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BIOMAGNETISM: A REVIEW*

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Abstract

In this survey we concentrate on certain authenticated biological effects of static and low frequency magnetic fields, and present the potential hazards associated with human exposure.

1. - Introduction

Many applications of current and future technology implicitly require that living organisms be exposed to enhanced magnetic fields over significant time intervals. Thus static fields of considerable magnitude and extent are envisioned for magnetohydrodynamic and thermonuclear electric power production and localized magnetic fields are used in certain medical applications, while magnetically levitated high speed ground transportation will expose the traveler to appreciable fields for extended periods of time. More and more manufacturing processes employ dynamic magnetic fields for shaping, handling, and transport of materials, and of course high frequency fields are encountered in telecommunications. Exposure to elevated magnetic fields is a new experience for the terrestrial biosphere, particularly for the human body, which has evolved in a geomagnetic environment that by and large has not exceeded 100 microtesla during the last 80 million years. Prolonged exposure to a magnetic environment that is much different is likely to lead to some physiological reaction. The degree to which the organism responds will most likely be dictated by the nature of the change in background flux and by the source causing it. A projected medium-sized thermonuclear power reactor has a magnetic signature that extends over many kilometers: how will it affect bird migration and navigation and, even more important, how will the plant operators respond to a combined environment of radiation and magnetic fields? And what new social problems will be catalyzed by the additional physiological stresses as the organism proceeds to adapt to the new conditions?

Many questions of this nature have been asked and much experimental evidence and speculation have been accumulated. Experiments contradict one another as frequently as they agree in their inferences. In searching for a systematic trend, we have collected an extensive bibliography and examined published experiments judged by others to be of particular significance. Our conclusions should come as no surprise: biomagnetism while generously documented is still very imperfectly understood. In this paper, we propose to review those effects where the reaction of the biological systems to static and slowly varying magnetic fields is particularly well defined, and to speculate both on the association of magnetic field induced phenomena to the understanding of physiological processes and on the possible deleterious effects these phenomena may have on the biological system.

2. - Historical Review

Man's curiosity into the action of magnetic and electric forces on the human body dates back almost to prehistoric times: we have found references dating back to 2000 B.C. alluding to observations of unusual consequences of exposing the human body to the action of a magnetic field produced by a lodestone. In fact, much of the work dealing with the effects of magnetic fields on organisms, tissues, denizens of the animal kingdom, and on humans has an unreal aspect to it. Practice of quack medicine, human prejudice and beliefs, and sheer ignorance have resulted in a vast collection of semiscientific and mythological literature on the subject. Even in recent times this work has often been surrounded by an aura of mysticism. In 1888 Herrmann[1] published the results of his very systematic biomagnetic experiments from which he concluded that no magnetophysiologic effects could be obtained. Herrmann's paper is the archetype for much subsequent literature on the subject of biomagnetics: the biological aspects of the experiments are presented with meticulous care, while the physical parameters, such as the magnetic field intensity, are ignored completely. As if to compensate for this lack of information, Herrmann indulges in an amusing diatribe condemning "the irresponsible charlatans who use hypnosis and magnetism as the universal panacea for mankind's ills." Peterson and Kennelly[2] in 1892 followed in Herrmann's footsteps in that their experiments designed to detect the physiological action of magnetic fields also produced negative results. In 1893 d'Arsonval,[3] working with alternating magnetic fields, discovered magnetophosphenes - luminous sensations seen in the eyes when the head is interposed between the poles of the electromagnet. Next, Drinker and Thomson[4] became interested in the effects of magnetic fields on neural physiology while investigating chronic manganese poisoning of workers in the zinc industry. Apparently the workmen blamed their ailments on the constant exposure to the relatively strong magnetic fields produced by the ore separators. Drinker and Thomson undertook a series of carefully planned experiments from which they concluded that there was no evidence for physiological effects that could be ascribed to the magnetic fields.

In 1930 Ssawostin[5] reported experiments which seemed to show a stimulation in the growth rate of plants in fields of 20 to 210 mT. Leusden,[6] Jennison,[7] and Kimball[8] examined the effect of magnetic fields on the growth and morphology of bacteria and yeasts. Negative results were obtained in fields up to 1.1T. In 1940 Lenzi[9] reported temporary inhibition in the growth rate of implanted tumors in fields of 150 mT. Investigations into the animal response to magnetic fields in excess of 10T were begun by Beischer in 1964.[10]

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Earlier Jonnard[11] reviewed prior work on neuromuscular contraction, and he concluded that certain effects may have been observed thirty years earlier but incorrectly interpreted. Galvanomagnetic effects on the nervous system were studied by Liberman[12] and Becker.[13]

The interest in biomagnetics has grown tremendously in the past two decades: symposia and conferences have proliferated,[14] and monographic surveys of the field have appeared.[15,16,17] Even with this considerable amount of scientific interest there remains much controversy over the actual extent of the impact magnetic fields have on the biosphere. This diversity of opinion is very apparent in the rather large differences between the East European and Western World safety standards for exposure to a magnetic field, and in the appreciation of the biological mechanisms which underlie its effects. Presman's monograph[18] is an excellent representative example of the East European approach to the subject. He devotes much space to a discussion of the cumulative effects of repeated exposures to magnetic fields even at very low field intensities. Presman postulates that, in the course of evolution, organisms have come to rely on magnetic (and electric) fields to convey, in conjunction with the sensory, nervous, and endocrine systems, information to the organism as a whole as to its state of coordination and integral behavior. Therefore, even very weak magnetic fields would tend to disturb this process down to the cellular and possibly even to a lower level, which could result in disordering of the information transfer process to some degree.

Current Western opinion inclines towards synergysm: abrupt changes in specific biological functions are often due to local phase transitions, which can be reinforced (or weakened) by the presence of externally applied disturbances. For example, the effect of forces which are capable of molecular reorientation should be observable most easily around transition temperatures. Furthermore, the superimposed effect of two or more external stimuli, such as a magnetic field and radiation, is reported as being capable of inducing in its totality effects which are more disruptive for the organism than when either stimulus is applied separately.

Each point of view is of course supported by a considerable amount of indirect experimental evidence and to this day the opinions remain resolutely diverse.

3. - Classification of Biomagnetic Effects

A survey of the hundreds of experiments performed in the last 20 years, in which countless thousands of mice, plants, insects, lower organisms, primates, and even men were subjected to magnetic fields of varying degrees, shows that magnetic fields do indeed provoke a response from the biological system, even though it may not be a very spectacular one. The diversity and number of experiments notwithstanding, the observed biological effects readily fall into four classes according to the mechanism or reaction which produces them.

In the first class we find effects which seem to originate in some kind of sensory apparatus through which the organism can detect magnetic fields of the order of the geomagnetic field. The organ is of course not a compass needle, but some exceedingly sensitive current detector. To this class we assign the navigation mechanisms of some migrating birds,[19] the magnetic directional sensing of insects,[20] the orientation of planaria,[21] and possibly dowsing phenomena.[22]

The second class encompasses physiological stress effects which result from the many physical processes which must occur in an organism subjected to a magnetic field. These processes include (a) inductive effects in alternating fields, (b) semiconductor effects in neuronal functions, (c) physical rearrangement of paramagnetic and diamagnetic substances in homogeneous and gradient fields, (d) diffusion effects across membranes, (e) rate changes in hormonal secretion, (f) transient free radical interactions with the field, (g) distortion of bond angles via paramagnetic molecules, thereby affecting the fit between enzyme and substrate, and (h) changes in rotational polarization of molecules with specific reactive sites.

The cumulative physical consequences will tend to disturb the normal functioning of the organism: they represent a kind of stress to which the organism has to adapt and to which it will respond with some form of countermeasures. This stress effect may take time to develop, perhaps only after days or weeks of exposure to the field. Moreover, frequent changes in position of the test organism with respect to the direction or gradient of the external field would presumably tend to reduce the cumulative contributions from the individual physical processes so that the overall effect of the magnetic field would decrease. This class of effects includes growth retardation,[23] hematologic changes,[24] morphological changes,[25] and delayed wound healing.[26]

Many of the fundamental biochemical processes in living systems are directly connected with the transfer of electrons and protons. In 1963 Löwdin[27] drew attention to the fact that quantum mechanical proton tunneling in the hydrogen bonds between the complementary nucleotide bases in the DNA molecule is possible, with far-reaching biological implications. Theoretically, therefore, the tunneling probability should be affected by a magnetic field, thereby leading to alterations in the genetic code.

The third class therefore encompasses all possible mutagenic effects of magnetic fields. The evidence for these is rather mixed[28-30] so that the question of possible genetic effects is still wide open.

Magnetic effects which appear only in the presence of other physical parameters such as ionizing radiation, temperature, oxygen tension, etc., belong to the fourth class. As we have noted earlier, an organism rendered metastable by means other than a magnetic field will be susceptible to phase transitions triggered by the application of a magnetic field. This may explain why so many studies of enzyme-substrate reactions, cell membranes, and biological liquid crystals subjected to magnetic fields have produced such inconclusive results. Away from a transition phase it may simply take much greater fields or forces to cause structural rearrangements that lead to functional changes.

4. - Slowly Varying Magnetic Fields

In 1838 Sevigny defined "phosphene" to be any luminous sensation caused by pressure on the eyeball. Later the term was extended to include the electrically induced phenomenon which at a certain period was much in vogue as a parlor game: a group of people would join hands in a circle and receive a shock from a high voltage electrostatic generator. Flashes of light could be seen even with the eyes closed at the moment of making and breaking the circuit. Volta and later Purkinĕ gave detailed accounts of these electrophosphenes. It remained for d'Arsonval[3, 31] to demonstrate that a varying magnetic field is equally capable of producing visual effects.

Magnetic phosphenes in the human eye are observed as diffuse luminous flashes when the temporal areas of the head are exposed to pulsed dc or alternating magnetic fields. The flashes are seen when the frequency of the magnetic field lies between 10 and 100 Hz and its intensity is 20 to 100 mT. The intensity of the magnetophosphene attains a maximum between 20 and 30 Hz, at which point the flicker sensation seems to be synchronized with the field.

In 1902 Müller[32] observed that the illumination in the experimental room was important for the visibility of the flashes: the brighter the room the more noticeable the magnetophosphenes became. However, like Peterson and Kennelly[2] before him, he was unable to demonstrate the flicker with interrupted direct current fields, presumably because the time constant of his equipment was too long. Beer,[33] apparently unaware of d'Arsonval's discovery, extended Müller's work. He observed a correlation between the strength of the colorless flashes and the duration of the exposure to the magnetic field. He also noticed that movement of the eyes seemed to enhance the intensity of the flicker sensation. Beer questioned the then prevailing theory that the optic nerve was stimulated as he was unsuccessful in stimulating other nerves in the body to produce the same or similar effects.

Frankenhäuser[34] offered two possible explanations for the effect. One invoked induced currents of very short duration, which, following the tortuous conductive paths in the organism, would produce local heating. The second hypothesis required that the paramagnetic and diamagnetic constituents of the cellular components in the eye be forced to vibrate in accordance with the applied magnetic field.

In the first two decades of this century, magnetophosphenes were extensively studied, even rediscovered.[35] Danilewski[36] mentions the negative correlation between the estimated flicker rate and the known frequency of stimulation. He also noted that the orientation of the applied magnetic field is important; fainter phosphenes are obtained when the axis of the optic nerve is parallel to the flux lines. Martin-Freiburg,[37] searching for possible applications of magnetism to medicine, suggested that magnetic fields may have catalytic qualities, while Dunlap[38] postulated that the magnetic field may stimulate that portion of the visual mechanism which is not affected by visible light. Magnusson and Stevens[39] determined the relation between the intensity of the phosphenes and the frequency of the alternating field, and they discovered that the effect is always more intense in the temporal regions of the retina. They also found that with constant stimuli the phosphenes would decrease in brightness.

Barlow, Kohn, and Walsh[40] concluded that phosphenes produced by either magnetic or electric methods are colorless, maximal in the periphery of the visual field, temporarily abolished by pressure on the eyeball, subject to fatigue, induced by frequencies up to 90 Hz, and prolonged by eye movement. The phosphenes differ in that closure of the eyes raises the threshold for electric but not for magnetic stimulation. Figure 1 compares electrical and magnetic phosphenes for several values of stimulus strength: the fatigue effect is present at all intensities, but it becomes much more apparent as the duration of the phosphene effect increases. Barlow et al. believe that the locus of excitation is retinal; otherwise, they claim, the effect of localized magnetic stimuli, pressure on the eyeball, and movements of the eyeball could not so profoundly influence the phosphene.

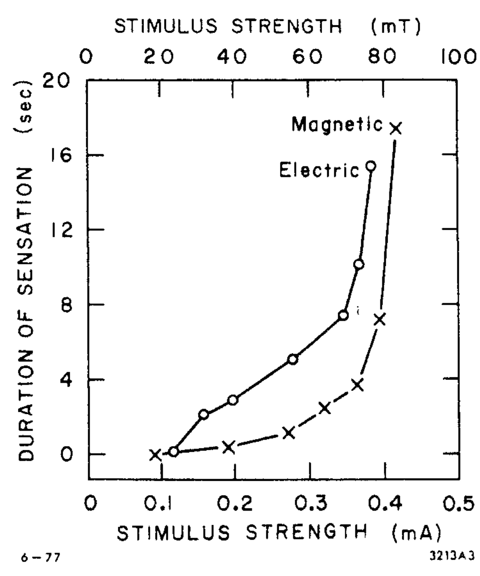

Fig. 1--Duration of the phosphene as a function of the intensity of the stimulus, at 30 Hz. After Ref. 40.

The inherent similarity between electrically and magnetically produced phosphenes led Valentinuzzi[41] to formulate a theory of electrophysiological stimulation wherein the retina is stimulated by induced currents. However, Liberman[42] suggests that the emf produced is too small to account for the effect: a field of 2T oscillating at 30 Hz normal to a loop 10 μm in diameter will induce an emf of only about 10^{-8} V. Even if all the retinal cells were coupled, an amplification of only about 10^6 would be achieved. Liberman therefore proposed that the phosphene was produced by the Hall effect or some photomagnetic effect upon a light-activated electron transfer system in the retina. This theory seems rather incomplete as phosphenes may be observed in the complete absence of external light.[43]

The other mechanism for phosphene formation which has been advanced is that of direct retinal stimulation. The basis for this proposal is the extreme sensitivity of the retina. In the spectral range extending from 400 nm down to 0.1 nm, the retina has a thousandfold lower threshold than other neurological elements. An energy input of only about 1 eV per molecule is sufficient to trigger the important cis-trans isomeric transformation of retinene.[44] Oster,[45] in reviewing his work on pressure-induced phosphenes and that of Seidel et al.,[43] concluded that as the flickering does not wander with the gaze the phenomenon may arise deeper than at the retina. Indeed, Brindley and Lewin[46] have induced phosphenes in noncongenitally blind people via direct electrode stimulation of the visual cortex.

5. - Macromolecular Orientation Effects

In rare instances it is possible to observe directly the action of a magnetic field on a macromolecular system. The magnetic moments of certain molecular aggregates can be lined up in specific arrays and an external magnetic field will then produce striking orientation effects. For example, the sickle cell hemoglobin molecules are stacked along the long axis of the sickled erythrocyte. As the hemoglobin molecule in this instance is a truncated tetrahedron, the heme plates will lie parallel to the long axis of the sickled erythrocyte, so that the magnetic vector of each of the hemes is perpendicular to that axis. In an applied magnetic field the sickled erythrocytes will then orient themselves perpendicular to the lines of force. Figure 2, due to Murayama,[47] illustrates this behavior in a rather striking manner. The magnetic field in this experiment was provided by a permanent magnet with a flux density of 350 mT in a 3 cm gap between 4 cm diameter pole pieces.

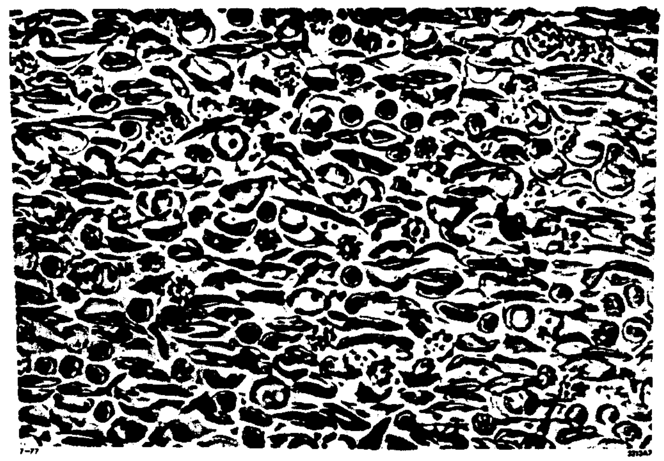

Fig. 2--Sickled erythrocytes oriented perpendicular to a magnetic field. The magnetic flux is directed downwards.

It is interesting to note that some time prior to Murayama's experiments Neurath[48] analyzed a simple model appropriate to normal erythrocytes and he concluded that neither translational nor rotational alignment of the cells was possible without recourse to magnetic fields of at least 30T. Neurath thereupon devised an experiment[49] involving cellular components which are relatively large in volume and have appreciably larger paramagnetic susceptibilities than the rest of the tissue. Ferritin, a protein complex of iron, containing as much as 20% by weight of the metal, is relatively paramagnetic and it plays an important function in plants and animals. Neurath's experiment was designed to detect the existence of large aggregates of ferritin in a suitable organism and to observe the motion of these ferritin particles in a highly inhomogeneous magnetic field (83.5 T/m). Although he was able to detect an effect which was clearly due to the magnetic field, Neurath concluded that his results did not substantiate the hypothesis of bulk ferritin transport.

6. - Very Weak and Null Magnetic Fields

The normal geomagnetic field at the earth's surface is approximately 50 μT but it varies somewhat with geographic location. The earth's magnetic activity - that is, changes in the geomagnetic field with time - also varies in a rather systematic, cyclical manner: an approximately eleven-year cycle associated with the appearance of sunspots, a diurnal variation, the circadian rhythm, and, finally, short period disturbances and random fluctuations or micropulsations whose origin is tied to solar activity. In spite of this short term "noisy" magnetic environment, life on earth has developed in a weak but remarkably uniform geomagnetic field. Even though the physiological significance of this magnetic field is open to conjecture, it is reasonable to assume that in the process of evolution the developing organisms must have become adapted to the magnetic background and may even have come to rely on the electromagnetic fields to obtain information about the changes in the environment and other processes important to evolution. It is interesting to note here that experimentation which progresses from simple discrete organisms through assemblies of greater hierarchical complexity to more complicated forms of life has yielded very unconvincing results. On the contrary, complex living organisms appear to be much more sensitive to variations in low level magnetic fields; the sensitivity climaxes in man.

This rather surprising conclusion assumes a new dimension when we consider some of its implications: extraterrestrial excursions in the form of space travel remove man from the geomagnetic field. Astronauts in the environment of the Spacelab will be exposed for extended periods to fields considerably below those on the earth's surface. What will they experience and how will their bodies react to the sudden disappearance of what would appear to be a vital component in the physiological makeup of man?

Similar questions must be asked for situations where man is required to spend long periods of time in a magnetic field environment that slightly exceeds the geomagnetic background. In the not too distant future, thermonuclear reactors will spread their fringe magnetic fields over relatively large areas, thus possibly exposing an appreciable fraction of the population to magnetic fields of 200 to 1000 μT.

Many studies have been made of various organisms in magnetically quiet (to 10^{-10}T) and in magnetically enhanced (to 120 mT) environments, and a number of effects have been reported, particularly by Conley.[50] Ordnance workers who spent most of their working hours for several years in the magnetically quiet environment in degaussing coils did not reveal any ill effects.[51] On the other hand, several studies have indicated a possible correlation between various health problems and either geographic variations in the geomagnetic field[52] or time-dependent fluctuations in the local magnetic field.[52-54] Unfortunately it is not quite clear whether these correlations truly reflect a cause and effect relationship.

Two closely related and well-monitored studies[55,56] have been made in which male volunteers were kept in magnetic fields not exceeding 50 nT for extended periods of time. The subjects all remained in good health and felt no ill effects. A wide variety of physiological and psychological tests were carried out to determine the effects of the magnetic field deprivation. With one exception, all tests yielded negative results. A significant change in the scotopic critical flicker-fusion threshold was detected. This threshold is the frequency at which a flickering light cannot be visually distinguished from a steady one. As Fig. 3 shows, this threshold frequency tended to diminish gradually during the deprivation period and then recover rapidly to baseline levels in the post-exposure period.

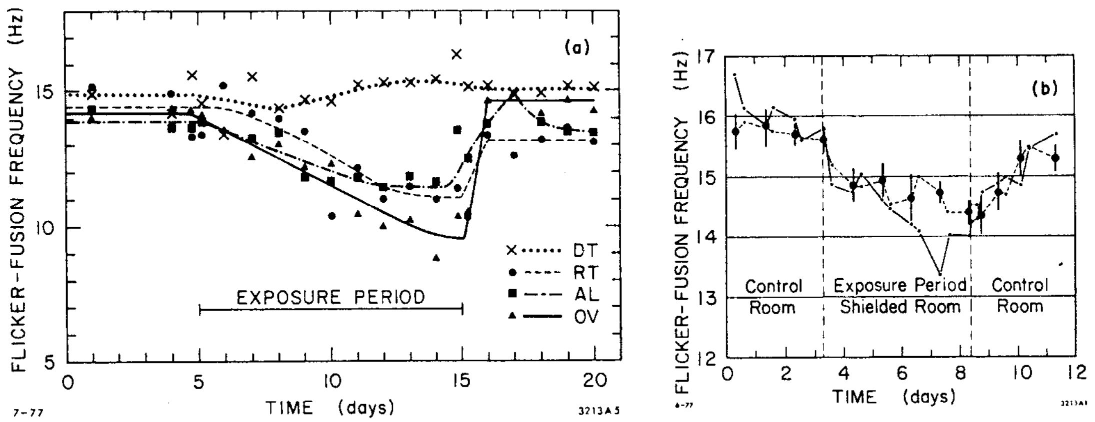

Fig. 3--Flicker fusion threshold change during exposure of a human subject to a 50 mT magnetic field (a) in a Helmholtz coil system; (b) in a magnetically shielded room.

The course of this possible decrease in visual acuity and its relation to the low magnetic field remains to be established. The changes are too subtle to be considered harmful, but they do indicate that removal of the geomagnetic field has a biological effect which could cause more severe effects during prolonged deprivation.

7. - Strong Magnetic Fields

There is considerable evidence that man can tolerate exposures to high magnetic fields for considerable periods without apparent ill effects. In 1962 Beischer[51] solicited comments from a number of nuclear physics laboratories on the experiences of their personnel who in the course of their work were accidentally exposed to magnetic fields up to 2T. From the results of his survey, Beischer concluded that beyond mild taste sensations and tooth pain associated with metal fillings at the time of exposure no other effects ascribable to the magnetic field were observed either during or after the exposure. He stated further that 2T 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 due to cumulative exposures to fields of 0.5T for a total of three days per year per man.

Primates, rodents, and low animal forms have been exposed experimentally in reasonably uniform magnetic fields up to 12T. Beischer[10] maintained mice for one hour in a uniform field of 12T and in an inhomogeneous field of 4.5T with a gradient of 70 T/m without observing any changes in either the growth rate or hemogram for a period of eight months after exposure. More detailed experiments were carried out with squirrel monkeys at similar field strengths. Some changes in the electrocardiograms (ECG)[58] and electroencephologrames (EEG)[59] of these monkeys were seen, but it is not clear whether these changes were due solely to the magnetic field. Kholodov[60] has also reported changes in the EEG of rabbits in fields of 80 mT.

Experimental results obtained with very high magnetic fields, often for a very short duration, and with the larger mammals cannot readily be extrapolated to the environment of a scientific or industrial installation. Moreover, the fixation of the animal or of body parts in the field certainly does not simulate the magnetic exposure of a plant operator. Inconsistent findings in similar experiments conducted by different investigators have made it virtually impossible to establish definite effects of high magnetic fields, particularly on submammalian systems. Finally, the information so vital for a critical assessment of magnetic field effects, namely the strength gradient and directional characteristics of the fields used in experiments, is often omitted in the biomagnetic literature.

In spite of these difficulties, and even though our present knowledge seems inconclusive, limits on human exposure to static magnetic fields must be set. A set of safety guidelines was recommended by the Director of the Stanford Linear Accelerator Center (SLAC) in 1970; these are summarized in Table I. No integrated dose limits were proposed. The guidelines also strongly urged that exposures above 2T for arms and legs, and above 0.2T for the whole body or head, be avoided altogether. These recommendations, which have found their way into the safety codes of many laboratories in the West, reflect the results of a survey of biomagnetic literature to 1970. As no significant developments in the field have taken place since that time, the standards have remained unchanged.

TABLE I

SAFETY STANDARDS FOR MAGNETIC FIELDS RECOMMENDED BY THE STANFORD LINEAR ACCELERATOR CENTER

	Extended Periods (hours)	Short Periods (minutes)
Whole body or head	20 mT	200 mT
Arms and hands	200 mT	2 T

TABLE II

SAFETY STANDARDS FOR MAGNETIC FIELDS RECOMMENDED BY A. M. VYALOV

	Field	Gradient
Whole body	30 mT	50-200 mT/m
Hands	70 mT	100-200 mT/m

The Soviet literature on biomagnetic phenomena has been reviewed by Novitskii, Gordon, Presman, and Kholodov.[52] These authors reported on a study by Vyalov on 1500 workers who were occupationally exposed to magnetic fields. A number of general symptoms were reported, as a result of which Vyalov recommended the safety standards listed in Table II. While these standards are of similar magnitude to the SLAC standards for long-term exposures, they differ in that Vyalov restricts hand exposures to a much lower value.

Beyond the observation of magnetophosphenes, so little is known about the biological effects of low frequency magnetic fields that meaningful exposure standards cannot be set at this time.

8. - Some Biomagnetic Speculations

One of the most striking manifestations in biomagnetics is the sensitivity of various organisms to a very weak magnetic field, or even to the lack thereof. As we mentioned earlier, it is well established for many species other than man: amoebae,[61] flies,[62,63] bees,[64] beetles,[65] snails,[66,67] and birds.[68] Several mechanisms for biological magnetoreception which have been proposed appear to be rather ill-adapted for, if not quantitatively incapable of, operating at levels of high sensitivity. The Hall effect has been invoked quite often as a possible explanation: unfortunately fields in excess of 100 mT are required even in common semiconductors to yield potential differences of the order of a few millivolts. Magnetoresistance is another phenomenon which requires inordinately large magnetic fields, from 0.1 to 1T, to produce 2 to 3 percent changes in the electron mobilities in ordinary semiconductors. Magnetic effects on the energy levels in organic compounds have been studied quite extensively, and again fields between 0.1 and 1T seem to be required to produce measurable effects.[69,70] Many organic molecules have an anisotropic magnetic susceptibility and hence experience a torque when placed in a magnetic field. As I have mentioned before, the eye is the organ seemingly most sensitive to magnetic fields, yet fields of 0.5 to 1T are required to induce measurable rotations of the retinal rods.[71-73] Plant chloroplasts require similar fields to make them rotate.[74]

It would appear that this high sensitivity to small magnetic fields must be due in some way to solid state biological processes which involve both the solids and the solutions making up the biological system. There is considerable evidence for semiconduction and for solid-liquid interferential electron conduction in the biological system.[75,76,77] Let us therefore extend this electron conduction process to include electron tunneling between two microregions in a cell with very specific properties: we require that at physiological temperatures these regions exhibit enhanced electrical conductivity with long range order.[78,79] Organic superconductivity is not a new idea: Pauling[80] and London[81] have proposed that electron currents around unsaturated organic compounds may be considered superconductive. Little[82,83] has used the BCS theory of superconductivity to propose that long chain organic polymers with polarizable side chains should display this phenomenon at or near room temperatures. In his view DNA is just the sort of biological molecule in which superconductivity might be found. Ginzburg[84,85,86] has postulated that high temperature superconduction may be expected in a sandwich consisting of a thin conductive film or filament adjacent to a dielectric layer. Others[87] have theorized that electron pairing is in principle possible for two electrons in <u>separate</u> conductive films by interaction <u>across</u> thin dielectric layers.

Suppose now that some of the microregions in the cell are organized into an array in which the superconductive portions form a series of sufficiently localized "weak links" (Josephson junctions)[88] in a generalized superconducting circuit. The "weak links" can take on any number of forms: a short constriction in the cross section of a superconducting microregion, a point of contact between two such regions, even two superconducting regions separated by a thin insulating dielectric layer. All weak links share a common property: they are exceedingly sensitive to magnetic fields. Thus we arrive at a mechanism which can impart to a biological system great sensitivity to magnetic fields. With this hypothesis we can also make a number of qualitative predictions: (1) a well-defined temperature effect can be expected; (2) the effect of the magnetic field is the same irrespective of the field polarity - in contradistinction to the Hall effect; (3) very small changes in the magnetic field are capable of producing relatively large changes in the Josephson current even in the presence of moderately large constant magnetic fields.[89]

What is the architecture of this microregion in the living organism? We do not know, but we can estimate its size by its reaction to an applied magnetic field because the size of the Josephson junction or loop determines its sensitivity. The region might be as small as a benzene ring or a single unsaturated lipid chain, or it might be as large as an array of molecules in the section of a membrane. The dependence of the maximum supercurrent through a simple Josephson junction resembles that of a "single slit" Frannhofer diffraction pattern in optics. At each nodal point the magnetic flux threading the junction is an integral multiple of the flux quantum (2.07×10^{-15} Wb). Therefore a single period fluctuation in the Josephson current can be induced by a single quantum: an organism exposed to a field of 100 μT would thus experience a supercurrent equivalent to a current loop approximately 2.5 μm in radius. For comparison, a mitochondrion is an ovoid approximately 3 μm long and 1 μm in diameter.

The sensitivity of a weak link is increased considerably when two such junctions appear in parallel: the "fringe" interval in the interference pattern then can be measured to about one thousandth of a fringe, which corresponds to a detection of magnetic flux with a sensitivity approaching 10^{-19} Wb. As there is no reason why the organism cannot do equally well, the detection of 100 μT by the organism would require weak links only 56 nm in diameter, which is well within molecular dimensions. Bear in mind that a DNA chain in even the simplest bacterium can have a total length approaching 4 cm!

9. - Conclusions

In spite of the considerable amount of experimental work which has been done in the field of biomagnetics, our understanding of the effect which magnetic fields have on an organism and in particular on the human body remains rudimentary. We can deduce from past experience that by and large the magnetic effects are fully reversible once the organism is permitted to return to its original environment. No experimental evidence exists which would indicate a cumulative effect caused by repeated exposures without adequate recovery times between exposures. Answers to these questions can come only from carefully conducted experiments which not only closely simulate such exposures and look for physiological, psychological, and pathologic changes, but also recognize that man is an exceedingly complex mechanism and that the cause and effect relationship due to the magnetic field may be completely masked by unrelated but competing processes.

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