CHAPTER 25

MAGNETISM AND THE LIFE SCIENCES

The curiosity of "magneticians" has recently extended to magnetic substances synthesised by some living organisms: bacteria, bees, pigeons, dolphins... The list gets longer every year. This is one aspect of ***magnetobiology,*** *which also studies the influence of magnetic fields on the growth of plants or on animal metabolism. The magnetic properties of organic matter, whether living or inert, will be treated in the first part of this chapter.*

On the contrary, the term ***biomagnetism*** *is reserved for the study of magnetic fields generated within living beings by muscular movements or by a cerebral activity, and also embraces those magnetic techniques used to explore living beings. These will all be presented in the second part of this chapter.*

Medicine *does not restrict itself to the exploration of the living, it also intervenes in vivo, and a description of some magnetic intervention techniques on living beings will be given in the third part.*

1. MAGNETIC PROPERTIES OF ORGANIC MATTER

1.1. INERT ORGANIC MATERIALS

Organic matter is based on the *chemistry of carbon,* associated with H, O, N and various other elements. Pure carbon is diamagnetic, as are hydrogen and nitrogen, whilst oxygen is antiferromagnetic at very low temperature. Some interesting magnetic properties were observed on organic compounds containing only C, H, O and N. Such is the case of tanol suberate $(C_{13}H_{23}O_2NO)_2$ every molecule of which contains two free radicals N-O. An electron is localized on every N-O bond, and this substance behaves antiferromagnetically below 0.38 K, which shows how weak the interactions are in this case [1]. For an induction of only 10 mT, a metamagnetic transition occurs, and at less than 60 mT the material is practically saturated with a moment of the order of $10\ \mathrm{A.m^2}$ per mole.

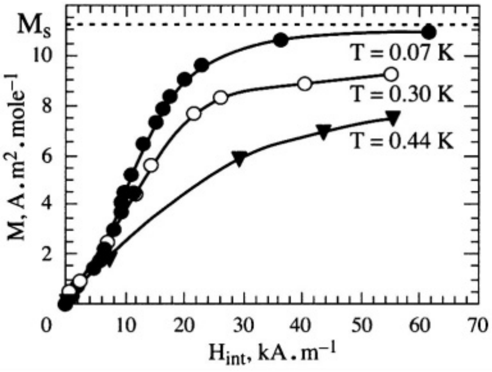

Figure 25.1 - Magnetization of tanol suberate powder as a function of the internal field

Note the S-shape of the isotherms measured at temperatures lower than the critical temperature $T_N = 0.38$ *K.*

In 1996, the world record for the Curie temperature of a purely organic substance $T_C = 1.46$ K, was established by the dupeyredioxyl molecule (1,3,5,7-tetramethyl-2,6-diazaadamantane-N,N’-dioxyl) [2], whose ferromagnetism originates from two spins 1/2 situated on two N-O groups.

Molecular magnetism, as this very young science is called, is concerned with the magnetic properties of organic molecules, including the search for molecules that might have an ordering temperature above room temperature. The potential candidates are to be found amongst the organo-metallic compounds where the magnetic centers are atoms of the 3d metals, for example iron or chromium. There are a great variety of more or less complex organic molecules that include one or several metallic atoms. Their magnetic properties are sometimes interesting: for example, it has been known for the last twenty years that TTF BDT(Cu) or tetrathiafulvalene-$CuS_4C_4(CF_3)_4$ has a noticeable transition at 1.5 K in a magnetic field and a saturation moment approaching $0.25\ A.m^2$ per mole in 15 teslas [3]. This molecule contains one 3d atom, that of copper.

For more information on molecular magnetism, the reader is referred to the comprehensive survey published by Olivier Kahn in 1993 [4], and to a more recent review article that authoritatively covers organic molecular magnetic materials and organo-metallics [5].

1.2. LIVING ORGANIC MATERIALS

Even when they are diamagnetic, the organic molecules that make up plants can sometimes present a sufficient magnetic anisotropy to produce orientation phenomena in intense magnetic fields: for example, G. Maret at the High Magnetic Field Laboratory (LCMI) in Grenoble observed in the 1980’s that the orientation of the barbs growing on lily pollen grains (at a rate of 0.5 mm per hour) is random in the absence of a magnetic field, or in a field μ_0H less than 3 T. On the contrary, in 14 teslas, these barbs are all aligned with the field. The benzene rings contained in the plant try to rotate so as to minimize their diamagnetic energy, and in doing so drag with them all of the barbs.

1.3. ORGANOMETALLIC MATERIALS AND BIOLOGY

In the following treatment, we will only discuss the magnetism of organometallic molecules that are found in living organisms, or which could present a therapeutic interest: these molecules almost always contain iron atoms, with the exception of the gastropod family (snails) where nickel replaces iron.

Iron is an indispensable element for life due to its presence in certain molecules that accept oxygen or electrons (such as haemoglobin). It is stored in the organism under various organic or mineral forms. Iron sometimes acts as an acceptor of electrons in metabolism, which explains how certain bacteria are capable of catalysing the production of large quantities of iron sulphide or extra-cellular magnetite. The crystallized minerals can become structural elements, magnetite in chiton teeth, goethite in the radula of the patella (a molluscan gastropod), oxyhydroxides in some unicellular organisms, or to form within a cell ferrimagnetic single domain grains whose role will be discussed later. In a normal adult man, one finds 3 to 4 grams of iron, of which 60 to 65% are in haemoglobin and 25 to 30% as ferritin, the remainder being distributed in myoglobin (3 to 5%) and in trace quantities as heme-containing enzymes.

We will first consider the properties of some complex molecules that include iron atoms, because of their fundamental importance in biology.

1.3.1. Haemoglobin

It is a heteroprotein consisting of globin (a protein) and of a prosthetic group called a heme that contains iron and represents only 4% of the total mass of this heteroprotein. This group gives blood its red color in the oxidized state and a bluish color in the reduced state. The principal constituant of red cells, haemoglobin is responsible for the transport of oxygen from the lungs to the cells in the tissues. Iron is in a divalent form, and it is bound by four of its six coordination valences to the four nitrogen atoms of the four pyrrole rings of the protoporphyrine molecule. The low iron concentration explains the paramagnetic behavior of this molecule. For more information the reader should look up the article “blood” in an encyclopaedia.

1.3.2. Ferritin and haemosiderin

Ferritin and haemosiderin are the two main forms of iron storage in living organisms. The molecular weight of ferritin is on the order of 400,000 to 500,000 Da, and this molecule contains about 16% by weight of nitrogen. Its iron content, measured via its ratio to nitrogen (Fe/N), varies considerably according to the physiological conditions and can reach 4,500 atoms, that is 26% of its weight, in the form of trivalent iron (colloidal micelles of ferric hydroxide and iron phosphate). It occurs as 7.5 nm grains of ferri-hydrate ($9\ Fe_3O_4 - 9\ H_2O$) encapsulated in a spherical envelope of proteins about 2 nm thick. These grains contain about 4,500 spins coupled antiferromagnetically, with a *weak uncompensated moment:* they could therefore act as magnetic field sensors. Haemosiderin, a related molecule, is considered to be a degraded form of iron reserves in the body.

1.3.3. Fibrin

Fibrin is a polymer that forms during the final stage of blood coagulation. Jim Torbet studied its polymerization under an intense magnetic field: as in the case of the previously mentioned lily pollen, the diamagnetic anisotropy of this molecule is large enough to produce perfect orientation of the fibers at the end of the process. This orientation, which was achieved at the Matformag laboratory of the CNRS, has improved our knowledge of the structure, the assembly and the destruction (lysis) of the fibrin under conditions close to those of the physiological state.

1.4. MAGNETIC MINERALS ENCAPSULATED IN ORGANIC MATTER

Systems belonging to this class are particles of magnetite synthesized by certain algae and bacteria. So are those nanoparticles and encapsulated microspheres, natural or synthetic, which all present the characteristic of being magnetic minerals completely surrounded by organic matter. They all provide notably magnetic and possibly biocompatible assemblies. These materials can be used very effectively in imaging (one can localize zones containing magnetic matter), or as separating agents in the purification of biomaterials, or again to identify minute quantities of organisms, of cells or of genomic material, and finally in the treatment of malignant tumors.

1.4.1. Algae and magnetotactic bacteria

The presence in living organisms of ferrimagnetic single domain grains, generally magnetite (Fe_3O_4) but also greigite (Fe_3S_4), suggests that these organisms can use such grains to sense the orientation and perhaps the intensity of the magnetic field due to the torque the field produces on a grain with uniaxial anisotropy. This is undoubtedly the case in magnetotactic bacteria. These were discovered in 1975 by Blakemore [6]. They feature a chain of single domain grains along the length of their bodies, which are in the shape of rods terminated by one or two cilia that propel them through water.

Figure 25.2 shows a bacterium that has a flagella at each of its extremities, while most other bacteria only possess a single flagella at only one extremity. All these bacteria are permanently oriented parallel to the magnetic field lines. They can remain in their preferred environment, fine grained sediments, thanks to their magnetic orientation with respect to their unique direction of motion. In the northern hemisphere, they move toward the north pole, and in the southern hemisphere toward the south pole. In either case, due to the inclination of the earth magnetic field, they are thus led toward the bottom of the water. This assures their survival as these organisms do not withstand an excess of oxygen. It should be noted that a small proportion of these bacteria is born disoriented and rapidly disappear, but these will save the species in case of a reversal of the geomagnetic field! Bacteria containing magnetite and those containing greigite do not have the same genes and developed independently. The decomposition and sedimentation of greigite-based bacteria could be the origin of mineral greigite.

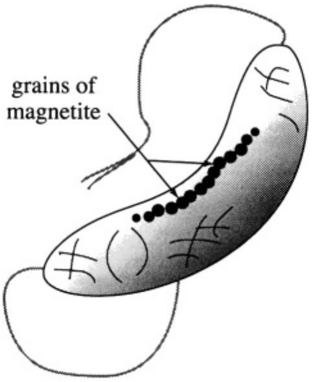

Figure 25.2 - Bacterium Aquaspirillum magnetotacticum, enlarged about 20,000 times

1.4.2. Animal magnetism

A sensitivity to magnetic fields has been demonstrated on numerous animal species which habitually travel with few visual references or over large distances: flying insects (bees), migratory birds (pigeon), migratory or deep water fish (salmon, selachians), cetaceans (dolphins, whales), reptiles (sea turtle), amphibians (salamander), mollusks (sea slug), arthropods (lobster)… However, their detection device is not necessarily based on the incorporation in a sensory organ of a magnetic moment as in bacteria. A competing system could be envisaged, based on the current induced in a conducting loop moving through the field. This hypothesis was proved in selachians, which are also sensitive to an electric field. They can refind a direction only after having turned in circle several times, inducing in their electric "circuit" a current which depends on its orientation with respect to the ambient magnetic field. The joint demonstration of sensitivity to a magnetic field, and of the presence of magnetite in the pigeon, bee, salmon or dolphin, is therefore a strong presumption, but not a proof, of the integration of this magnetite in a magnetometric organ. For further information on magnetic orientation in animal species, one should consult reference [7].

1.4.3. Encapsulated Microspheres

Ferritin

This substance, essential to the life of higher organisms, was already described in § 1.3.2. These particles are found in a natural state in all sorts of organisms and in particular in the bacteria *Escherichia coli* and *Azotobacter,* and one now knows how to synthesise them. They are of interest both to physicians, because they are a material of choice for applications, and to physicists who are looking for a macroscopic quantum tunnelling effect [8].

Dextran ferrite

These are microspheres of colloidal magnetic iron oxide, coated in dextran. They have a sizeable specific magnetic moment, from 16 to $48\ \mathrm{A.m^2.kg^{-1}}$, and they reach saturation in fields of 20 to 60 mT. The grains, which are 3 to 15 nm in diameter, are single domain, and have a superparamagnetic behavior. This system is biocompatible and presents a very low toxicity. The surface properties of these particles are determinant in their ability to spread in living organisms. We will see in § 3.6 the use that can be made of this type of material in medicine.

1.5. HUMAN SENSITIVITY TO MAGNETIC FIELDS

Yves Rocard conducted a scientific survey on dowsers, and concluded that a magnetic effect exists in certain particularly sensitive individuals [9]. One can estimate the magnetic fields involved in this type of phenomena to be $B_0 = 10^{-9}$ T. Let us evaluate the energy involved by considering only the contribution of the ferritin molecules: a molecule of ferritin has around 4,500 Fe^{3+} cations coupled antiferromagnetically, but with a compensation defect that one can estimate as 1% of all the sites. Under such a field, the absolute value of the potential energy $\mathfrak{m}B$ is therefore the energy of a magnetic moment $\mathfrak{m}$ of $0.02\times10^{-19}\ \mathrm{A.m^2}$ subject to B_0, that is 2×10^{-30} J. If one compares this energy to that associated with the threshold sensitivity of the eye (around 10^{-17} J), one sees that a human being will theoretically only be capable of detecting such a signal if a very large number of molecules carrying a magnetic moment ($N > 10^{13}$) react collectively to this magnetic field. However, as there are around 2×10^{18} molecules of ferritin in the human body, and if one considers that all of these molecules take part, then such a magnetic energy becomes easily detectable, but by what mechanism? The terrestrial magnetic field corresponds to a much larger signal but no convincing experiment has yet shown the existence of magnetotropism in a human being. This topic therefore still remains very controversial.

The recent discovery of particular tissues or of lineages of white blood cells enriched in magnetite, has probably more to do with the metabolism of iron, in relation to a possible pathological differentiation. *This presence calls for caution regarding the present claims of the harmlessness of exposure to strong fields or field gradients during MRI scans. Cells rich in magnetite could, in theory, suffer lesions during their exposure.*

On the other hand, the sensitivity of living cells to *variable* magnetic fields has been abundantly proven, but it concerns effects related to the frequency, rather than to the intensity of the field.

2. MAGNETIC EXPLORATION TECHNIQUES FOR LIVING ORGANISMS

Magnetic clinical examination methods are very often non-invasive, that is completely painless. They are at present undergoing a rapid development. For example electromyography, which consists in inserting a needle into a muscle of the hand, and then measuring the electrical potential associated with the work of this muscle, will be advantageously replaced by magnetomyography. The latter monitors at a distance the magnetic field associated with the same electric signal, but without any pain for the patient! Without being exhaustive, the list of magnetic techniques which will be described below shows the diversity of the approaches used:

- resonance methods (MRI),
- detection of magnetic fields produced by living tissues,
- magnetic marker techniques,
- magnetic sensors.

2.1. RESONANCE METHODS

MRI (magnetic resonance imaging), because of its importance, is treated separately in chapter 23. We just note that this technique submits the patient to intense static magnetic fields whose harmlessness at the cell level appeared to be accepted but has again become controversial (see § 1.5).

2.2. DETECTION OF MAGNETIC FIELDS PRODUCED BY LIVING TISSUES

The biological functions associated with muscular work or nerve impulse set off a cascade of chained chemical transformations, electric polarizations and depolarizations, which result in peaks of electric activity detectable using appropriate voltmeters (electromyography, electroencephalography). This electric activity generates varying magnetic fields at the same relatively low frequencies: the electric potentials involved (typically in the range of μV to mV) are closely correlated to the associated magnetic fields, which vary from of 2×10^{-14} to 2×10^{-11} T, as was shown by Williamson and Kaufman in an early but still remarkable review article [10] dedicated to biomagnetism.

The detection and the measurement of such weak magnetic fields requires magnetometers with a very high sensitivity (SQUIDs), which have to be very well protected against all spurious outside sources, liable to produce much larger fields. The present terrestrial magnetic field has a mean value of 45 μT (4.5×10^{-5} T), greater by six orders of magnitude than the most intense biomagnetic field, that associated with the activity of the heart (magnetocardiography or MCG).

The ultimate limit of magnetometer sensitivity depends on the “noise equivalent signal”, S_N that is universally expressed in $T^2.Hz^{-1}$. The magnetic field equivalent to the noise, measured over a band width ΔF, is thus given by $(S_N \Delta F)^{1/2}$. Hence $(S_N)^{1/2}$, which is expressed in tesla.(hertz)$^{-1/2}$, will be the noise equivalent field for $\Delta F = 1$ Hz.

A survey dating from the 1980’s [10] compares the sensitivity of different magnetometers at 10 Hz:

- 3×10^{-11} T for a commercial flux gate,
- 2×10^{-12} T for a laboratory flux gate (NASA),
- 3×10^{-13} T for an induction coil with a ferrite core,
- 8×10^{-14} T for a SQUID system in an urban environment,
- 8×10^{-15} T for a SQUID with magnetic shielding, and
- 6×10^{-15} T for a SQUID far away from any urban noise.

These performance figures do not seem to have been surpassed in the recent literature. Experimentally one observes a 1/f decrease in the noise at low frequencies, until one meets the Johnson noise. The noise that experimentally limits the best present day magnetometers seems to come from the magnetic fields generated by the thermal agitation of electrons in conductors situated close to the SQUID, principally in the cryostat walls and superinsulation, but also in the laboratory shielding itself. The lower limit in the $(S_N)^{1/2}$ would seem in practice to be a few 10^{-15} T.Hz$^{-1/2}$. Certainly, the magnetic noise of thermal origin produced by the human body is 10 times weaker, but the noise caused by the measurement system will never allow this ultimate sensitivity of 10^{-16} T.Hz$^{-1/2}$ to be reached [11].

However, it can happen that some parts of the human body produce magnetic fields several orders of magnitude greater than this limit: for example the field produced by magnetic dust in the lungs of certain workers (arc welders) and magnetised by external fields. Without magnetic shielding, the sensitivity is poorer, but it can already be sufficient to allow magnetocardiography measurements. In order to cancel external noise to first order, many magnetometers operate as gradiometers: two coils are placed some centimeters apart and connected in opposition. Thus, all noise coming from distant sources is eliminated, while only the differential signal from the source, that is situated closer to one coil than the other, is measured. Closed circuit liquid helium systems allow lighter and even portable equipment to be used. Thus, it is now possible to examine by MCG the cardiac rhythm of a six month old fœtus.

2.3. *MAGNETIC MARKING TECHNIQUES*

These techniques can be applied either on the macroscopic scale (for example, to measure the gastro-intestinal transit speed of a meal charged with magnetic powder), or on the microscopic scale, for example to follow cellular division or to measure the concentration of a medicine in the blood. In the first case, a portable magnetometer will localise zones presenting a strong magnetism. The second case will require much finer analyses of magnetic susceptibility on a sample taken from the organism (blood sample), or again detection by a SQUID of the magnetism induced by a weak magnetic field in the magnetic microspheres. When a bacterium is marked, it is possible to separate it from the other non-marked cells, by applying a magnetic field gradient: this is the **magnetic separation technique** or **magnetotaxy** that appeared in the middle of the 1970's. Today, the marking and magnetic separation allow a more reliable, simple and fast detection of the tuberculosis bacterium, than by traditional methods [12].

2.4. MAGNETIC SENSORS

The foreseeable development of microsensors will allow the measurement *in situ* of all sorts of physical parameters. Strain or pressure gauges will be able to take advantage of magnetoelastic effects, for example for measuring the pressure in the eye toward detecting a possible risk of glaucoma. This measurement should be carried out during the entire night-day cycle (24 hours in a row), which is impossible at the present time due to the invasive character of the techniques used and the size of the equipment. A miniaturization of these measurements would require a microsystem including a magnetostrictive microactuator acting at regular time intervals on the cornea, a deformation microsensor and a microprocessor capable of transmitting information to a receiver located close to the patient. All the necessary energy would be transmitted by induction, and the signal would also be picked up remotely: the system would be contained in a corneal lens and could therefore be carried by the patient for 24 hours. The interest in magnetic sensors obviously lies in their essential property of being able to be read remotely, without any connecting wires, and important developments can be expected in this promising field.

3. MAGNETIC TECHNIQUES FOR INTERVENTION IN VIVO

This does not concern an examination, but an intervention in order to treat the patient. This area too is in full evolution, and its field of application grows all the time. An excellent review article deals with magnetically aided instrumentation in medical research [13]. We will only describe some typical applications, going from the macroscopic to the more microscopic aspects.

3.1. CARDIAC VALVE

The heart is made up of four cavities (two atria and two ventricles) with four valves opening passages between atrium and ventricle or between ventricle and artery. The essential role of the valves is to ensure a unidirectional blood flow in the heart.

When a natural cardiac valve is deficient and cannot be repaired by a surgeon, it is necessary to replace it by an artificial valve (120,000 implants per year worldwide, 1/3 of these valves are biological and the remaining 2/3 are mechanical). The classic mechanical valvular prostheses consist in general of a circular ring (the seat) inside of which shutters (called leaflets) rotate about hinges. When they are open, these leaflets allow blood to flow; when closed, they prevent the blood from returning. The opening and closing movements of these valves are guided by the thrust exercised respectively by the flow and ebb of the blood. *This mode of operation is fundamentally different from that of natural valves.* In the case of the mitral valve, tendons fixed to the edge of the valve membranes and the ventricule wall pull on them to open the valve, and the combined action of an adverse atrioventricular pressure gradient and post-valvular turbulence closes the valves without any reverse flow. Contrary to natural valves, the energy necessary for the displacements of the mechanical prosthesis shutters is taken from the total energy of the blood flow at each pulse. This results in *an extra workload and therefore an unnecessary strain on the heart* to maintain an identical flow.

To overcome this disadvantage, Professor Carpentier (Broussais Hospital, Paris), invented an active prosthesis whose leaflets are moved partly by magnetic forces. Samarium-cobalt magnets are included in the leaflets and the valve seat in order to produce an opening torque on the closed leaflets, and a closing torque on the open leaflets. Thus, magnetic energy is used to open and to close the leaflets of this prosthesis. The key to the working of the prosthesis lies in the fine balancing of the opening and closing magnetic torques created by the stationary magnets attached to the valve seat on the mobile magnets fixed to the leaflets. The adjustment of the opening and closing magnetic torques is performed experimentally *in vitro* on a cardiovascular simulator, developed by the Laboratory of Cardiovascular Biomechanics, Ecole Supérieure de Mécanique, Marseille. This active mechanical valve prosthesis was developed recently by a French company (SICN, F-38113 Veurey-Voroize).

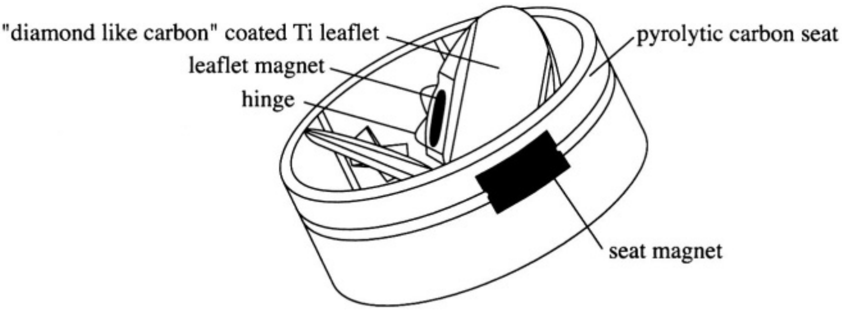

Figure 25.3 - Active cardiac valve *(SICN document)*

3.2. MAGNETIC MANIPULATION OF CATHETERS

An increasing number of surgical operations call on microsurgery techniques, which in their preliminary phase require a micro-instrument to be directed towards the site of the intervention. Generally, this micro-instrument is carried by a catheter that passes along the blood vessels; but at a bifurcation, it can happen that the catheter obstinately takes the wrong path.

It is then impossible to carry out the operation, and the patient could die: this is why, as from 1951, the technique of magnetic guidance of intravascular catheters was developed under the leadership of Tillander in Sweden [14]. The first applications only concerned those vessels that were sufficiently large to admit these devices, which were at that time quite bulky: aorta, renal and pancreatic arteries.

The technique is still the same: a magnet is fixed to the end of a flexible catheter. During the progression of the catheter along the artery or vein of the patient, should the catheter try to take the incorrect route, then the application of an ad hoc magnetic field gradient will deviate the extremity of the catheter towards the correct direction and allow the micro-instrument to continue its progress towards the target.

This remarkable technique has continued to progress, in particular with the appearance of magnets of much higher energy density so that the same result is achieved for a considerably reduced volume.

Such progress has since allowed this technique to be applied to neurosurgery: for example in the case of the treatment of aneurysms, A. Lacaze (CNRS Grenoble) developed a magnetic guidance system which takes advantage of the remarkable properties of modern samarium-cobalt magnets.

Figure 25.4 illustrates the principles of this technique: the catheter C should reach the aneurysm A, but it has a tendency to pass into the vein B1. A strong mini-magnet M under the influence of a field gradient in the direction of the arrow H attracts the catheter into the vein B2, then by reversing the field gradient, into the aneurysm A.

This magnetic guidance technique is used in a number of different operations, because it is less invasive than classic surgical techniques and avoids the necessity of making large incisions which take longer to heal: for example the treatment of varicose veins can now be carried out from inside the veins, without having to perform multiple incisions along the length of the vein.

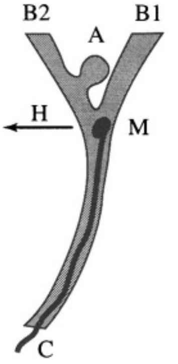

Figure 25.4
Aneurysm therapy

3.3. DENTAL CARE

In odontology, it can be sometimes advantageous to fix a crown on to a base by magnetic means: a Japanese group has developed a dental prosthesis incorporating rare earth magnets, which despite their small size, develop a force of 4.9 N. The magnet is sealed by laser to its stainless steel cover to provide protection against corrosion [15]. The effects of the permanent exposure of brain cells to this magnetic field are unknown.

The filling of the dental channel can also use cements (based on phosphates) containing 50% magnetic particles: their application is carried out under an alternating magnetic field gradient that encourages the penetration of the cement.

3.4. MICRO-ACTUATORS

When we discussed microsensors in § 2.4, we mentioned the need for a microactuator to apply a local pressure, at regular intervals, on the cornea. Such microactuators are due for a considerable development, to assist in many surgical or medical tasks. For example, the use of remote-controlled micro-scalpels is being studied, as well as that of magnetostrictive micro-pumps intended to deliver minute doses of drugs on demand. In cardiology a micro-pump could be inserted during an operation, and it will then function for many years. Should a cardiac problem occur, the starting up will be done using an external magnetic field, which is triggered by an alarm signal produced by a sensor and controlled by a microprocessor. The pump will then deliver into the patient's blood the correct dose of cardiac tonic to overcome the crisis. Such microsystems will use thin film magnetostrictive techniques (see chap. 18 and 20).

3.5. USE OF MAGNETOTACTIC BACTERIA

It is possible to produce magnetic patterns on the surface of very soft transformer sheet metal (coated FeSi) without any damage, by the Bitter method (see § 6.1.1 of chap. 5) using solutions with a high concentration of magnetotactic bacteria to reveal the magnetic domain walls via the gradients in the intensity of the stray field [16]. Apart from this very technical application, the main applications envisaged for these bacteria lie in the medical field. The first of these concerns the treatment of malignant tumors by heat. Under the action of appropriate field gradients, the magnetotactic bacteria are concentrated in the tumor, then heated up to 40°C by the application of an alternating magnetic field. This hyperthermal treatment will selectively destroy only those cells localized in the tumor. Another application concerns fixing poisonous chemicals by magnetotactic bacteria, then guiding these bacteria. When concentrated on the tumor, the bacteria are killed, and the released poisonous substance can act solely on the tumor, without any of the secondary effects that are observed with classical chemotherapy.

3.6. USE OF OTHER MAGNETIC MATERIALS

To create a local hyperthermia, without a risk of overheating, Japanese researchers have used amorphous magnetic materials based on Fe, P, C and Cr with a low Curie temperature: as soon as the temperature rises too much, the material loses its magnetism and so warms up less under the action of the variable magnetic field. The temperature is thus stabilised in the neighborhood of the Curie temperature.

Another approach uses synthetic colloidal magnetic iron oxide. Chan *et al.* optimized the manufacturing process of this material in order to ensure, not only a low toxicity and a good biocompatibility, but also an excellent energy yield. The dextran stabilised magnetic iron oxide produced by ultrasonic treatment gives heating rates of the order of 5°C per minute on tissues doped with only 1 mg of iron per cm^3 when they are submitted to a radiation of $1\ W.cm^{-3}$ at 1 MHz, while the heating of unloaded tissue remains negligible [17].

3.7. MAGNETOTHERAPY

Here we are faced with a vast topic, and in certain regards controversial. Since antiquity, the Chinese healed otitis by applying magnets to the sick ear. Shortly before the French Revolution, Mesmer claimed he could heal all kinds of illnesses using magnetism, but was convicted of fraud by the Academy of Sciences in Paris.

The famous Japanese company TDK sells gold necklaces inset with a chain of rare earth magnets; these “shoulder TDK” are patented and are claimed to heal pains in the neck, shoulders and the back [18].

In auriculotherapy, one of the techniques used consists of fixing very small needles on the ear and then waving a small magnet close by.

So magnetotherapy is nowadays thriving, with an increased following, but still remains unexplained: the main affections liable to being healed by magnetotherapy seem to be benign rheumatology, minor traumatology and problems concerning tonic posture activity [19].

Some scientific studies attempt to specify the mechanisms that could be involved, for example at the cell level. Thus, the circulation of blood under a static magnetic field would lead to a change of the clotting rate [20].

It is possible to relieve some affections of purely mechanical origin with the help of magnetic fields: for example foreign metallic bodies (copper) have been extracted from the eye using pulsed magnetic field gradients [21].

All these treatments rely on the influence that a magnetic field exercises on a biological substance, via *magnetic dipolar interaction,* which is a well-established scientific fact and that is employed by *magneticians.*

They have nothing in common with the treatment by *hypnotisers* who also claim to use Magnetism, but whose action at a distance has never been analysed quantitatively, nor explained scientifically, and whose results have never been subjected to scientific study and rigorous statistics.

4. CONCLUSIONS

Since ancient times magnetism has fascinated mankind, who has tried to appropriate its virtues, including those for healing. Living organisms generally contain very small quantities of magnetic material, but our knowledge on the interactions between magnetism and biologic functions remains embryonic even to this day, and one cannot yet establish with any certainty the existence of effects of a static magnetic field on the behavior of living organisms.

However, this situation should evolve rapidly since research is very active in this field, as is shown in the already old but excellent review article of Williamson and Kaufman [10], and the more recent book by Wadas [22], both of which are devoted to biomagnetism. In the same way, biotechnologies associated with magnetism are making great strides forward.

This science, situated at the crossroads of magnetism, biology and organic chemistry, calls more and more on the most modern techniques of data processing to interpret a magnetoencephalogram or to refine the structure of a magnetically active macromolecule. With such a variety of investigative tools, one can very shortly expect an abundant harvest of fascinating results.

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