCHER *et al.*, 1967) has postulated that a substance or factor

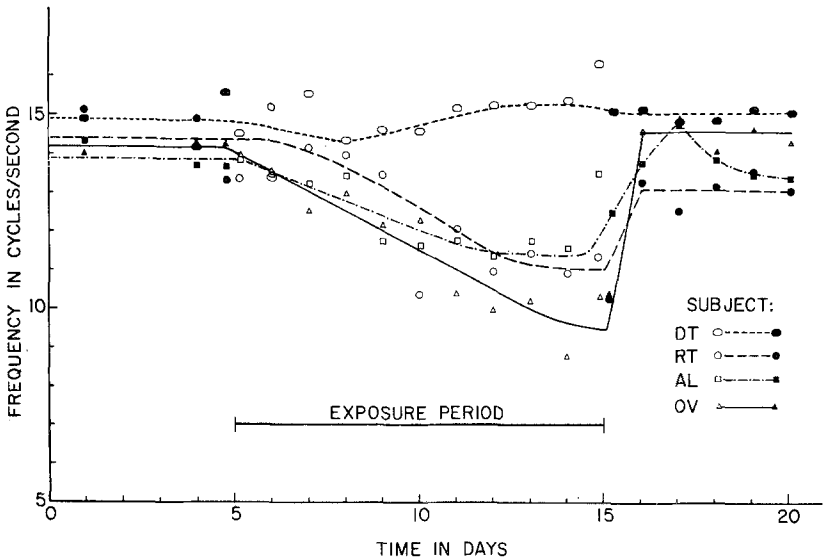


Fig. 3. Scotopic critical flicker-fusion frequencies in 4 subjects before, during and after exposure to a magnetic field less than 50 gammas in intensity, in a Helmholtz coil system. (After BEISCHER, 1966b.)

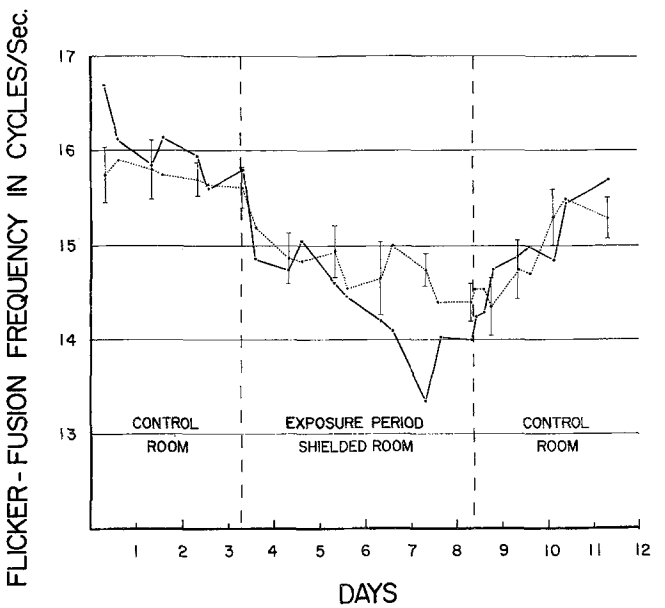


Fig. 4. Scotopic critical flicker-fusion frequencies in 2 subjects before, during and after exposure to a magnetic field less than 50 gammas in intensity, in a magnetically shielded room. (After BEISCHER *et al.*, 1967.)

essential in the visual process might be formed during exposure to low magnetic fields, being gradually depleted as exposure proceeds and replaced slowly during the recovery period in the geomagnetic field. Further studies are indicated in this area to establish definitely whether or not 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 (1963) 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 a 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 (HALPERN, 1966; HALPERN and VAN DYKE, 1966; VAN DYKE, 1966; VAN DYKE and HALPERN, 1966). 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 has been pointed out in a preliminary, unpublished report (VAN DYKE and HALPERN, 1966), an unspecified number of originally 4-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 are 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 (HALPERN, 1966; VAN DYKE and HALPERN, 1966). By the $F_4$ generation, reproduction has usually ceased (HALPERN, 1966). Unanticipated cannibalism and abortions of newborn mice have 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 (VAN DYKE and HALPERN, 1966). At an early age, large numbers of mu-metal mice have become docile and inactive. Many mice have exhib-

ited the highly unusual behavior of lying on their backs for prolonged periods of time (HALPERN, 1966). About 14% 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 (VAN DYKE and HALPERN, 1966). Connective tissue and epithelial tumors, which have frequently been found in various loci, remain to be studied further microscopically (HALPERN, 1966).

The skin has been found to be hyperplastic, but only in areas of alopecia. In these areas it has characteristically had 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 (HALPERN, 1966; VAN DYKE and HALPERN, 1966). The livers of all experimental mice studied have shown the presence of hemosiderin crystals in the Küpfer cells to a variable degree (HALPERN, 1966; VAN DYKE, 1966). 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 (VAN DYKE and HALPERN, 1966). 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 (VAN DYKE and HALPERN, 1966). 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 (HALPERN, 1966). 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 (VAN DYKE and HALPERN, 1966). Few follicles were in evidence, in spite of the high incidence of pregnancy in these animals (HALPERN, 1966; HALPERN and VAN DYKE, 1966). 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 their mu-metal mice is a diffuse, hyperplastic condition (HALPERN, 1966; HALPERN and VAN DYKE, 1966; VAN DYKE, 1966; VAN DYKE and HALPERN, 1966). They cannot foresee any possible cause of this condition other than the chronic exposure to the extremely low-intensity magnetic field (HALPERN, 1966; VAN DYKE, 1966). It is sugges-

ted 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 (BECKER, 1963). 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, Greene and Halpern found that the growth of HeLa, KB, WI-38, Chinese hamster and chick embryo cultures was unaffected by a 4-day exposure to a magnetic-field intensity of about 50 gammas (GREENE and HALPERN, 1966).

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 (CONLEY *et al.*, 1966). 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 investigator to attempt a theoretical explanation for biological phenomena observed during exposure to low-intensity magnetic fields (BEISCHER, 1963a). 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 (BARNWELL and BROWN, 1964), 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 (1966) 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 or not 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 should 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.

## 4. 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 if activated magnetohydrodynamic engines must be serviced, up to several days if pure magnetic or plasma-radiation shielding is used for astronaut 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 section 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 (J. BARNOTHY, 1964a; BEISCHER, 1962a, c; BEISCHER and KNEPTON, 1964b, 1966; KHOLODOV, 1966), most biomagnetic research has been stimulated by discoveries that magnetic fields inhibited tumor and other cell growth (AMBROSE *et al.*, 1963; J. BARNOTHY, 1964c; BUTLER and DEAN, 1964; GROSS, 1964c; HEDRICK, 1964; PERAKIS, 1947), slowed aging (M. BARNOTHY, 1964a), conferred radiation protection (AMER, 1963; M. BARNOTHY, 1964c), altered plant growth and development (DYCUS *et al.*, 1966; MERICLE *et al.*, 1964), affected spatial orientation (BARNWELL and BROWN, 1964; BROWN, 1966a), reduced mutation rates (MULAY and MULAY, 1964), and could be used to characterize biologically active radicals and study basic biological mechanisms (M. BARNOTHY, 1964b; DEAVER *et al.*, 1964; GROSS, 1963; GUALTIEROTTI, 1964; HACKEL *et al.*, 1964; HANNEMAN, 1966; NEURATH, 1966; WILEY *et al.*, 1964). The results of most of these experiments considered pertinent to this report are summarized in Table I. Studies on plants are referenced in the biomagnetic bibliographies prepared by GROSS (1964b), Davis and co-workers (DAVIS *et al.*, 1962), and other authors (DYCUS *et al.*, 1966; MERICLE *et al.*, 1964).

In general, it is readily apparent that Table I 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 possible astronaut situations. Moreover, fixation of body parts in fields might not simulate magnetic exposure of an astronaut, who

TABLE I

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) | 2500 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 5000 Oe | Essentially homogeneous | Random | Accumulated exposure time up to 3 days/year/man | No deleterious effects | 21 |
| General effects | Man (occupational exposures) | Up to 20000 Oe | Essentially homogeneous | Random | Up to 15 min 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 | 1000 to 2000 Oe | – | Random–horizontal field | 5 hours | No apparent effect | 117 |
| Motor activity Food consumption Appearance | Mouse (70 days of age) | 4200 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) | 4200 Oe | Homogeneous | Random–vertical field | 4 weeks | No apparent effect | 5 |

* With respect to exposed biological system.

*(Table I, cont.)*

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Cardiac and respiratory activities | Squirrel monkey | 62500 Oe at heart (70000 Oe at head) | 2400 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 | 100000 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 60000 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 min | Rise in number of spindles and slow waves in all recorded areas of brain; latency reaction 5–100 sec, latency recovery 15 sec; in order of decreasing responsiveness were hypothalamus, sensorimotor cortex, optic cortex, specific nuclei of thalamus non-specific 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 I, cont.)*

| 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 40000 Oe, then to 72450 Oe | Homogeneous | Head-to-foot (body fixed in field) | 45 min 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 20000 Oe, then to 40000 Oe, then to 60000 Oe | Homogeneous | Head-to-foot (body fixed in field) | 3 min each step | | |
| | | To 22540 Oe, then to 45472 Oe, then to 68414 Oe, then to 91258 Oe | Strongly inhomogeneous | Head-to-foot (body fixed in field) | 1 min each step | | |
| Brain-electrical activity | 'Animal' (head only exposed) | 2500 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 I, cont.)*

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Brain-electrical activity | Pigeon (head only exposed) | Up to 3000 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 | 4200 Oe | Homogeneous | – | 1 hour | No change of oxygen uptake | 127 |
| Body-temperature restoration | Mouse | 4500 Oe | 500 Oe/cm | – | 1 hour | Delay of body-temperature restoration after hypothermia | 128 |
| Body temperature | Mouse | 4200 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 | 4200 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 the zona fasciculata; and bone-marrow megakaryocytes were decreased in number | 134 |
| Organ effects (spleen, liver, adrenal glands, bone marrow, lymph nodes and jejunum) | Mouse | 4000 Oe | 500 Oe/in | Random–horizontal field | 30 days | No apparent effects | 65 |

*(Table I, cont.)*

| Effects studied | Biological system | Field strength | Field gradient | Field direction | Duration of exposure | Effects observed | Ref. |
|---|---|---|---|---|---|---|---|
| Organ effects (liver and adrenal glands) | Mouse | 4200 Oe | Homogeneous | Random–vertical field | 35 days | Livers showed centrolobular necrosis and pyknosis; adrenal glands unaffected | 134 |
| Organ effects (spleen, liver) | Mouse | 13500 Oe | 400 Oe/cm | Random–horizontal field | 25 days | No liver or spleen-weight changes | 53 |
| Organ effects (adrenal glands) | Mouse | 2500 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 | 4200 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 1 hour, glial hyperplasia and hypertrophy in rabbits; after 10 hours, same, associated with cloudy swelling of neurons in rabbits and cats; after 60 to 70 hours, glial hyperplasia, hypertrophy and atrophy, and dystrophic nerve lesions in all animals | 85 |
| Blood parameters Liver and spleen weights | Mouse | 13500 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 |

*(Table I, cont.)*

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Blood leucocyte response | Mouse | 4200 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 | 4200 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 | 13000 Oe | 450 Oe/cm | Random–vertical field | 1 week | Increase in red-blood cell count | 11 |
| Blood-coagulation response | Mouse | 13000 Oe | 450 Oe/cm | Random–vertical field | 2 days | Increase in blood-coagulation time | 11 |
| Antibody production | Mouse injected with sheep red blood cells | 4000 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) | 9400 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 4 days after each exposure period | 8 |

*(Table I, cont.)*

| Effects studied | Biological system | Field strength | Field gradient | Field direction | Duration of exposure | Effects observed | Ref. |
|---|---|---|---|---|---|---|---|
| Body growth | Mouse (30-day female) | 4200 Oe | 80 Oe/cm | Random–vertical field | 30 days | Weight decrease to minimum on second day in both field groups; subsequent weight gain poorer for the more homogeneous field group | 8 |
| | | 3600 Oe | 650 Oe/cm | Random–vertical field | 30 days | | |
| Body growth | Mouse (young) | 5900 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 | 4000 Oe | 500 Oe/in | Random–horizontal field | Up to 2 months | Slowed skin-wound healing due to marked delays in fibroblast proliferation and fibrosis | 65 |
| Pregnancy | Mouse (mated in magnetic field) | 2500 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) | 4200 Oe | Homogeneous | Random–vertical field | Duration of pregnancy | Fetus re-absorbed if placed in field before tenth gestational day; homogeneous vertical field of 8000-Oe exposure after eighteenth gestational day had no effect | 12 |
| Pregnancy | Mouse (pregnant) | 4200 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 |

*(Table I, cont.)*

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Tumor growth | T2146 adenocarcinoma in mouse | 3000 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 adenocarcinoma in mouse | 4000 Oe | 200 Oe/cm | Random–horizontal field | From time of tumor implant | No apparent effect | 64 |
| Tumor growth (effect of magnetic pre-treatment) | dbrB mammary adenocarcinoma, sarcoma I, H2712 mammary adenocarcinoma, C4461 pulmonary adenocarcinoma, L1210S lymphoid leukemia and Erlich's ascites adenocarcinoma in mouse | 4000 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 | 4200 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 13500 and 14400 Oe | 400 Oe/cm near ends of magnet core | Random–horizontal field | From time of tumor implant | No apparent effect | 53 |

*(Table I, cont.)*

| Effects studied | Biological system | Field strength | Field gradient | Field direction | Duration of exposure | Effects observed | Ref. |
|---|---|---|---|---|---|---|---|
| Cell-culture growth | 12 genera of bacteria, 4 genera of yeasts, and 4 genera of molds | 3000 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 |
| Cell-culture growth | *Escherichia coli* and *Staphylococcus aureus* | 3000 Oe | – | Random | 48 hours | No apparent effect | 92 |
| Cell-culture growth | *Staphylococcus aureus, Sarcina lutea* and *Escherichia coli* | 14000 Oe | Homogeneous | Random | 24 hours | Only growth rate of *Staphylococcus aureus* affected, being decreased beyond the sixteenth hour (did not occur if culture taken out of field hourly for 3 sec) | 76 |
| Cell-culture growth | *Escherichia coli* | 4250 Oe | 1750 Oe/cm | Random | 9 hours | No apparent effect | 76 |
| Cell-culture growth | *Serratia marcescens* | 15000 Oe | 2300 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* | 15000 Oe | 5200 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 |

*(Table I, cont.)*

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Cell-culture growth | Chick-heart cell culture | 1000 Oe | – | Random | – | Growth retardation; presence of abnormal giant cells | 91 |
| Cell-culture growth | Embryonic heart tissue | 5000 Oe | – | Random | 3 to 6 hours | No effect | 114 |
| Cell-culture growth | Mouse-lung fibroblast cells | 7000 Oe | – | Random | – | Growth retardation | 118 |
| Cell-culture growth | Guinea-pig macrophages | 2000 to 8000 Oe | Homogeneous | Random | 4 hours | Increased number of viable cells, especially around 4000 Oe | 141 |
| Cell-culture growth | Rabbit myocardium | 14600 Oe | 5000 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 | 4000 Oe | Homogeneous | Random | 3 days | Decreased growth rate | 40 |
| Cell-culture growth | HeLa cells | 5000 Oe<br>27000 Oe<br>77000 Oe | Homogeneous<br>Homogeneous<br>Homogeneous | Random<br>Random<br>Random | 10 days<br>10 days<br>10 days | No apparent effect<br>No apparent effect<br>No apparent effect | 69 |
| Cell-culture growth | KB, Chang's liver and sarcoma-180 cells | 12000 Oe | Homogeneous | Random | 3 and 4 days | No apparent effect | 107 |

*(Table I, cont.)*

| 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 | 4400 to 8800 Oe | Up to 1000 Oe/cm | Random | 18 hours | Some degeneration of cells | 108 |
| | Mouse sarcoma-37 solid tumor cells | 4400 to 8800 Oe | Up to 1000 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 10000 Oe | Homogeneous | Random | 10 min on, 10 min off | Oxygen uptakes of embryo kidney decreased 27% above 85 Oe, adult kidney unaffected, sarcoma-37 decreased 28% above 80 Oe and yeast increased 40% 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 | 2900 Oe | 1040 Oe/cm | Random | 42 hours | No apparent effect | 102 |
| Cell-culture oxygen uptake | *Chlorella pyrenoidosa* | 100000 Oe | – | Random | 17 to 25 min | No apparent effect | 73 |
| Cell-culture oxygen production (photosynthesis) | *Chlorella pyrenoidosa* | 10000 Oe | – | Random | 40 min | No apparent effect | 73 |

*(Table I, cont.)*

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Cell division | Sea urchin | 70000 to 140000 Oe | Homogeneous to 4500 Oe/cm | Random | From time of fertilization | Over 100000 Oe, division retarded regardless of gradient; between 80000 and 100000 Oe, division delay more pronounced in high-gradient fields; below 80000 Oe, delay related more directly to gradient than field strength; about 70000 Oe and a gradient of 4200 Oe/cm, effect on cell division negligible; mitotic apparatus appeared unaffected in this study | 121 |
| Cell division | Sea urchin | 100000 to 140000 Oe | Homogeneous and inhomogeneous | Random | From time of fertilization | Early cleavage retarded | 26 |
| Genetic effects | *Drosophila melanogaster* | 6000 Oe | Homogeneous | Random | 60 min (newly hatched eggs) | No change in hatching ratio or time necessary for eggs to develop into flies; enhanced mortality when 165r *x*-irradiation given with magnetic exposure | 54 |
| Genetic effects | *Drosophila melanogaster* | 100 to 4400 Oe | – | Random | From one to three generations | Frequency of deformities increased above 3000 Oe | 108 |
| Genetic effects | *Drosophila melanogaster* | 10000 Oe | Homogeneous | Random | 30 min (adult fly) | No subsequent effects | 26, 45 |
| | | 100000 Oe | Homogeneous | Random | 2 hours (adult fly) | No subsequent effects | |
| | | 18000, 21000 and 22000 Oe | Homogeneous | Random | From egg to newly hatched fly | No apparent effect | |
| | | 11000 Oe | 1500 Oe/cm | Random | From egg to newly hatched fly | No apparent effect | |
| Genetic effects | *Drosophila melanogaster* | Several thousand Oe | Several hundred Oe/cm | Random | 24 hours – eggs | Induced visible wing and lethal mutations | 44 |

*(Table I, cont.)*

| Effects studied | Biological system | Field strength | Field gradient | Field direction | Duration of exposure | Effects observed | Ref. |
|---|---|---|---|---|---|---|---|
| Genetic effects | *Tribolium confusum* eggs | 3600 Oe | Homogeneous | Random | 7 days after irradiation | Decreased induction of wing abnormality by 1200 r, 250 Kvp X-rays; most effective where synergism between temperature and X-ray | 4 |
| Genetic effects | Mouse (70-day female) | 4200 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 | 5000 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* | 8000 Oe | 220 Oe/cm | Random | up to 3 hours | 5 to 23% activating effect on enzyme during first 2 hours, leveling-off during third hour | 47 |
| Enzyme activity | Trypsin and chymotrypsin *in vitro* | 13000 Oe | Homogeneous | Random | up to 4 hours | Activating effect on trypsin at pH3, inactivating effect at pH8; activating effect on chymotrypsin | 132 |

*(Table I, cont.)*

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Enzyme activity | Carboxy-dimutase *in vitro* | 20000 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 48000 Oe | Homogeneous | Random | 5 and 6 min | No effect | 103 |
| Enzyme activity | Ribonuclease, polyphenol oxidase, peroxidase and aldolase *in vitro* | up to 170000 Oe | Homogeneous | Random | up to 20 min | No effect | 119 |
| Enzyme reactivation | Trypsin inhibited by egg white | 5000 Oe | Homogeneous | Random | 17 hours | Partial reactivation at pH 3.0 | 146 |
| Enzyme reactivation | Partially inhibited trypsin by ultraviolet | 5000 Oe | Homogeneous | Random | up to 18 hours | Reactivation | 47 |
| Chromatographic migration rate | Catalase, cytochrome-C and hemo-globin | 1220 Oe | Homogeneous | – | – | No apparent effect | 107 |

*(Table I, cont.)*

| Effects studied | Biological system | Field strength | Field gradient | Field direction | Duration of exposure | Effects observed | Ref. |
|---|---|---|---|---|---|---|---|
| Response of isolated denervated heart | Turtle-heart preparation | 3400 to 15600 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 | 4000 Oe<br>15000 Oe | 830 Oe<br>3700 Oe | Side-to-side<br>Side-to-side | –<br>– | 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-min exposure to lower field, diminished within 1 min 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 I, cont.)*

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Transmembrane sodium transport | Frog skin | 250 to 650 Oe | Homogeneous | Across skin | – | Reduction of sodium influx and efflux by 10 to 30% within 1 sec of applying field; ouabain prevented this effect | 37 |
| Transmembrane sodium transport | Frog skin | Up to 10000 Oe | – | Across skin | – | Reduction of skin polarization at thresholds between 800 to 8000 Oe (mode 5000 gauss); effect disappears by blocking sodium pump with asphyxiation, cyanide and ouabain | 67 |
| Transmembrane sodium transport | Frog skin | 3500 Oe | – | – | – | No apparent effect | 107 |
| Urinary electrolyte excretion | Mouse | 14000 Oe | Homogeneous | Random–horizontal field | 5 days | Significant increase in sodium and potassium excretion; calcium excretion unchanged | 74 |
| Estrus cycle | Mouse | 4200 Oe | Homogeneous | Random–vertical field | 2 weeks | Estrus cycle 'disappeared' | 6 |
| Red-blood cell agglutination | Human red cells with type-specific antisera | 20 to 50000 Oe<br>16000 Oe | 'Moderately Homogeneous'<br>1500 Oe/cm | Random<br>Random | 5 min 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 | 3500 Oe | Homogeneous | Random | – | Sickled erythrocytes oriented perpendicular to long axis of field | 109 |
| Survival | Mouse | 43000 Oe | Homogeneous | Random–horizontal field | 1 hour | Survived | 21, 22, 30 |
| | | 100000 Oe | Homogeneous | Random–horizontal field | 2 hours | Survived | |
| | | 120000 Oe | Homogeneous | Random–horizontal field | 1 hour | Survived | |

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 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 (BEISCHER, 1962a). Such random observations, summarized in Table I, 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 20000 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 I, 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 (BECKER, 1963; FRIEDMAN *et al.*, 1963, 1965). 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 (1963) 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 neurological irritability, possibly through a galvanomagnetic effect, as magnetic fields interact with electric-current flow in the brain stem (BECKER, 1963). 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 (FRIEDMAN *et al.*, 1963, 1965). 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 (BECKER, 1963). 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 resembling 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 (1965), who exposed squirrels to high magnetic fields. Taking this and other observations noted above into account, BECKER (1963) 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 (BECKER, 1966). Becker's postulates, which have been supported in the Russian literature (VASIL'YEV, 1961), 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 (1962) 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 (1964) 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, how-

ever, 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 I brings out several points for discussion. Although recordings of motor activity, food consumption and appearance indicated that the mouse is unaffected by several weeks of exposure to vertical, homogeneous magnetic fields in the range of 4000 oersteds (M. BARNOTHY, 1964a), autopsy studies showed that the mouse could experience liver damage, bone-marrow suppression and alterations of adrenal cortical structure during such an exposure (SUMEGI *et al.*, 1964, 1966). Since the adrenal glands were unaltered in mice exposed to horizontal fields of up to 13500 oersteds in strength with a gradient of 400 oersteds per centimeter (EISELEIN *et al.*, 1961), 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 (J. BARNOTHY, 1966). J. M. BARNOTHY (1964b) 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 inhomogenous, 70000-oersted magnetic field for 3 hours, or in a homogeneous, 100000-oersted field for 24 hours, respiratory rate was unaltered and only a small decrease in heart rate and increase in sinus arrhythmia occurred (BEISCHER, 1966b; BEISCHER and KNEPTON, 1964a, b; BEISCHER *et al.*, 1966). This should not lead to the assumption that a monkey's 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, was recorded (BEISCHER and KNEPTON, 1966; KNEPTON and BEISCHER, 1966). Above a 60000-oersted homogeneous field level, the monkeys stopped punching a lever for food (BEISCHER, 1966b; BEISCHER *et al.*, 1967). 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 (KHOLODOV, 1964, 1966c). 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 oersted (GUALTIEROTTI, 1963). 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 (BECKER, 1963). 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 exposure, permanently damage both glial and neural brain cells (KHOLODOV, 1966a, b, c). 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 (KHOLODOV, 1966c; LUSE and HARRIS, 1961). Hence, from magnetic-field effects observed on brain-electrical activity and structure to data, it is apparent that close attention must be given to determining whether or not static and fluctuating 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 (M. BARNOTHY, 1964b). 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 (EISELEIN *et al.*, 1961). 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 13000 oersteds in strength, with a gradient of 450 oersteds per centimeter (J. BARNOTHY, 1966). Whether or not 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 (GROSS, 1963) 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 (M. BARNOTHY, 1963, 1964c). 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 13000 oersteds in strength, with a gradient of 450 oersteds per centimeter (J. BARNOTHY, 1966). 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 (LENGYEL, 1960). This fiber system was thought to be the path along which tumor cells migrated from malignant tissues into healthy tissues (J. BARNOTHY, 1964c). Since exposure of mice to several thousand oersteds had an inhibitory effect on pregnancy (J. BARNOTHY and M. BARNOTHY, 1966), body-growth rate (J. BARNOTHY, 1964b) and fibroblast proliferation in healing tissue (GROSS and SMITH, 1964), mitosis was also thought to be retarded by magnetic fields (J. BARNOTHY, 1964c). 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 (J. BARNOTHY, 1964c). This seemed supported by observations that certain tumors injected into mice exposed to vertical homogeneous and heterogeneous magnetic fields were either rejected (J. BARNOTHY, 1964c) or obviously limited in spread, so lengthening survival time (J. BARNOTHY, 1964c; GROSS, 1964c). On the other hand, horizontal fields of similar intensities failed to alter growth of any one of a variety of tumors injected into mice (EISELEIN *et al.*, 1961; GROSS, 1964c). 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 (PERAKIS, 1947; PUMPER and J. BARNOTHY, 1966; VALENTINUZZI *et al.*, 1966), unaltered (GREENE and HALPERN, 1966; HALL *et al.*, 1964; HALPERN and GREENE, 1964; HANNAN, 1964; JENNISON, 1937; LEUSDEN, 1966; MONTGOMERY and SMITH, 1963; NEURATH, 1966; PAYNE-SCOTT and LOVE, 1964) or decreased (BUTLER and DEAN, 1964; GERENCSER *et al.*, 1964; HEDRICK, 1964; LENGYEL, 1960; PUMPER and J. BARNOTHY, 1966) their growth rates. Such has also been the case in various studies of cell-culture oxygen uptake (MOHR and CASHIN, 1966; PEREIRA *et al.*, 1966; RENO and NUTINI, 1964). 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 10000-oersted field (HANNAN, 1964). 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 70000 oersteds, have field strength and gradient been related to the degree of biomagnetic effect observed (BEISCHER, 1964; RENO, 1966). 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 (RENO, 1966). Other studies of biomagnetic effects on growth (AMER, 1963; M. BARNOTHY, 1964a; BEISCHER, 1964; CHEVAIS and MANIGAULT, 1962; FORSSBERG, 1940; MULAY and MULAY, 1964) have indicated that prolonged magnetic-field exposures can increase the mutation rate of Drosophila (CHEVAIS and MANIGAULT, 1962; MULAY and MULAY, 1964), counteract radiation-induced mutations in Tribolium (AMER, 1963) and decrease the incidence of mammary-gland carcinoma in the mouse (M. BARNOTHY, 1964a). These and other experiments mentioned above em-

phasize 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 (AKOYUNOGLOU, 1964; COOK and SMITH, 1964; MALING *et al.*, 1965; RABINOVITCH *et al.*, 1967; SHYSHLO and SHIMKEVICH, 1966; SMITH, 1966; WILEY *et al.*, 1964). 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 (SHYSHLO and SHIMKEVICH, 1966). 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 (PEREIRA *et al.*, 1966; RENO and NUTINI, 1964), the decrease of body temperature of mice exposed to magnetic fields for prolonged periods of time (SHYSHLO and LEKTORSKY, 1966), and the delay of body-temperature restoration of a hypothermic mouse by a magnetic field (SHYSHLO and MASLOV, 1966). 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 (BIANCHI *et al.*, 1963; GUALTIEROTTI, 1964) may also explain the increased urinary sodium and potassium excretion of a mouse placed in a magnetic field (HANNEMAN, 1966) and the abnormal electrical activity which slowly began with and disappeared after an isolated, denervated, turtle-heart preparation was exposed to a magnetic field (RENO and BEISCHER, 1966). 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 (AKOYUNOGLOU, 1964; COOK and SMITH, 1964; SMITH, 1966; WILEY *et al.*, 1964), and that increased acetylcholine hydrolysis, possibly due to acetylcholinesterase activation, occurred in an isolated, vagal frog-heart preparation exposed to a magnetic field (YOUNG and GOFMAN, 1965). 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 I deserve comment here. One wonders whether the disappearance of the estrus cycle in mice exposed to a vertical, homogeneous, 14200-oersted magnetic field may be related to adrenal gland structural, and no doubt functional changes noted previously (J. BARNOTHY, 1960). 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 (MONTGOMERY and SMITH, 1963). Reports that magnetic fields enhanced red-blood cell agglutination (HACKEL *et al.*, 1964) and oriented sickled erythrocytes (MURAYAMA, 1966) have led investigators to speculate that the form of hemoglobin in red-blood cells may possess remarkable paramagnetic properties (MURAYAMA, 1966; NEURATH,

1966). The last experiment recorded in Table I points out that mice survive exposures to 100000- and 120000-oersted fields for 2 and 1 hour durations, respectively (BEISCHER, 1962a, b; BEISCHER and KNEPTON, 1964a). This experiment, as well as a recent one in which two squirrel monkeys were exposed to a homogeneous, 100000-oersted field for 24 hours (BEISCHER, 1966b; BEISCHER and KNEPTON, 1964a), 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 (SCHWAN, 1967).

On a physiological basis, J.M. BARNOTHY (1966) 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 (SUMEGI *et al.*, 1964, 1966). 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 (J. BARNOTHY, 1966), such as retardation of body growth (J. BARNOTHY, 1964b; J. BARNOTHY and M. BARNOTHY, 1966) and wound healing (GROSS and SMITH, 1964), diminished antibody formation (GROSS, 1963), depression of the leucocyte count (M. BARNOTHY, 1963, 1964b), and rejection and limitation of spread of transplanted tumors (J. BARNOTHY, 1964c; GROSS, 1964c). 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 submolecular levels. Some theories have been mentioned above; others deserve mentioning here, if only to acquaint the reader with this 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 (J. BARNOTHY, 1963; BEISCHER, 1962c, 1963b, 1964; GROSS, 1963; RAGLE, 1964; VALENTINUZZI, 1964). It has been pointed out, however, that biological actions are frequently rate dependent, where small changes in energy may be important (BUTLER and DEAN, 1964; MONTGOMERY and SMITH, 1963). 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 (HACKEL *et al.*, 1964; LABES, 1966; MONTGOMERY and SMITH, 1963). In line with this reasoning, GROSS (1963, 1964a) 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 (1964, 1966) 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 (BEISCHER, 1963a). RENO (1966) 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 (MONTGOMERY and SMITH, 1963).

DEAVER and co-workers (1964), and others (VALENTINUZZI, 1964) 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, 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 (1966). GUALTIEROTTI (1963) and many others (BEISCHER and KNEPTON, 1964a; BIANCHI *et al.*, 1963; LEVENGOOD, 1967a; b; LIBOFF, 1965, 1966; RAGLE, 1964; RENO and BEISCHER, 1966; SHYSHLO and SHIMKEVICH, 1966) 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 (1963) 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 (1964a, 1966) 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 (1966) has postulated that the rotational unwinding of the double DNA helix prior to mitosis might be retarded by a magnetic field. BUTLER and DEAN (1964) 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 (1964) and BELOUSOVA (1965) 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 (AKOYUNOGLOU, 1964; COOK and SMITH, 1964) have attributed the activation of various enzymes by magnetic fields in their experiments to an increase in hydrogen bonding and consequently in the helicity of the polypeptide backbone of the enzymes. This was presumed to stabilize the enzymes against denaturation, so that after prolonged exposure to a magnetic field, they would not denature as fast as unexposed enzymes.

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 activated 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.

## Acknowledgements

I am most grateful to Drs. A.H. Schwichtenberg, Head, and E.M. Roth and T.M. Fraser of the Department of Aerospace Medicine and Bioastronautics, The Lovelace Foundation for Medical Education and Research, for their many constructive comments which greatly assisted me in the preparation of this report. Gratitude is also expressed to my secretary, Mrs. J.H. Rigler, and to the document library staff of the Foundation for their immense help.

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