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Abstract: *We present a short review of the major advances of the magnetic materials in medical technology and practice. Apart from enumerating the various applications, emphasis is given on unraveling the links between physical principles and mathematical modeling. Moreover, we outline some of our recent results on the modeling of specific problems.*

1 INTRODUCTION

Magnetism is one of the major research areas in biology and biomedical engineering[1]. The interest for new applications of magnetism in medicine increased during the last years, due to advances in micro- and nanotechnology and its migration into biotechnology. The developed instruments and new biomaterials span from imaging equipment (magnets in MRI), and magnetic field measurements (magnets in MEG, etc.), to invasive (magnetic catheters and thermoseed for tumor treatment, magnetic gels as artificial biomimetic muscles, valves, membranes, etc.), noninvasive techniques (controlled drug release, tumor thermotherapy), and in vitro applications (magnetic separation, blood purification, mechanical measurement of cells and biological tissues and gene delivery into cells). The materials can be either solid, fluid (magnetic fluids or ferrofluids) or polymeric in nature (magnetic gels or ferrogels). The terminology used is also dense, sometimes elusive for each particular application, and possibly related to more than one application. Our review is divided into two parts. In the first part we present the physical principles of magnetic materials, as well as the emerging physical peculiarities for each specific phase (solid, fluid or polymeric). In the second part a classification of the applications is given. This review in no manner aims to be complete, since the research fields are many and evolving and the publications enumerable. Representative articles or books are cited for each field, based on the authors knowledge and information resources available. Emphasis is given on magnetic microparticles applications, due to their relevance with recent advances in microfluidic and medical microdevices (Bio-MEMS) technologies, and since they are promising for performing thrombolytic drug targeting and tumor necrosis therotherapy with high efficiency. Some or our recent theoretical works, for quantitative modeling of specific problems on magnetic microparticles, are also outlined.

2 PHYSICAL PRINCIPLES

The origin of magnetism in materials is the tendency of the neighbouring electron spins in atoms to be aligned parallel to each other, due to quantum mechanical exchange interactions, and thus produce a net magnetic dipole moment per atom. Some representative magnetic fields of different objects are listed in Table 1. Macroscopically this magnetic polarization of atoms is replaced by the notion of the

magnetization vector $\boldsymbol{M}$, which is the number of mean magnetic dipole moments per unit volume. In the presence of an applied magnetic field, $\boldsymbol{H}$, the magnetization experiences a torque, $\boldsymbol{M} \times \boldsymbol{H}$, that tends to align it with the applied field. In the general case $\boldsymbol{M}$ is a nonlinear function of $\boldsymbol{H}$, $\boldsymbol{M} = \chi(\boldsymbol{H})\boldsymbol{H}$, where χ is the magnetic susceptibility of the material. The way the materials respond to the presence of an applied magnetic field classifies them as: *diamagnetic* ($\chi < 0$, there is no field penetration inside the material), *paramagnetic* ($0 < \chi < 1$, there is a field penetration), or *ferromagnetic* ($\chi \gg 1$, they posses magnetization even in the absense of an applied magnetic field). Diamagnetic and paramagnetic materials loose their magnetization in the absence of an applied field.

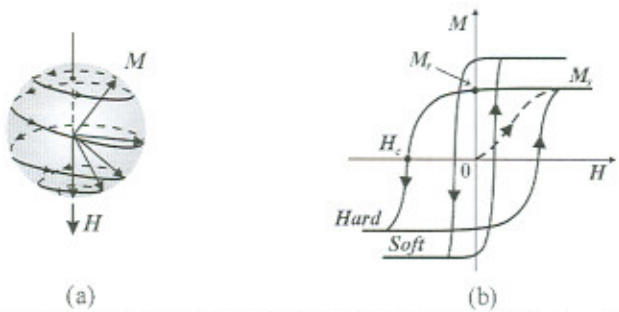
-	**Magnetic Field (in Gauss)**
Galaxy	10^{9}
Superconducting Electromagnet	10^{5}
Permanent Magnet	10^{4}
Sun Spot	10^{3}
Earth	1
Temporary Magnet	10^{-2}
Human Heart	10^{-6}
Human Brain	10^{-8}

Table 1. Magnetic fields in nature.

The dynamics of the magnetization in the presence of an applied magnetic field are analogous to the precession of the top in gravitational field (Fig. 1a) and are expressed through the Landau - Lifshitz equations for the magnetization:

$$\frac{\partial \boldsymbol{M}}{\partial t} = \gamma_0 \boldsymbol{M} \times \boldsymbol{H}, \tag{1}$$

where γ_0 is the gyromagnetic ratio and t denotes time. Phenomenologically we can incorporate into Eq. (1) any type of material properties, by replacing $\boldsymbol{H}$ with the effective field $\boldsymbol{H}_{eff}$. These include: exchange (due to neighbouring spin alignment), magnetostatic (due to the self magnetic field of the material), anisotropy (since there are preferred orientations for the magnetization) and magnetoelastic interactions (since the change of the magnetization, due to an applied magnetic field, results in elastic deformations and vise-versa, *direct* and *inverse magnetostriction effect*, respectively). The time needed for the magnetization to relax along the applied field direction (*relaxation time*) is an important physical parameter for each ferromagnetic material. The constitutive law $\boldsymbol{M} = \boldsymbol{M}(\boldsymbol{H})$ is also accompanied by hysteresis in ferromagnetic materials, if we reverse the direction of the applied field $\boldsymbol{H}$ (Fig. 1b). The dashed line corresponds to the virgin magnetization curve, since in the absense of any external magnetic field the magnetic dipole moments inside the material tend to cancel one antother. A material is classified as *hard* (permanent magnet) or *soft* (temporary magnet), if the force H_c needed to demagnetise it is strong or small, respectively (Fig. 1b). H_c is known as *coercivity* or *coercive force*.



(a) (b)

Figure 1. (a) Precession of magnetization along the applied field. (b) Hysteresis in magnetic materials.

The product of H_c with the value of the magnetization, when the material is magnetically saturated M_s, determines the energy loss during that process and is a technologically important factor for hard and soft magnets. When the initially applied field, that was needed to saturate the sample is switched

off, the magnetization does not vanish (the process is irreversible) and is known as *remanence* or *remanent magnetization*, M_r (see Fig. 1b). The solution of Eq. (1) is important in any field of magnetic research (from calculating nuclear spin distribution in MRI, to estimating the amount of magnetization recorded in a magnetic tape or a hard disk drive, or predicting the performance of magnets). Moreover, above a critical temperature, unique for each material (Curie temperature), the saturation magnetization vanishes and the material switches to the paramagnetic phase (posses magnetization only in the presence of an applied field). Coercivity varies with the size of the ferromagnetic particle, and the determination of this variation is important for the classification of the material according to material properties. Rather large samples $>1\mu m$, are characterized by the presence of regions uniformly magnetized, *domains*, separated from each other by sharp boundaries, *domain walls*. Smaller samples $<100nm$, have just one domain and they are called *single domain particles (SDP)*. For even smaller ferromagnetic particles $<20nm$, thermal agitation is responsible for the spontaneous transition of the particle from the ferromagnetic to the paramagnetic phase and they are called *superparamagnetic particles (SPP)*. In order to completely describe the properties of magnetic materials, we must add to the Eq. (1) the Maxwell's equations for the quasistatic magnetic field:

$$\begin{aligned} \nabla \cdot \boldsymbol{B} &= 0, \\ \nabla \times \boldsymbol{H} &= 0, \end{aligned} \tag{2}$$

where $\boldsymbol{B} = \mu_0(\boldsymbol{H} + \boldsymbol{M})$ is the magnetic induction (in the international system of units) and μ_0 is the magnetic permeability of vacuum. SDP and SPP and their material properties (M_s, H_c, sensitivity to thermal effects) are important elements in most of the medical applications which are described next. They are fabricated with spherical shape and thus they are usually named *magnetic microspheres (MMS)*. Colloidal suspensions of MMS form new artificial materials, either fluid (*magnetic fluids*, or *ferrofluids*, or *magnetoreological fluids, MF*), or polymeric in nature (*magnetic gels*, or *ferrogels, MG*). Classical textbooks on the physics of magnetism are the works of Morrish[2] and Cullity[3], while the short monograph by Brown[4], provides with the fundamentals of the theoretical approach.

Phenomenologically the dynamics of such complex materials (either fluid, elastic or viscoelastic in nature) is described by the Cauchy law of motion[5]

$$\rho \frac{d\boldsymbol{u}}{dt} = \mathrm{div}\boldsymbol{T} + \boldsymbol{f}_m + \boldsymbol{f}, \tag{3}$$

where ρ is the density of the material, $d/dt \equiv \partial/\partial t + \boldsymbol{u} \cdot \nabla$ is the material time derivative, $\boldsymbol{T}$ is the Cauchy stress tensor, $\boldsymbol{f}$ is the gravitational body force and $\boldsymbol{f}_m = \mu_0 \boldsymbol{M} \cdot \nabla \boldsymbol{H}$, is the magnetic body force. Notice that there is no magnetic force $\boldsymbol{f}_m$, in a uniform applied field. Eq. (3) describes either fluid or elastic dynamics. Thus, with the substitution

$$\boldsymbol{T} = (-p + \lambda \,\mathrm{tr}\boldsymbol{D})\mathbf{I} + 2\mu \boldsymbol{D}, \tag{4}$$

Eq. (3) reduces to the Navier-Stokes equation for the MF (p is the fluid pressure, λ and μ are viscosity constants and functions of ρ, $\mathbf{I}$ is the identity tensor, and $\boldsymbol{D}$ is the symmetric part of the velocity gradient). Similarly, if we write Eq. (3) in the material configuration, with the nominal stress tensor[5]

$$\boldsymbol{S} = J\boldsymbol{F}^{-1}\boldsymbol{T} \tag{5}$$

instead of the Cauchy stress tensor $\boldsymbol{T}$ (gravitational and magnetic body forces differ from those of Eq. (3) by the multiplication factor $J \equiv \det\boldsymbol{F}$), we obtain the equation of motion of the nonlinear elasticity for a MG. Here $\boldsymbol{F}$ is the deformation gradient, $\boldsymbol{F} = \nabla_X \otimes \boldsymbol{x}$, and $\boldsymbol{x} = \boldsymbol{x}(\boldsymbol{X})$ is the position vector in the deformed configuration. Incompressibility constraints pose limitations to Eqs (4-5). Constitutive laws $\boldsymbol{S} = \boldsymbol{S}(\boldsymbol{F}, \boldsymbol{M})$ should also be provided or estimated, depending on the specific problem that is studied (design of a specific device, or extracting information for material properties, respectively).

Frequently in biomedical applications, one has to take into account thermal effects inside the body, either physiological in nature, or induced in the body tissues from applied magnetic fields along (*magnetic hyperthermia*), or in conjunction with implanted magnetic thermoseeds or arterially injected

MFs (*ferromagnetic hyperthermia*, or *MF hyperthermia*). These thermal effects are studied using the *bioheat equation*[6]

$$\rho_p c_p \frac{\partial T}{\partial t} = c_p \nabla \cdot (k_p \nabla T) + h_b + h_m + h_r. \tag{6}$$

Eq. (6) is the well known heat diffusion equation, augmented with: (a) the heat flux transfered between the blood and the tissue, introduced by Pennes[6]

$$h_b = c_b \rho_b V (1-\kappa)(T_a - T), \tag{7}$$

(b) the metabolic heat production of tissue h_m, and (c) the rate of heat absorbed from the tissue and from the arterially injected MF (or the implanted magnetic thermoseed), due to eddy currents induced by the applied time varying magnetic field, $h_r \propto \mu_0 \boldsymbol{M} \cdot \boldsymbol{H} / 2$. In Eqs (6-7) c_i and ρ_i $(i = p, b)$ are the specific heats and densities of the tissue and blood, respectively, k_p is the tissue thermal conductivity, V is the perfusion rate per unit volume of tissue, T_a is the arterial blood temperature, T is the tissue temperature, and κ is a factor accounting for incomplete thermal equilibrium between blood and tissue.

Of vital importance, for estimating the performance of MMS in MF and MG in biomedical devices, is the way they respond to the presence of an applied magnetic field (Fig. 2).

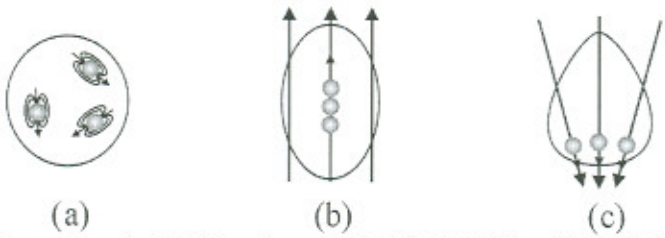


Figure 2. Deformation of a MF drop in an applied field. (a) Zero field. (b) Uniform field. (c) Nonuniform field. The solid spheres correspond to MMS, with their self magnetization.

If we assume that the MF or the MG has spherical shape in the absence of the applied magnetic field (Fig. 2a), then in the presence of a uniform field the MMS form long chains aligned with the applied field. Accordingly, the original spherical in shape MF or MG deforms into an ellipsoid (Fig. 2b). In the presence of a nonuniform applied magnetic field the MMS aggregate along the region of the high magnetic force, and the deformation is more complicated and highly dependent on the geometry of the magnetic field lines of force (Fig. 2c). The mobility of the MMS, due to the magnetic field (*magnetophoresis*), is very sensitive on the viscosity of the carrier MF or MG, their concentration, and the strength of the applied field.

Mathematical theories based on Eqs (1-7), along with appropriate boundary conditions, are important for the simulation of related experiments and control of biomedical devices, for a variety of applications: drug delivery, artificial muscles, valves and membranes, tumor thermotherapy, gene transfer into cells, mechanical and elastic effects of tissues and cells, and many more as it is discussed in section 3.

3 APPLICATIONS

The following classification, may not be complete, but it is representative. We classify the applications of magnetic materials in medicine in two major caterogies: (1) magnets in biomagnetometers and (2) magnetic materials of macro and micromanipulation. The first category comprises: (1) MRI, (2) biomagnetic field detection, (3) liver iron susceptometry, (4) magnetic stimulation, (5) diamagnetic levitation and (6) magnetic twisted cytometry. The second category contains: (1) magnetic prostheses and catheters, and (2) MMS or MNS: (a) as contrast agents in MRI, (b) in magnetic separation (immunoassays, blood purification, biosensors), (c) in magnetic drug targeting, (d) in ferromagnetic hypertheria of tumors, (e) in gene delivery (magnetofection) and (f) in MGs as artificial organs (muscles, valves, mebranes). The first category is primarily related to measurement techniques for diagnostic purposes, while the second one to noninvasive and interventional techniques for therapeutical purposes.

3.1 Biomagnetometers

Magnetic materials are used in medical devices that provide tomographic images (MRI), measure biomagnetic fields, stimulate magnetically nerves or tissues, or detect magnetoelastically the viscoelastic properties of cells.

3.1.1 MRI

The quantum mechanical analog of Eq. (1) determines, among others, the way nuclear spins resonate in an applied magnetic field. The human body is composed mainly from water (70%). The nuclear spins of the hydrogen atom of the water molecule, easily senses magnetic field alternations and respond (resonate) to them. The phenomenon is observed, when in an initialy uniform applied field, that saturated almost all the spins, a transverse time varying magnetic field of the proper (resonant) frequency is applied. This process is known as nuclear magnetic resonance (NMR). The detection and visualization of these measured resonant nuclear spins inside the human body resulted in the non-invasive magnetic resonance imaging (MRI) technology[1].

3.1.2 Biomagnetic Field Detection

The human body produces very weak magnetic fields (see Table 1). Biomagnetic fields measurements initiated with the pioneering works of Cohen (magnetic shielded room) and Zimmerman (Superconducting Quantum Interference Device, SQUID), who both managed to measure the magnetic field of the human heart[7], and proceeded by Cohen with the detection of the magnetic field of the brain[8]. Further advances, that abandoned the use of the magnetic shielded room, resulted in devices that detect with high sensitivity biomagnetic fields of the heart (magnetocardiography - MCG), brain, (magnetoencephalography - MEG), lungs (magnetopneumography - MPG), eye, (magnetooculography – MOG, magnetoretinography – MRG), stomach (magnetogastrography – MGG) peripheral nerves (magnetoneurography – MNG) and other organs[1].

3.1.3 Liver Iron Susceptometry

The assessment of the elevated liver iron stores in patients with primary (e.g. hemochromatosis) or secondary (e.g. thalassemia) iron overload, is attained with non-invasive biomagnetic SQUID liver susceptometry technology[1]. The protein ferritin plays a vey important role in the iron metabolism, by sequestering the toxic free iron[9]. Ferritin is present not only in liver, where its concentration is the highest, but also in spleen, kidney, bone marrow, pancreas and brain[10]. Attempts for in vitro synthesis (*magnetoferritin*) have also been announced[11].

3.1.4 Magnetic Stimulation

Applied time varying magnetic fields, result in magnetic nerve stimulation. This technique is widely used in neurophysiological studies and clinical diagnosis[1]. Moreover, there are available technologies which use time varying magnetic fields (also known as pulse electromagnetic fields, PEMF), for bone healing and growth, through induced eddy currents[12]. The use of PEMFs in the treatment of osteoporosis and other disorders of the musculoskeletal system is also under investigation[12]. However, the exact effects of time-varying magnetic fields on nerves[13] and biological tissues[12,14] is still a controversial issue, which requires further deep, systematic and long term investigation.

3.1.5 Diamagnetic Levitation

One more controversial issue is the effect of high static magnetic field (HSMF) on biological organisms. It has been already argued that diamagnetic materials oppose the magnetic field penetration inside them, by developing a repulsive force. Most biological organisms are diamagnetic in character, since they are composed mainly of water. Recent advances on developing HSMF ≥ 10 Tesla, with the aid of superconducting electromagnets, resulted on diamagnetically levitating grasshoppers and frogs[15-17]. One primary application of HSMF is on space shuttle-type (low-gravity) experiments, with pure protein crystallization, for the production of drugs with high purity. The plant growth is also studied under HSMF conditions[17]. Nevertheless, HSMF strong enough to levitate a human being has not yet been achieved. If such strong HSMF will ever be achieved, and possible life threatening effects will be obliterated or diminished, it might lead to new elevation, transportation, or even not yet conceived medical technologies.

3.1.6 Magnetic Twisting Cytometry (MTC), Magnetic Tweezers

The present paragraph could equivalently be included in the subsection 3.2.2.6 on MMS and MNS below, but it is provided here, as an in vitro measuring application technique. In the era of nanotechnology, detailed knowledge of the elastic properties of cells and tissues is required. Pioneer in such investigations, by employing MMS, was Francis H. Crick[18-19]. The dragging and twisting of the cells in a magnetic field, due to controlled mechanical stresses applied to specific cell surface receptors using ligand-coated ferromagnetic beads (*Magnetic Twisted Cytometry* - MTC), was further advanced by Wang and Butler[20] and nowadays is a standard technique[21]. Frequently, it is also used the term *magnetic tweezers*[22]. While Crick preferred to phagocytise the magnetic beads, Wang and Butler "glued" them on the cell surface.

3.2 Magnetic Materials for Macro- and Micromanipulation

Magnetic materials, apart from being parts of medical instruments (MRI and biomagnetic field detection devices), they can also be used for macro and micromanipulation (catheters, prosthetics, microrobots). Nowadays, MFs and MGs are fabricated, by utilizing MMS or MNS, in a liquid or a viscoelastic solution, respectively. Therefore, they can be used as contrast agent in MRI, in purification and immunoseparation techniques and in semi-invasive or non-invasive therapeutical treatments (drug carriers for thrombolysis, or tumor or necrosis thermotherapy, and as constituents of biomimetic biomaterials: artificial muscles, valves, membranes).

3.2.1 Magnetic Prostheses and Catheters

Magnetic prostheses have been used for the management of ptosis in patients with eyelid myasthenia[23] and for the management of urinary incontinence and bladder disfunction[24]. Magnetic catheters were used for the removal of foreign metal objects from the human body (eye[1] and esophagus, stomach and duodenum[25]). The first stereotactic frame for intracranial navigation was developed by Zernow in 1889[26]. Recent advances on stereotactic methods concern the manipulation of magnetic catheters in brain neurosurgery[27]. The technique called *magnetic stereotaxis*[28], has been applied to human patients[29]. It might be promising for a variety of neurosurgical operations (delivering biopsy tools to specific areas, Parkinson and epilepsy syndromes, as well as on brain aneurysms). Magnetic swimming micromachines (microrobots) driven by an external rotating magnetic field have been announced recently[30-31]. They can be used to provide heat treatment within the body and as catheters in bronchial tubes.

3.2.2 MMS and MNS (Magnetic Beads)

Magnetite nanoparticles (called *magnetosomes*) have been detected in bacteria (magnetotactic bacteria)[32] and in many animals (bees, fish, turtles, birds) and it is conjectured that they help them to navigate in the geomagnetic field (*magnetoreception*)[33]. Magnetite nanocrystals detected on Martial meteorites, might provide evidence for life on Mars[34]. They have also been traced in the human hippocampus[35] and might shed some light to the process of iron biomineralization[36]. Therefore, medical practice can mimic nature and use MMS on a variety of applications, so diminishing toxicological side effects, since they are biocompatible and biodegredable. Cultivated magnetotactic bacteria for magnetosome production, can also be used for that purpose. One application of MMS, that has already been reported (subsection 3.1.6), is on the use of MTC for measuring cells elasticity. The MMS can be constituents of MFs and MGs. The applications of MNS in biosciences have been reviewed recently[37]. An extensive list of companies involved on the producion of SPP, MNS and MMS is given in a website specializing on the technology of MMS[38].

It has been argued that silicone ferrofluid internal tamponade (SFIT) can provide (360°) tamponade of the retina in retinal detachment surgery[39]. Provided that the produced SFIT is biocompatible, exact knowledge is needed of its elastic stability in the magnetic field produced by the semi-solid magnetic silicon band (MSB) used as a scleral buckle. We proposed a quantitative, phenomenological model to estimate the critical magnetic field produced by the MSB that "closes" retinal tears and results in the reattachment of the retina[40]. The magnetic "deformation" of SFIT was modeled in accordance with the deformation of a ferrofluid droplet in an external magnetic field. The geometry of the problem is depicted in Fig. 3a. The retinal elasticity was modeled as an Ogden hyperelastic material and the stress-strain constitutive law is given in Fig. 3b, with the dashed line corresponding to the modeling and the full to retinal properties extracted from available geometrical and materials data, in the limit of infinitesimal strains of the constitutive law. Simple geometrical and variational considerations yielded the critical magnetic field for retina reattachment, as a function of the deformation of the SFIT. The

strain as a function of the magnetic Bond number is shown in Fig. 3c, for varying MF concentration (the full and dashed lines correspond to hyperelastic and Hookean linear elastic material, respectively).

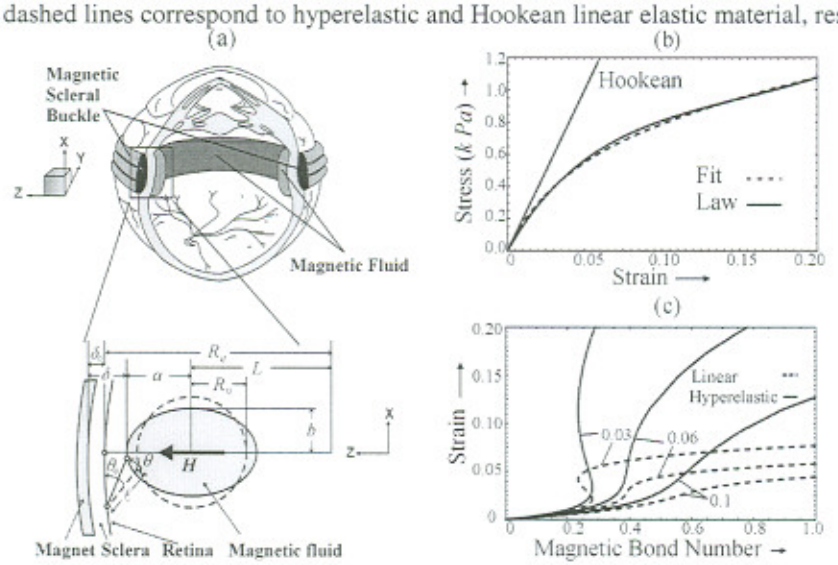


Figure 3: (a) The SFIT and model geometry. (b) Stress–strain law for the retina. (c) The strain vs. the magnetic Bond number for varying MF concentration.

3.2.2.1 Contrast Agents in MRI

SPP or MNS are used as contrast media to enhance the image of the MRI, and to increase contrast between the target organ and surrounding tissues. It is used to enhance simple tissues imaging, as well as to tumors and thrombus clots imaging and other pathogenic mappings. The bibliography is lengthy and still growing, and thus is not provided.

3.2.2.2 Magnetic Separation (Immunoassays, Blood Purification, Biosensors)

Another field of medical instrumentation is based to the magnetophoteric mobility of SPP, MMS and MNS, due to the magnetic body force term f_m of Eq. (3), discussed in section 2. It is also evolving rapidly due to its link with the advancements of nano-biotechnology and its applications to the genome project. Usually, when antibodies are attached to SPP, MNS or MMS, and then injected in a solution with bacteria, they will adhere with specific harmful bacteria. Therefore, the harmful bacteria can then be separated from the solution by magnetic forces. The technique is known as bioseparation or *immunomagnetic cell separation* and has become a powerful tool in microbiology[41]. We mention a pioneer in the field, John Ugelstad, who managed to make of uniform magnetic polystyrene spheres of exactly the same size[42] and was also the founder of a major firm, which is highly involved in the field, Dynal Corporation[43]. The magnetic separation has also been used in bone marrow and blood purification by removing carcinoma cells[44] and in mRNA isolation in DNA sequencing[45]. Lately, an immunomagnetic separation assay (immunomagnetic biosensor, IMBS) was developed, by integrating various MEMS technologies (microfluidics, giant magnetoresistance sensors) with MMS. The IMBS can detect up to 64 different cells in single microchannel flow[46-48], and it is used for detecting biological warfare agents. Moreover, the IMBS can be redesigned in order to participate in blood purification, or in other biological purification procedures.

3.2.2.3 Magnetic Drug Targeting (MDT)

MMS in properly prepared MFs may also be employed as carriers, in order to deliver drug to specific location within the human body. The concept is not new[49-52] and it was investigated by the magnetic material experts Freeman and Arrott[49]. The biochemical, pharmaceutical and chemical engineering community seams to have primary role in such investigations[53-55]. Recently the interest was refreshed, due to promising experiments with tumor treatment in animals[56-58]. Also FeRx Corporation received fast track designation from the USA food and drug administration (FDA) for its product MTC-DOX (doxorubicin) in primary liver cancer[59]. Nevertheless, insurpassable obstacles related to the non-invasive character of the technique, as well as to the design and strength of the applied magnetic field and the MMS concentration of the MF drug carrier, need to be surpassed for

efficient MDT. Detailed and long term studies and sequences of experiments are required, in order to achieve such a goal. Some theoretical problems have been addressed by us, in an attempt to obtain a condition for the adherence of a MF drug carrier drop on a blood vessel wall[60]. We selected this particular problem for study, because it concerns any type of MDT treatment (thrombolysis, tumor necrosis, etc.), since most drugs are injected, delivered and released through the vascular network. An overestimated solution of Eqs. (2-4) was obtained. The geometry of the problem is depicted in Fig. 4a. The dimensionless magnetic force as a function of the viscosity ratio (blood viscosity over magnetic drug viscosity) is shown in Fig. 4b, for varying dimensionless mean blood velocity. The open circles correspond to experimental data extracted from related experiments[61].

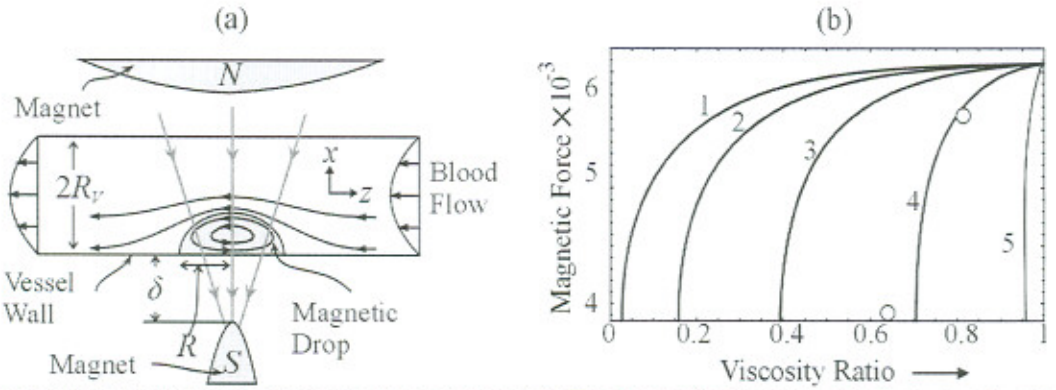


Figure 4: (a) A magnetic drop in the blood stream. (b) The dimensionless magnetic force as a function of the viscosity ratio, for varying dimensionless mean blood velocities. The open circles are experimental data[61].

3.2.2.4 Ferromagnetic Hyperthermia (MF or Magnetic Hyperthermia)

It has been found more than a century ago that cancer growth stopped at temperatures higher than 42°C while normal cells tolerate even higher temperatures[1]. A traditional technique employed for that purpose is through induction coils. However, the eddy currents produced by the induction coils are not localized to the tumor area and are also harmful for neighbouring healthy tissues. Brezovich proposed the use of injected MMS, MNS or SPP (also known as ferromagnetic thermoseeds) as a way to solve the problem of temperature localization in and close to the tumor area[62]. The interest for this problem was increased lately, from the experimental[63-65] and from the theoretical point of view[66-67]. Frequently, apart from the use of MFs in hyperthemia thermotherapy, thermosensitive liposomes (magnetoliposomes) are also employed[63]. The problems in MF hyperthermia are many. Apart from localizing the temperature gradient close to the tumor, we have also to increase it inside the tumor. For this purpose the material properties of the SPP in the MF or the magnetoliposomes have to be optimized. Detailed theoretical investigation of the material properties of SPP is required for that purpose, by solving Eq (1) for the effective field including also the damping term. The power dissipation in a heated MF was recently addressed[68]. Coupled problems with the bioheat Eq. (6) should also be useful for modeling purposes.

3.2.2.5 Magnetofection

Apart from measuring elastic properties of cells through MTC, MMS are also used to manipulate DNA[69] and transfer gene into cells[70]. Such techniques are important for future biotechnological applications.

3.2.2.6 MGs (ferrogels).

There is an increasing need for new materials in many medical applications, with biomimetic functionalities that combine low cost, high efficiency and minor side effects. MGs are good candidates, since they combine better biocompatibility (hydrophilic) along with more efficient actuation or sensory mechanism (large deformation) and minimum investment on expensive raw materials. Soft condensed matter scientists where always triggered from the capabilities of such hydrogels either experimentally[71], or theoretically[72]. The use of such magnetic membranes as tymbanic prosthesis has also been proposed[73], and clinical trials proved about 87% of patients with middle ear system abnormalities had stable improvement[73]. New experiments confirmed their capability to mimic muscle contraction and thus used as possible artificial muscles[74-76]. Also theoretical models have been

developed[77-78] and links with a more general physical mechanism were investigated[79-80]. Recent experiments with electrically polarised gels left unexplained the observed bending as a function of the applied electric field, or voltage, for varying gel length[81-82]. We have proposed a quantitative electro-mechanical model, based on the nonlinear theory of electro-elasticity of Eqs. (2,3,5) but with an electric body force, instead of the magnetic one in Eq. (3)[83]. The model geometry is shown in Fig. 5a and the comparison of the analytically derived theoretical formula with experimental results[82] is presented in Fig. 5b. Further, we extended the theory in order to account for MGs, and proposed a way to control a magnetically biomimetic valve based on its hyperelasticity[84].

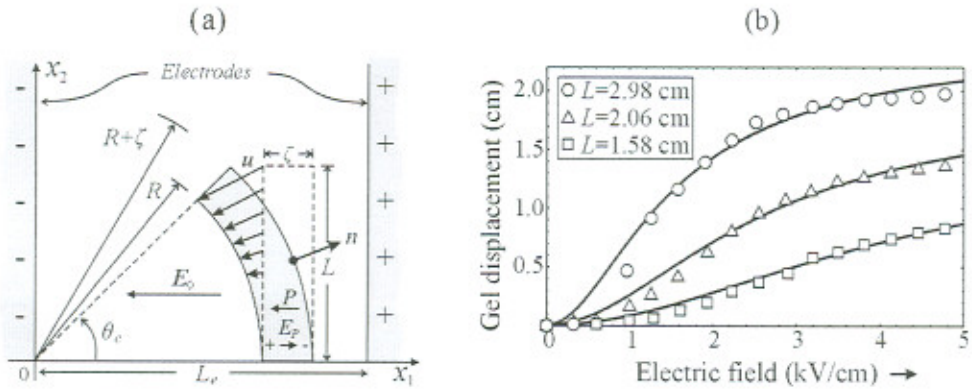


Figure 5: (a) Plane hyperelastic deformations of an electro-gels. (b) The gel displacement as a function of the applied electric field, for varying electro-gels length. The circles, squares and triangles are experimentals data[82].

CONCLUSIONS

Magnetism was and still is an active research field in biology and medicine. The unique properties of raw or properly synthesized magnetic materials, in combination with the magnetophoretic mobility that they develop in an applied magnetic field, might be proved useful for future diagnostic and noninvasive therapeutical techniques. They may also provide a way to conceive better the physiology of living organisms and therefore uncover the not yet recorded biological laws of nature.

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Acronym	Meaning
FDA	food and drug administration
HSMF	high static magnetic field
IMBS	immunomagnetic biosensor
MCG	magnetocardiography
MDT	magnetic drug targeting
MEG	magnetoencephanography
MEMS	micro-electro-mechanical systems
MF	magnetic fluid
MG	magnetic gel
MGG	magnetogastrography
MMS	magnetic microspheres
MNG	magnetoneurography
MNS	magnetic nanospheres
MOG	magnetooculography
MPG	magnetopneumography
MRI	magnetic resonace imaging
MRG	magnetoretinography
MSB	magnetic silicon band
MTC	magnetic twisting cytometry
PEMF	pulsed electromagnetic fields
SFIT	silicon ferrofluid internal tamponade
SDP	single domain particles
SPP	superparamagnetic particles

Table 2. Acronyms.

Περίληψη: *Παρουσιάζεται μια σύντομη επισκόπηση σχετική με την πρόοδο στην χρήση των μαγνητικών υλικών στην ιατρική τεχνολογία. Εκτός από την παρουσίαση των ποικίλων εφαρμογών, δίνουμε έμφαση στην διαλεύκανση των δεσμών μεταξύ φυσικών αρχών και μαθηματικής μοντελοποίησης. Επίσης περιγράφουμε συνοπτικά μερικά πρόσφατα αποτελέσματά μας για την μοντελοποίηση συγκεκριμένων προβλημάτων.*