# Magnetobiology: A historical view

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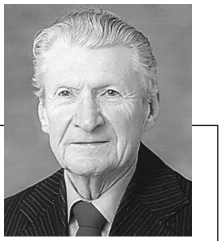

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# magnetobiology: a historical view

by M.E. Valentinuzzi

My father, Maximo Valentinuzzi (1907–1985; M.D. and B.A. in physics and mathematics), may be considered a pioneer in the modern era of *magnetobiology*. He left me some handwritten notes that I am using as the initial material to start up this historical project. Let me dedicate it to his unforgettable memory, as a man who loved science, knowledge at large, and, above all, the human being and life.

My mentor at Baylor College of Medicine, in Houston, Texas, Dr. Hebbel E. Hoff (1907–1987), gave me precisely this very project back in the 1960s as part of one of his history courses in physiology and medicine. I never quite finished it. Let me now pay, a little late, that internal academic debt. Hebbel was a true teacher and an extraordinary human being who played a significant role in my life.

To both of them, may this modest contribution serve as a token of deep recognition reminding, at the same time, the often-mentioned concept of intellectual progeny.

## Background

Back in 1952 or 1953, Maximo Valentinuzzi was a professor of biophysics (which was actually called "biological physics") at the Universidad Nacional del Litoral (Rosario City, Argentina). He wanted to introduce new subjects in order to update the undergraduate curriculum of the Biochemistry School and started to search for books and papers making use of the few available bibliographic sources at the time. It was while doing this that he ran across magnetochemistry, as the discipline dealing with the magnetic properties of chemical elements and compounds. From here stems the wide division of ferromagnetic, paramagnetic, and diamagnetic materials. The first are attracted to a magnet's poles, the second are sucked in by the field (i.e., displaced from the points of lesser to the points of greater intensity), and the third are expelled from the magnetic field (i.e., they are displaced from the points of greater intensity to those of lesser intensity) ([29]; this is based on a course offered 11–19 November 1955 in the Department of Biophysics of the Medical School of the University of Uruguay, in Montevideo, Uruguay, when the director and professor was Dr. Miguel A. Patetta-Queirolo. Thereafter, the same department published a book in Spanish in 1958.).

Immediately thereafter, Valentinuzzi's attention was caught by the fact that there was an *electrobiology* and an *electrophysiology* (both words covering, in fact, the same area) but, apparently, there was no *magnetobiology*. The idea and concept became a driving force that led to a long series of theoretical and experimental studies, to finding other people involved in similar efforts, and to the organization of three symposia (in 1961), all held in Chicago, sponsored by the College of Pharmacy of the University of Illinois. One of the leading organizers was Dr. Madeline F. Barnothy, professor of physics at the latter university and a native of Hungary.

Magnetobiology studies the effects of magnetic fields on biological systems and also deals with the magnetic fields generated by these systems. We might say that the latter represents the true and purest magnetobiology, somewhat analog to electrophysiology, or its counterpart. Such definition clearly establishes two distinct areas: the magnetic field as a stimulus to the tissues, as the electric field can be, and the biological tissue as a magnetic generator, in a way paralleled by the electrical action potential elicited from excitable cells. Some investigators, like Oswaldo Baffa, in Brazil, restrict the word magnetobiology only for the first group of phenomena, while they prefer to use *biomagnetism* instead, for the second group; that is, when the magnetic field originates in the living tissues.

The objective of this article is to uncover as much as possible the origins and development of magnetobiology, going backwards in time and trying to stick to the second concept given above—biomagnetism; that is, excitable tissues as true generators of magnetic fields. However, in many respects, the external fields' influence may not always be excluded and reference to such view will be necessary and even, perhaps, mandatory.

Questions that the potential reader may ask deal with the use of magnetobiology today. They include: Can it be applied as a diagnostic tool? As such, is there a technology associated with it? The answer to both of these questions is yes; however, the latter is not readily available because of cost and practical difficulties, even though there are research groups with modern, well-equipped laboratories specifically designed and installed for that purpose.

## The Pseudoscientific Line: Mesmer, His School, and Some of His Followers

It would be pretentious to try an exhaustive historical review of the subject considering, first, the amount of material dealing with it, and, second, the excellent and detailed texts that have been published so far, for example, Alan Gauld's history of hypnotism (1992), which goes extensively into animal magnetism, or that by Adam Crabtree (1993), on magnetic sleep and the roots of psychological healing. Thus, this is only a partial and focalized vision, oriented to a more modern and objective view, where psychological or placebo

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factors are left out. Moreover, we are also leaving out the origins and development of magnetism in the physical sciences, for they go back to ancient times, obviously belonging to another chapter of the history of science at large.

The most prominent and known contributor is perhaps Franz Anton Mesmer (1734–1815), born in Iznang, Germany, who died in the same country in the city of Meersburg. It was a period when medicine was attempting to assimilate advances in the physical and biological sciences and when scientists often indulged in cosmological speculations.

Mesmer was perhaps one of the first, if not the first, to speak of animal magnetism, tracing it back to his doctoral thesis, "Dissertatio Physico-Medica de Planetarum Influxu (Physico-Medical Dissertation about the Influences of the Planets)," submitted in 1766 to the University of Vienna [6]. However, at the time of its defense, the thesis did not strike the Viennese authorities as a revolutionary new theory of medicine. Mesmer, in his medical practice, applied magnets to his patients but did not attribute his cures to any power in the magnets themselves. Instead, he argued that the body was analogous to a magnet and that the fluid ebbed and flowed according to the laws of magnetic attraction. He announced his new theory in *Schreiben über die Magnetkur* (*Writings on Magnetic Healings*, Vienna, 1775; see also [6]); however, he did not produce any proof of his theory or any rigorous description of experiments that could be repeated and verified by others. Mesmerism, as this theory came to be called, offered only a thin and unoriginal assortment of ideas, but nothing proves that Mesmer was a charlatan for he seems to have believed sincerely in his statements, although he also showed a fierce determination to convert them into cash.

The techniques of mesmerizing proved more influential than the theory he maintained. By concentrating on the rapport of patient and doctor, Mesmer seems to have dealt effectively with nervous disorders. He certainly influenced in the practice of hypnosis through the famous French physician, J.M. Charcot, and also through him, mesmerism exerted some influence on the development of psychoanalysis. Somnambulism was another condition that was also somehow linked to animal magnetism and the practice of mesmerism. From the point of view of magnetobiology, he was only right in his concept (or belief) of animal magnetism (biomagnetism) but he never proved anything about it and his understanding of the subject was completely astray of our current accepted knowledge.

George Cristopher Würtz (1756–1823), one of Memer's direct disciples, wrote a small book on animal magnetism in 1787. However, its information content is extremely feeble, with an excess of unnecessary words and no attempt of describing what animal magnetism might be. It cannot be deemed as significant in any respect.

In 1845–1846, Professor Lisimaco Verati published a long treatise (four volumes) on animal magnetism. His discourse does not comply with any of the accepted rules of the current scientific methodology. For example, he refers to the original biblical sin (Adam and Eve) as a "magnetic crisis" and that the following punishment by an angel—a cherubin—was a "magnetic catalepsy." The author frequently refers to Mesmer and, sometimes, not in very good terms. Almost at the end, Chapter 35 (or as he calls it, Letter 35) deals specifically with Mesmer's theory but without bringing any new light to it. The whole treatise shows an enormous overwording and mixture of concepts.

Of particular interest is a paragraph from the publisher's preface to the book by Deleuze on animal magnetism, a translation reprinted in the United States in 1880: "Under the influence of magnetism important and protracted surgical operations have been effected without the slightest knowledge of pain to the patient, and with no evil effects; but our hospitals and the medical faculty at large adopting the application of anaesthetics, magnetism ceased to be made available in practice, saved by a few."

As critical modern readers, and in an attempt to understand the accepted philosophical attitudes or perhaps the concept of "science" of many people in those days (that is, about 120 years ago), the questions we should pose are:

1) What objective evidence did they have of those supposedly painless operations?
2) Why did they think the medical community shifted to chemical anaesthetics?

It should be recalled that in mathematics, physics, and chemistry, knowledge was rather advanced, already offering in many respects essential hard-core material for the discoveries that were to come in the early 1900s.

One can easily discover in all these publications on animal magnetism that their titles are misleading because rarely, if ever, did authors actually go into the demonstration and/or explanation and/or discussion of magnetic fields generated by living bodies, either as a whole or from sample pieces. Magnetism, as a physics chapter, was in the meantime well established. Let us briefly browse for that matter the contents of this book by [15], taking a few excerpts from it. Besides, that will take us also a little back in time.

In its first chapter, "General Views and Principles," the author writes: "man has the faculty of exercising over his fellow-men a salutary influence, in directing towards them, by his will, the vital principle. The name of magnetism has been given to this faculty: it is an extension of the power which all living beings have of acting upon those who are submitted to their will." And he proceeds, further down: "As we cannot comprehend how a body can act upon another at a distance, we suppose that a substance emanates from him who magnetizes, and is conveyed to the person magnetized, in the direction given by the will. This substance, which sustains life in us, we call the magnetic fluid." At best, and under the light of present knowledge, we might interpret such a statement as meaning the magnetic lines of the magnetic fields sustained, say, by the heart, brain, or by any other excitable tissue. On page 31 in the same chapter, Deleuze states: "the action of the magnetic fluid will be salutary only so far as it is accompanied with a good intention." No other comment is necessary.

Joseph Philippe François Deleuze (1753–1835) is a central figure in the history of animal magnetism. Observe that 55 years after his death, his concepts were still having an influence (see above). After serving as a lieutenant in the French infantry, he decided to devote himself to the study of the natural sciences.

Deleuze was highly respected by his contemporaries as a great scholar with a balanced approach to scientific issues. He was impressed by a demonstration on magnetization of a human being and began to pursue his own study of animal magnetism. One of the scientists of those days who most influenced him was Amand Marie Jacques de Chastenet, *marquis de Puységur* (1751–1825), who stands second to Mesmer in the development of animal magnetism ideas. To avoid confusion, it should be mentioned that Puységur had two younger brothers, Antoine Hyancinth Anne (*comte de Chastenet*) and Jacques Maxine Paul (*comte de Puységur*), also involved in animal magnetism but to a lesser degree. The *Histoire Critique du Magnétisme Animal*, published in 1813, is Deleuze's first work on the subject, and it can be considered as one of the most important ever written on animal magnetism. He conveys a great deal of information about the theory and practice and, very importantly, does not ignore legitimate criticism [13].

Puységur (les Marquis) presented in 1784 (published later on, in London, 1786) his *Memoirs on the History of Animal Magnetism*. It is a work of great significance for the development of modern psychology, though not for animal magnetism as we understand it today. Crabtree ([13]; see p. 26) clearly states the contributions of this author (paraphrased and summarized after Crabtree):

> Having heard about animal magnetism and its marvelous curative powers, he went to Paris to learn from Mesmer. Returning to his estate, he began to use animal magnetism to alleviate the ills of local residents. A peasant named Victor Race was suffering from fever and congestion of the lungs. When applying the magnetic passes, Puységur noticed that his patient had fallen asleep, but he could still communicate. When returning to his normal state of consciousness, Victor remembered nothing of what had happened. Puységur also noted a dramatic change in personality that Victor underwent between the state of magnetic sleep and his normal state. In the latter, he was of rather ordinary or even slow wit, while in the former he became extremely bright and perceptive.

Puységur introduced, thus, the terms "magnetic sleep" and "magnetic somnambulism" to distinguish the new condition from the alert one. His discovery of artificial somnambulism started a whole new trend in the practice of animal magnetism, shifting the emphasis from the physical to the psychological. Eventually, this led to the concepts of "subconscious," the "subliminal self," and the "unconscious" in the latter part of the nineteenth century.

Practically from its inception, controversy doomed the application of animal magnetism. The very King of France wanted a report on it. Thus, a special committee, presided by Benjamin Franklin, was designated to take over the task [16]. At its beginning, the report says that "by some it has been applauded [animal magnetism] as the greatest of philosophical discoveries, and by others decried as the juggle of an unprincipled impostor." Further on, the report recalls that, in 1776, the Academy of Sciences of Berlin rejected Mesmer's theory as "destitute of foundation and unworthy the smallest attention." Mesmer refused to have any communication with the members of this new committee, presided by Franklin. It should be mentioned that Dr. Joseph Ignace Guillotin (inventor of the guillotine, widely used during the French Revolution) and Antoine-Laurent Lavoisier (a victim of that instrument) were members of that committee.

The conclusions produced by this committee were not favorable. At the end (p. 105), the report states:

> The commissioners having convinced themselves, that the animal magnetic fluid is capable of being perceived by none of our senses, and had no action either upon themselves or upon the subjects of their several experiments; being assured, that the touches and compressions employed in its application rarely occasioned favourable changes in the animal economy, and that the impressions thus made are always hurtful to the imagination; in fine having demonstrated by decisive experiments, that the imagination without the magnetism produces convulsions, and the magnetism without the imagination produces nothing; they have concluded with an unanimous voice respecting the existence and the utility of magnetism, that the existence of the fluid is absolutely destitute of proof, that the fluid having no existence can consequently have no use, that the violent symptoms observed in the public process are to be ascribed to the compression, to the imagination called into action, and to the propensity to mechanical imitation, which leads us in spite of ourselves to the repetition of what strikes our senses.

Franklin, Majault, Le Roy, Sallin, Bailly, D'Arcet, De Bory, Guillotin, and Lavoisier, in Paris, signed the document on the 11 August 1784.

In spite of this report, the practice continued in the hands of many enthusiastic followers in France, Germany, and England. That is the case of John Bell, trained in Paris at the Society of Harmony. He wrote the most influential of the early British works on animal magnetism [4] and, evidently, was strongly influenced by Puységur, for he devotes a great deal of space to the subject of magnetic sleep. On page 77, Bell describes in a rather confusing fashion, an electric or magnetic apparatus (an eight-foot-diameter oak tub) which, in his own words, "is more like a grove." It was used in London and Dublin and, with it, several patients could be "put into crises." Bell made use of this book as a sort of written manual to supplement lectures [13].

As early as 1801, George Winter, a contemporary of Mesmer, states in the Introduction of his book on animal magnetism (p. 3): "The cures transcribed into this work, are for the purpose of informing the reader, that the author could not cure, even, one of those patients by Animal Magnetism, but that such cures were effected by the powers of medicines." Obviously, Winter was not a convinced believer in the procedure. Further on in his text, on page six, it is mentioned, "Paracelsus is to be regarded as the inventor of the magnetical system." Paracelsus died in 1541. On page seven, after some other pieces of historical information, Winter adds: "It is therefore certain, that the assertions of M. Mesmer, which are represented by him as principles of his own, do not belong to him; and that this theory, in the room of being an attractive novelty, is an ancient system, abandoned by the learned near a century ago." We should stress that these words were written in 1801. Dr. John Benoit De Mainauduc, who received his medical training and set up his practice in London, introduced Winter to the practice of magnetization. After a sojourn in Paris, De Mainauduc returned to London in 1785, where he started to claim for himself new discoveries about the science of healing, mainly sharing a number of concepts common to those sustained by Mesmer in those days [13].

Doubts about the new area of discovery were plaguing the scientific community during that time because another commission was created in France, in 1826; that is, more than 40 years after the previous report presided by Benjamin Franklin. The political stage had suffered substantial changes with dramatic events of long-standing effects in between, such as the French Revolution (1789–1796), the rise and fall of Napoleon (1799–1815), and the many aftermaths reverberating in Europe at large.

In the meantime, science kept advancing, sometimes in the midst of upheaval and turmoil. The Galvani-Volta controversy had given birth, on one hand, to modern electrophysiology (with the concepts of injury potential and excitable tissues), and on the other hand, to electrical engineering (with the invention of the electric pile). Intermixed with these remarkable achievements was considerable charlatanism, quackery, and confusion, trying, for example, to resurrect the dead or the quasi-dead, as Galvani's nephew, Giovanni Aldini, claimed in a book he wrote in 1804. His procedure, after all, was similar to the defibrillatory shock employed nowadays and every day in cases of cardiac fibrillation. The eagerness and fascination for the "electrical mystery" led to the emergence of the science fiction genre or style, as in the novel *Frankenstein*, by Mary Wollstonecraft Godwin Shelley [26]. (Her name is not mentioned in this original edition, probably because in those days women were not accepted as authors. Even more likely, it was because of her bad relationship with her father because she had run off as a teenager with the poet Percy B. Shelley. The book, however, is dedicated to her father, William Godwin.)

Hence, magnetism, being even less understood than electricity and its possible links to life, was another perfect stimulus for human curiosity. No wonder, then, that in spite of strong opposition, it continued to flourish for over a century even with very feeble, if any, true scientific support, and that a new report was considered necessary. The original report itself, dated 1826, covers only from p. 109 to p. 201 [11], for the rest is a preface and an introduction (pp. i–xii and pp. 1–105) plus an appendix (pp. 205–252), which were written by Colquhoun seven years later.

The 1826 report makes reference to the previous one of 1784 mentioning its unfavorable judgment and the decision of the French Academy of Sciences to appoint a new committee constituted by Bourdois, Double, Itard, Gueneau de Hussy, Guersent, Fouquier, Laennec, Leroux, Magendie, Marc, and Thillaye. All this took place in January and February of 1826. Hyacinthe Laennec (who invented the stethoscope and introduced it in clinical medicine) had to resign a little later because of health problems, and François Magendie (great physiologist and teacher of Claude Bernard) did not sign the report, as he had not assisted in the experiments. After overcoming several practical problems, the committee "made an appeal to all the physicians who were known to make animal magnetism the object of their researches. We requested them to allow us to witness their experiments, to accompany them during their progress, and to confirm the results" [p. 112]. The gentleman who first suggested the enquiry was Monsieur Foissac, who actively participated in its proceedings.

The report deals with four groups of experiments:

1) magnetism has no effects
2) magnetism has slight effects
3) effects are sometimes produced by ennui, monotony, or imagination
4) magnetism probably has some effects.

This fourth and last section is the longest. It describes different cases of persons of both sexes and of a wide range of ages. Out of all the collected information and material, the commission reached 30 conclusions, of which the last four are interesting enough to be at least partially quoted:

> 27. In order to establish with any degree of exactness the connection between magnetism and therapeutics, it would be necessary to have observed its effects upon a great number of individu-

> als, and to have made experiments every day, for a long time, upon the same patient.
>
> 28. Some of the magnetised patients felt no benefit from the treatment. Others experienced a more or less decided relief.
>
> 29. Considered as a cause of certain physiological phenomenon, or a therapeutic remedy, magnetism ought to be allowed a place within the circle of the medical sciences.
>
> 30. Your committee has not been able to verify, because they had no opportunity of doing so, other faculties which the magnetisers had announced as existing in somnambulism. But they have communicated in their reports facts of sufficient importance to entitle them to think, that the Academy ought to encourage the investigations into the subject of animal magnetism, as a very curious branch of psychology and natural history.

Thus, this report is much more open-minded than the 1784 one and partially makes up for the harsher concepts expressed in it. We might add that this attitude should be commended, especially when facing controversial scientific subjects.

Charles Richet (1850–1935) was a professor of physiology at the University of Paris, house physician in hospitals, and, later on, a Nobel Prize winner (1913) for his contributions in anaphylaxis. A man of varied interests and great personal charm, his curiosity led him into regions that other scientists would avoid; for example, hypnotic phenomena, which sprang after a casual attendance at a magnetic demonstration sometime in 1875 or 1876 [17]. Without much conviction, Richet played a role in the *somnambulism provoqué*, attracted by the peculiar psychological and physiological aspects involved in it rather than by the alleged therapeutic efficacy. Ideas spread to Germany, where the Dane Carl Hansen was highly successful as an itinerant magnetic demonstrator, so much that it was called the "Hansen phase" of hypnotism, roughly between 1879 and 1884. One of the many followers in those years was Christian Bäumler (1881), professor of medicine at Freiburg. He wrote a very useful guide to the literature and ideas of the Hansen phase. In this small book he attempted to represent the conduction relationships in the nervous system.

An International Congress on Human Magnetism was held in Paris in 1889, and its proceedings appeared the following year. The honorary president was Dr. Puel and the president was Comte de Constantin. It is of no surprise to find at the very beginning a commending letter from Camille Flammarion (1842–1925), who declares not being able to personally participate in the congress because of having been away from Paris, France and even the planet. As a well-reputed astronomer, he was engaged at that time in studies about the planet Mars [19]. The congress lasted a week, from Monday, 21 October until Saturday, 26 October. By and large, there is a lack of specificity in all the communications. Speakers tend to wander through philosophical and rather confusing considerations, not being able to render objective results and conclusions, most of the time away from actual scientific knowledge. Let us review some examples taken from these proceedings:

On Tuesday, 22 October (pp. 47–89), Dr. Gérard spoke about the "present situation of human magnetism." In his attempt to define it, he states: "*Le magnetisme humain, s'il n'est pas d'essence divine, est tout au moin d'essence humaine, et, comme tel, doit participer de deux états de l'homme: esprit et matière, de même qu'un sel renferme la plupart des vertus de ses composants*." Further down the text, this same author (pp. 75–78) refers to nerves and their electrical activity, mentioning du Bois Raymond and other scientists of those days active in the then still-developing field of electrophysiology. Besides, by the time this congress took place, electromagnetic induction (the transformer effect) and the generation of magnetic fields by electric currents, either constant or time varying (as described by Faraday, Gauss, Ampère, and others) had been well established and put into practical use. Thus, it is somewhat surprising that not even a hint is given in that direction; i.e., that the nerve electrical change during activity could have produced a magnetic field around it. Were these "magnetizers," as they called themselves, so much obliterated by other nonscientific ideas? In his conclusions, Gérard says (p. 85):

> *La doctrine magnétique, quant à ses effets, peut se diviser en deux branches bien distinctes: l'une physiologique, que nous revendiquons absolutement dans toutes ses parties; l' autre psychique, qui est du ressort de la métaphysique. C'est aux médecins d'apliquer l'une, c'est aux philosophes d'expliquer l'autre.*
>
> *Le magnétisme humain est une force naturelle développée par la volonté, produisant toujours des modifications hereuses dans le rythme nerveux d'une personne malade, placée à proximité de son influence.*

On Thursday, 24 October, Guyonnet Dupérat (p. 248–272) spoke about the magnetic entrainment phenomena. We may assume the meaning to be that the action of one person "entrains" the action of another. Confusion dominates from the beginning to the end of this contribution, in addition to a number of absolutely untenable concepts; for example (pp, 257–258): "*Un polariste, suivant la façon don't il entendra la polarité, vous annoncera qu'à l'instar de l'aimant il produira la chaleur, la répulsion, le sommeil, par opposition de son pôle positif au pôle positif du sujet; la fraicheur, l'attraction et le réveil, par la présentation de son pôle négatif au pôle positif de ce même individu. … et s'il se trompe dans ses pratiques, sa polarité obéissant à l'entraînement ne se trompera pas.*"

Finally, on Friday, 25 October—its seventh session—Monsieur Durville (p. 395) stated, "if we defined magnetisme as the action an individual can exert over another, *il est évident que tous les effets que nous observons ne sont pas des effets magnétiques*." A little further down the text he adds: "*Les effets qui sont réellement dus au magnétisme sont encore très diversement interprétés, même par le practiciens les plus autorisés. Le plus nombre d'entre eux les attribuent à l'action de la volonté sous la direction de laquelle l'agent magnétique serait placé*."

No doubt, then, ideas among many well-reputed people in 1889 were confusing, mixed, involved unrelated topics, and were completely incorrect as to what animal magnetism was or may have really meant. Similar concepts can be also found in other books around the turn of the nineteenth century [2], [27].

### Magnetobiology and Mainstream Science

It can be seen in what we have described so far that magnetobiology, within the definition given at the beginning of this article, had not been even hinted as by the turn of the nineteenth into the twentieth century. Science can be defined only when facts are logically assembled in a system founded on basic notions, which made up of one or more theories, explains, and foresees the facts [29]. This author also states that magnetobiology, as a scientific discipline, must follow the same rationale, and, specifically, has to be built upon:

1) precise experimental and theoretical knowledge of magnetism
2) methods, results, and theories of magnetochemistry
3) results of chemical magnetic means as applied to substances that make up living beings
4) possible modification of biological functions due to magnetic fields
5) existence of magnetic fields in living tissues.

This fresh approach appeared sometime in the middle or late 1950s, even though there are antecedents, mainly based on related disciplines, that go as far back as 600 B.C., since magnets (loadstones) and magnetism had been known by the Greek philosophers like Thales and Priscianus [23]. Besides for curious magnetic actions, they probably tried them as therapeutic means. Much later on, Paracelsus, in the sixteenth century, also made medical use of the same elements [28]. The first half of the twentieth century, apparently, did not produce any significant and true contribution to magnetobiology. Moreover, some people may include magnetobiology as a chapter of biophysics; such a stance would be understandable. However, biophysicists have traditionally been attracted to other areas (electric phenomena, excitable cell membrane, ionic channels, receptors). The possible relationships and interactions of biological systems and functions with magnetic fields, either external or self-generated, had not been considered or, at least, there was a paucity of knowledge.

Until rather recently (perhaps during the 1930s or the 1940s), the majority of the authors—if not all—who have attempted to study the effects of magnetic phenomena upon living beings have ignored the fundamental laws of magnetism, electromagnetism, and chemical magnetics. There is a lack of quantitative criteria; there is confusion and an excess of pseudoscientific lucubrations, mainly due to erroneous concepts. Even today, as can be easily verify by an Internet search, confusion and lack of objectivity persist. Methods tend to be flawed. Thus, one has to be highly selective when applying strict scientific criteria. As Valentinuzzi [29] pointed out, the authentic facts must be well delimited, and the false ones must be fully eliminated. The concept of magnetic moment fulfills a heurestic function, and, as such, it has to be interpreted and evaluated as a basic property in substances usually found in living tissues (carbon, nitrogen, oxygen, hydrogen, water, amino acids, proteins, and biomolecules at large).

Valentinuzzi [29] offers a good historic review of the origins and development of magnetism. The most outstanding contribution is that of William Gilbert [18], who produced his famous *De Magnete*. Gilbert gathered together everything, which was known about magnetism in his time and added such new notions as the disappearance of magnetism with heat, the magnetization of steel by rubbing, and the Earth considered as a magnet. His assertions were based on rigorous experimentation. The first artificial magnets are attributed to John Michell (1724–1793) and John Robison (1739–1805). Michell, in 1750, described a method of obtaining magnetism by means of three iron bars (see [22], pp. 62–68). Robison ([25], pp. 246–247) says: "If a bar of steel be long hammered while lying in the magnetic direction, it acquires a sensible magnetism [and it refers to a Gilbert's plate]." Further down in the text, it continues: "We can scarcely take up a cutting or boring tool in a smith's shop that is not magnetical. Even soft steel and iron acquire permanent magnetism in this way."

Until the nineteenth century, magnetism was considered as a physical property independent of electricity. We owe the discovery of the relations that exist between electric and magnetic properties to the studies of Biot (1774–1862), Ampère (1775–1836), Arago (1786–1853), and Savart (1791–1841). James Clerk Maxwell (1831–1879) included these properties systematically in his writing and was one of the important developers of their fundaments with his *Treatise on Electricity and Magnetism* [20], for he worked on the subject during practically all his productive life.

### Diamagnetism, Paramagnetism, and Ferromagnetism

The basic concepts of diamagnetism, paramagnetism, and ferromagnetism are essential for the development and understanding of magnetochemistry and magnetobiology (or biomagnetism) as interrelated disciplines within the broader field of *biophysics*. Among the magnetic properties that we collect under the general denomination of magnetism are three variants that were recognized only at a relatively recent date.

Let us first refer to diamagnetism. As expressed earlier in this article, diamagnetic substances are expelled from a magnetic field (i.e., they are displaced from the points of greater intensity to those of lesser intensity). If the body they form is elongated in shape, then it is positioned (while suspended) with its longest axis oriented transversely to the direction of the field. The field inside these substances is weakened; in other words, diamagnetic bodies are less permeable than vacuum to magnetic force lines connecting the North pole with the South pole of the magnet sustaining the field.

Antoine Cesar Becquerel (1788–1878), founder of a dynasty of distinguished scientists, worked and corresponded with Faraday on diamagnetism. He had noticed examples of it (around 1827) before Faraday (who did it circa 1847) but had failed to generalize from them. Michael Faraday (1791–1867) instead had a clearer understanding of the phenomenon. In fact, he coined the words "dia" and "paramagnetic." Alexandre Edmond Becquerel (1820–1891) was the second son of Antoine Cesar. From 1845 to 1855, Edmond devoted most of his attention to the investigation of diamagnetism. He was unwilling to accept Faraday's contention that diamagnetic phenomena were fundamentally different from those of ordinary magnetism [19].

The discovery of diamagnetism stimulated the production of theories to account for this new phenomenon. Maxwell (Faraday's student), in his *Treatise* [20], refers to Weber's theory of diamagnetism, stating that "there exist in the molecules of diamagnetic substances certain channels round which an electric current can circulate without resistance." Weber had worked in the subject back in 1852.

Wilhelm Eduard Weber (1804–1891) was one of twelve children of Michael Weber, professor of theology at the University of Wittenberg. Of four brothers and a sister who lived to an advanced age, the eldest brother became a minister, while the other brothers turned to science and medicine. Ernst Heinrich, who was almost ten years older than Wilhelm Eduard, became a leading anatomist and physiologist and a professor at Leipzig. Eduard Friedrich, a year and a half younger than Wilhelm Eduard, also became professor of anatomy at Leipzig. The interest of the three brothers in science was undoubtedly awakened by the family friend Christian August Langguth, in whose house the Webers lived, and the acoustician E.F. Chladni, a fellow lodger. During a scientific meeting in 1828, Wilhelm Eduard attracted the notice of Humboldt and Gauss for his work on organ pipes and the latter saw in Wilhem Eduard Weber a worthy coworker. Not long thereafter, the opportunity arouse and six years of collaboration and close friendship with Gauss followed.

At the end of 1832, Gauss presented a paper written with Weber's assistance introducing absolute units of measurement into magnetism; that is, the measurement of the strength of a magnetic property was reduced to length, time, and mass, and thus became reproducible anywhere without the need of specific precalibrated magnetic instruments. During the years 1837 to 1841, Weber developed sensitive magnetometers and other magnetic instruments, mostly in collaboration with Gauss. From 1848 to 1852, Weber reported his careful quantitative experimental work on the diamagnetism of bismuth. He was able to isolate and demonstrate the existence of the diamagnetic effect. Weber also extended Ampère's theory of magnetism to cover the phenomenon of diamagnetism. According to Weber, diamagnetism occurs when resistanceless molecular currents are induced in diamagnetic substances. These substances are characterized by molecules that do not contain permanent currents and that have fixed orientation in the substance (see [19]).

The study of paramagnetism is mainly due to Pierre Curie (1859–1906). Valentinuzzi [29], in 1961 mentions Edmond Becquerel as one contributor to this subject, but the references we found state that he only worked on diamagnetism (see above). The paramagnetic substances are sucked in by a magnetic field (i.e., they are displaced from the points of lesser to the points of greater intensity) and a body of such material is lined up with its greater axis in the direction of the field, reinforced in its interior (field lines are more concentrated). Between 1890 and 1895, Curie devoted a great deal of effort to studying the magnetic properties of substances at various temperatures. In fact, he studied the three groups of substances: ferromagnetic, such as iron, that always magnetize to a high degree; low magnetic, or paramagnetic substances, such as oxygen, palladium, platinum, manganese, and several salts, which magnetize in the same direction as iron but much more weakly; and also diamagnetic substances, which include the largest number of elements and compounds, whose very low magnetization is in the inverse direction of that of iron in the same magnetic field.

Curie studied many substances, concluding that no parallel can be drawn between the properties of diamagnetic substances and those of paramagnetic ones. The negative susceptibility of diamagnetic substances remains invariable when the temperature varies within wide ranges. Diamagnetism must be a specific property of atoms. It exists also in ferromagnetic or paramagnetic substances but is little apparent there because of its weakness. Ferromagnetism and paramagnetism, on the other hand, are properties of aggregates of atoms and are closely related. The ferromagnetism of a given substance decreases when the temperature rises and gives way to a weak paramagnetism at a temperature characteristic of the substance and known as its "Curie point." *Paramagnetism is inversely proportional to the absolute temperature*. This is Curie's law. A little later, Paul Langevin, who had been Curie's student at l' École de Physique et Chimie, proposed a satisfactory theory by postulating a thermal excitation of the atoms in the phenomena of magnetization. These are concepts that still constitute the basis of modern theories of magnetism (see [19]).

Ferromagnetic substances intensify the field extraordinarily. The reinforcement can be thousands of times greater than in the case of paramagnetic substances. The bodies made of these substances deform the lines of force to such an extent that the former tend to get nearer to the poles of the magnet generating the field.

When a paramagnetic body is placed in a magnetic field, it also acquires diamagnetism so that there is a superposition of both properties. To elucidate accurately the value of paramagnetism, it is necessary to make corrections relative to diamagnetism. Paramagnetism always conceals diamagnetism by virtue of its greater intensity. Ferromagnetic bodies are less common in nature than the paramagnetic bodies. Ferromagnetism can be considered a special form of paramagnetism that manifests when matter acquires a cristalline structure and depends on the intensity of the magnetic field.

The three variants of magnetism (dia-, para-, and ferro-) may be characterized by the concept of *magnetic permeability*, which becomes larger when going from diamagnetism to paramagnetism to ferromagnetism. Magnetic permeability is related to the concept of *magnetic susceptibility*. A contribution that belongs to modern science is the textbook by Bhatnagar and Mathur [5], where the essential bases of magnetochemistry are given.

## Current Trends, Discussion, and Conclusions

Magnetobiology and biomagnetism, as some investigators prefer to say now (as for example Oswaldo Baffa, in Brazil)—the former dealing with the effects of external magnetic fields on biological systems; the latter dealing only with magnetic fields generated by these systems—has taken a definite objective and well-documented path. Obviously, the biomagnetic sources can be found in electric currents (as action potentials), in diamagnetic and paramagnetic substances in the body, and also in the presence of ferromagnetic substances. We should mention also the well-documented existence of magnetic bacteria, found sometimes in sewage waters.

A visit to the many Web sites shows an enormous variety of information. An established and well-reputed group was formed by David Cohen [7]–[10], first at the Chicago Circle back in the 1960s and later on at MIT. Their contributions are outstanding and should be consulted by the serious student of the subject. There is research going on in Finland, too, and another younger group also in Brazil, led by Oswaldo Baffa (mentioned above). Unfortunately, there is still material that does not sound as reliable from a scientific point of view, and that fact creates confusion and may hurt the prestige of the discipline.

Biomedical applications of superconductivity broadly revolve around two different technologies. The most familiar application of superconductor technology is that of nuclear magnetic resonance imaging [MRI (the word nuclear was dropped to reduce the concerns of the general public, hence MRI) ]. The less familiar application is in biomagnetics. Biomagnetism (now called magnetic source imaging, or MSI) is the measurement of magnetic fields produced by biological systems such as the human body. It is different from magnetobiology, which is the study of magnetic field effects on biological systems. We will discuss both MRI and MSI applications and indicate the role of high temperature superconductors (HTS) in both applications. Since these applications of HTS materials are in their infancy, we discuss them as future developments. However, we are more directly involved with a technique related to MSI; namely, biosusceptometry. MRI is a noninvasive method for seeing inside the body without using ionizing radiation. The technique now has widespread use in hospitals in diagnosing injuries to joints and bones, detecting tumors, and in general detecting diseases that change human anatomy.

Briefly, MRI technology is based upon the detection of the positions in the body of hydrogen nuclei (protons). In a constant applied magnetic field, the magnetic moments (due to their spins) of the protons almost align with the applied field. This causes them to precess about the direction of the applied field with a characteristic frequency, called the Larmor frequency. This frequency is proportional to the strength of the applied field. Applying a second small magnetic field at radio frequencies (RF) flips the spins of the protons from a parallel to antiparallel orientation relative to the initial applied field direction. After the RF field is removed, the proton spins relax to their ground state energy (parallel field orientation) and emit an RF signal that can be detected. By computer processing that signal, we can obtain information about the distribution of the protons (hence, the hydrogen atoms) and their chemical environment. Modern MRI technology is more complex in that it applies a direct current (dc) field with a small gradient (nonconstant). This is done to obtain good spatial resolution. This also in turn requires sophisticated computer software and lots of computing power. The field strengths of modern MRI machines are typically 0.5 to 5.0 T (1 T = 10,000 Gauss; the earth's magnetic field is ~ 0.5 Gauss). If field strengths were the only requirement for high-resolution MRI, then conventional electromagnet (nonsuperconducting) MRI technology would have led to a much more rapid development of this field than has been the case. However, conventional magnets are not stable enough to generate the extremely stable (in both space and time) magnetic fields needed. It is the persistent currents present in superconducting magnets that provide the needed stability. The spatial variation of a modern superconducting MRI magnet is about 1 part in 105, and the time variation is about 1 part in 109. Without this stability, modern MRI pictures would be diffuse, unfocused, and of course, of limited use as a diagnostic tool. Conventional electromagnets do not come close to having this kind of stability. Even with superconducting magnets, it is difficult to control spatial variations. An ideal magnet in the form of a solenoid would have a uniform field inside but real magnets have fringe fields. To obtain uniform fields, MRI manufacturers must use tricks such as adding extra windings or small steel shims to the magnets.

Besides these scientific issues, there are also economic and operating concerns for hospital use of MRI machines. First, there is the price: a modern MRI unit costs from one to two million dollars, so it is a major investment for hospitals. The superconducting magnets are usually 20% of that cost. However, the maintenance contract can be US$100,000 to US$150,000/year. Also, for low-temperature superconducting (LTS) magnets the liquid helium usage can run US$8,000 to US$12,000/year. Cryocooler systems can reduce helium losses and hold refrigeration costs to this low level; otherwise they may be double that cost. There is also the extra cost of the load-bearing structures for these machines, which can weigh from 3 to 5 tons. If the hospital is lucky enough to have high usage of the MRI machine, the cost per patient per session may be as low as $1,000 to $1,500; with low usage the price goes up.

Despite these costs and concerns, MRI technology has become a valuable diagnostic tool worldwide. It first became available in large hospitals in large metropolitan areas of industrialized countries. In rural areas, transportable units built on a trailer bed may be used among smaller hospitals in the region. In underdeveloped countries where liquid helium technology is unavailable, more expensive closed-cycle refrigeration units must be used, and this increases costs. One way around this problem is to use permanent (nonsuperconducting) magnets. These can be made to produce a uniform field, but at lower field strengths (0.1 to 0.2 T). Because the signal-to-noise ratio decreases with lower magnetic field strength, these units require more sophisticated computer technology. However, these low-field MRI units may have a role as an initial diagnostic in rural or underdeveloped areas.

Do HTS magnets have a role in future MRI developments? Of course, the answer to this question depends on advances in HTS technology. With the development of coated conductor wire for magnets, we believe the price of HTS magnets will become more competitive with LTS magnets. Because HTS magnets will have an advantage in operating costs, need fewer infrastructures, and may be lighter in weight, they most likely will initially have a niche in markets in rural and underdeveloped regions.

Whereas MRI technology is based upon the generation of strong (10-T) stable magnetic fields, MSI technology relies on the ability of superconductors to detect very small magnetic fields (10–14 T). This sensitivity is achieved by what are called superconducting quantum interference devices, or SQUIDs. So, before describing MSI applications, we will briefly describe the basics of SQUIDs.

SQUIDs are based upon Josephson junctions. These junctions consist of two superconductors separated by a weak link of either nonsuperconducting material or a constriction in the superconducting material. The main criterion of the weak link is that superconducting electrons have to tunnel through the junction. A SQUID consists of a superconducting loop (or loops) with one or more tunnel junctions. The dc SQUID (two Josephson junctions connected in parallel) are the most widely used detector in medical applications discussed here. Without going into details, a SQUID is used to measure magnetic flux through a pickup loop. The tunnel junctions can be operated so that a small magnetic flux change is converted into a large voltage signal across the loop. For LTS the SQUID must, of course, operate at or below liquid helium temperature. HTS SQUIDS are operated at or below liquid nitrogen temperature.

As mentioned above, SQUIDS are used to detect small magnetic fields. In the human body, currents are generated that produce these small magnetic fields. It is the neurons in the brain and excitations in muscle fibers that generate these currents when they are activated. For example, when a single neuron “fires,” a pulse of charge flows along the neuron. The magnetic field from the current of a single neuron cannot be detected. However, neurons in the brain are aligned and clustered, so a cluster of thousands of neurons firing simultaneously generates a detectable magnetic field. A SQUID placed outside the skull can measure these fields. Also, the neuron cluster does not have to be near the surface to be detected. SQUIDS can detect neuron clusters firing deep within the brain. These magnetic biological signals from excitable cells (neurons, muscle fibers or nerve cells) are usually at low frequencies, i.e., below 50 Hz. In this frequency range only SQUIDS have the sensitivity needed for meaningful detection. Detection of magnetic fields generated in the brain is known as magnetoencephalography or MEG. Remember that like MRI, MSI is a noninvasive technology. Because these magnetic fields generated by brain activity are so much weaker than many external fields that may be present, such as urban noise or the earth’s magnetic field, extensive precautions must be taken to eliminate the effects of external fields in MEG applications. This is also true of all the applications discussed below.

An MSI unit is made up of many components. First, these units must be in a magnetically shielded room. These shielded rooms are typically built with two or three high magnetic permeability layers and one layer of aluminum, and so they are expensive. The sensors (SQUIDS) are coupled to the source by a flux transformer. This flux transformer consists of a detection coil connected to the source and an input coil connected to the SQUID. Also, of course, the SQUID must housed in a low-temperature dewar. Finally, the multichannel (many SQUIDS) MSI units used for medical diagnosis need to be easily operated but have fairly complex electronics.

There is also now a long list of applications of SQUIDS for detecting magnetic signals from muscle or nerve activity. The detection of signals from the stomach is called magnetogastrogram (MGG), signals from the small intestine are called magnetoenterogram (MENG), signals from skeletal muscle is labeled magnetomyogram (MMG), and signals from the heart leads to the technology of magnetocardiogram (MCG or MKG), to list a few. Finally, we mention that originally it was thought that HTS SQUIDS would play no role in these applications. Because thermal noise can degrade the signal, it was realized that operating a SQUID at liquid nitrogen temperatures would increase the thermal noise by a factor of 20 over operating at liquid helium temperatures. Fortunately, with technical development it has been demonstrated that HTS SQUIDS may achieve about the same sensitivity as LTS SQUIDS.

MSI has advanced rapidly in the last ten years and has become a unique diagnostic tool. Of the many applications of MSI, we just give examples from the most active areas. The full power of the technique is seen in studies and clinical applications of the functioning of the human heart (MCG) and brain (MEG). The superior spatial resolution of MCG or MEG as compared to ECG or EEG yields a more accurate picture of the heart or brain functionality.

MCG is applied to several different aspects of the functioning of the heart. It is used to study cardiac arrthythmias, to evaluate the risk of sudden cardiac arrest, or in evaluating heart transplant rejection, to mention a few. The traditional method of determining heart arrthythmias is by invasive catheter mapping. Now it is possible to perform noninvasive MCG measurements to obtain the same information. The risk of sudden cardiac arrest is associated with the malfunctioning of the left ventricle, which is seen as a strong peak in either a MCG or ECG recording. Also, the ability to noninvasively detect with MCG acute rejection events in heart transplant patients is becoming an important clinical tool.

Thus the introduction of magnetic resonance and SQUID techniques has greatly increased the possibilities in these fields, both in basic and applied research as well. There is no point to further dig in the matter because it would mean writing an essay on magnetobiology, which is not the objective of the present contribution.

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