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On the movement of an iron particle in a magnetic field

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Abstract. When moved by a magnetic field, an iron particle does not follow — quite oppositely to a widely held opinion — the field lines of the magnetic field. Rather, the force exerted onto the particle is directed towards the strongest increase of the magnetic field strength. The field lines and the force direction coincide only axially, radially they cross at an angle of 90°. This has implications for ophthalmic surgery, when an extraction of iron splinters by a magnet is required.

Introduction

A century ago the electric magnet was introduced to ophthalmology for removal of magnetizable intraocular foreign bodies by Hirschberg (1885, 1880). A physical theory of electromagnets in ophthalmology was presented by Volkmann in 1902. Smaller, more powerful and better shaped instruments were developed, which enhanced the use of the magnet in the operating theatre when surgery on perforated globes had to be performed (McCaslin, 1958; Mellinger, 1904).

Furthermore it was realized that even tiny iron particles may lead to siderosis bulbi with disastrous consequences (Brunette et al., 1980; Freyler et al., 1976; Neubauer, 1975; Weiss & Graf, 1975). Thus, removal of any intraocular iron splinter became mandatory. For years, removal by extraocular magnets was the most efficient way (Benson, 1983; Neubauer, 1977). Today however, with the possibilities of safe and well controlled vitrectomy, we prefer this technique when the foreign body has hit the posterior pole and caused a mayor haemorrhages which conceal the retina from inspection (Michels et al., 1981; Topping et al., 1979; Heimann et al., 1978). For splinters, which did not reach the posterior retina but float freely in the vitreous cavity, the magnetic extraction however still remains the method with the lowest risk. Therefore it is important to know how iron splinters move during magnetic extraction; surprisingly, this path has never been described explicitly from a physical point of view. Most ophthalmologists base their surgical procedure on an only partially correct picture of the direction of the force exerted on a foreign body during magnetic extraction.

The behaviour of magnetizable particles in a magnetic field

In most publications dealing with this topic (Landwehr, 1976; Duke-Elder, 1972; McCaslin, 1958; Kraus & Briggs, 1945; Volkmann, 1902) it is pointed out, that the forces exerted onto an iron particle are dependent not only on the magnitude of the magnetic field but on the product of the magnetic field strength time the field gradient. The field gradient points into the direction of the strongest increase of the magnetic field strength. Contrary to the case of an electrostatic field, the magnetic field gradient has not necessarily the same direction as the field lines (which indicate the direction of the field). To visualize these forces, consider the following example: In a magnetic field, a tiny iron particle is transformed into a magnet itself. If the magnetic field is homogeneous (the magnitude and the direction are constant, i.e. zero gradient of the magnetic field) the south and the north pole of the particle are pulled with equal power in opposite directions. Thus the iron particle will not move but rather rotate until its longitudinal axis is parallel to the field lines. However, if the magnetic field is inhomogeneous (different field strength in different places), thereby exerting different forces onto the south and the north poles of the iron splinter, the forces do not mutually cancel and the particle is attracted in the direction of the field gradient.

The path of the field lines is easily demonstrated by the well known setup of iron dust placed on a glass screen above a magnetic field. The iron particles align their longer axis along the magnetic field lines. However, supplementary to the view given in the above mentioned publications, it has to be pointed out that the direction of the attracting force exerted on the particle — and therefore the particle's trajectory — does rarely coincide with the direction of the magnetic field.

Results

Based on a simplified model of a magnet (see appendix) we have calculated and plotted the field lines and the gradient lines of the magnetic field from a typical ophthalmic magnet (Fig. 1). At the bottom of the picture the tip of the magnet is symbolized. The dashed lines represent the magnetic field similar to the pattern formed by iron particles on the screen in a magnetic field. The continuous lines represent the direction of the magnetic force

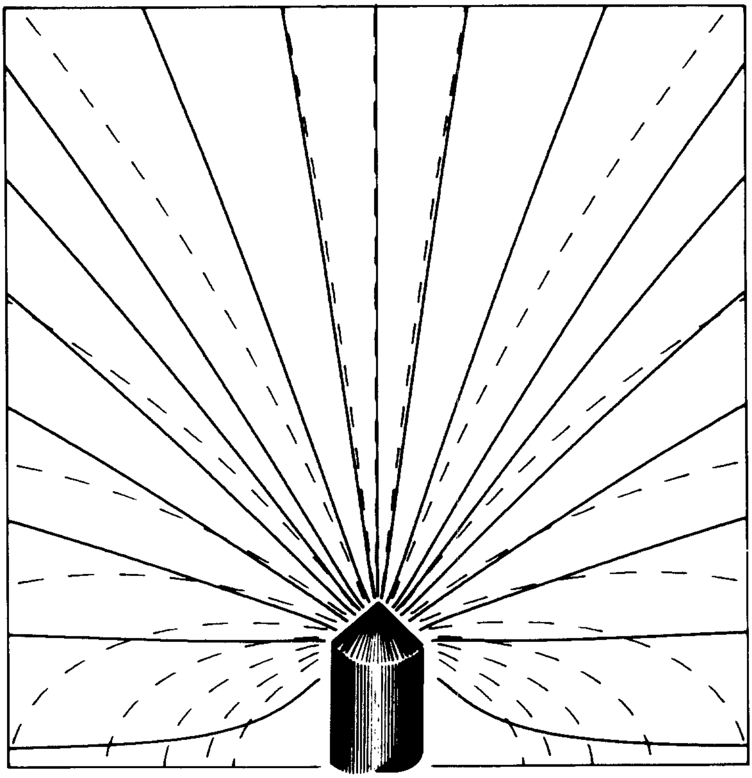

Fig. 1. The tip of the magnet is depicted at the bottom of the graph. The continuous lines follow the *magnetic field gradient*, indicating the direction of the force and thus the trajectory of a magnetizable foreign body; the *field lines* are dashed, forming the familiar pattern of iron-filings in a magnetic field.

exerted on a magnetizable particle. They may be called gradient lines or force lines. An iron particle in the vitreous will move along these force lines (inertia effects can be neglected due to friction in the quasiviscous vitreous). The picture shows clearly that the field lines and the field gradient lines (i.e. the directions of the exerted force) coincide only axially. The more the foreign body is found to the side of the axis of the core, the more its movement will deviate from the field lines. From a lateral position the path will cross the field lines at an angle of 90°. In all cases, however, the track of the intraocular foreign body will be fairly straight to the tip of the magnet.

Discussion

The simplified calculation presented in this paper can only give a rough estimate of the true movements of intraocular iron splinters when extracted by means of ophthalmic magnets. The shape of the foreign body and, even more important, the structural changes of the vitreous, i.e. degenerations, membranes and haemorrhages, will influence the path of the splinter considerably. In the past, an extraction of a foreign body via a limbal incision was advised. This implies forcing the foreign body through the zonula and, with larger particles, endangering the lens capsule at the region of the equator. Therefore the extraction via an incision at the pars plana region is presently preferred (Heimann et al., 1983).

Although the movement of an intraocular splinter, as described above, follows a fairly straight pathway to the tip of the magnet, the initial rotation of a longitudinally shaped splinter does not end in pointing either tip towards the tip of the magnet. Quite contrary, the rotation accords to the direction of the field lines, which may be at an angle of up to 90° (cf. fig 1) to the path the splinter will take when freed from vitreous or retinal tissue. This initial rotation, that is quite different from the final pathway of the splinter through the vitreous cavity, is highly dependent upon the angle of the axis of the magnet and may unexpectedly cause secondary injuries to the retina. Furthermore, it causes longitudinal splinters to arrive in an oblique or transverse position at the scleral incision, thus giving rise to difficulties when finally extracting the foreign body. These difficulties can be avoided by pointing the axis of the magnet as precisely as possible onto the splinter before switching on the coil.

From the results given by our simple calculation, the experience of most surgeons, not to place the tip of the magnet on the anterior pole of the cornea (as recommended by Blaskovics-Kettesy, 1970) is clearly supported. A perforation of the posterior lens capsule could ensue, because the splinter does not follow the magnetic field lines but moves straight towards the tip of the magnet.

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Appendix: Implementation of a simple mathematical model of an electric magnet

A magnet for extraocular use consists of a ferromagnetic core (i.e. iron or special alloys with a higher magnetic saturation) and a power coil. The magnetic field generated by such a device depends in a complicated manner on the overall geometry of core and coil and the magnetic properties of the core, making it very difficult to calculate. As we are dealing in this communication solely with the shape and topography of the magnetic field and not with its absolute strength, we may approximate the shape of the electric magnet by an arrangement of coils neglecting saturation effects of the iron core. This model is much easier to calculate and can be checked by comparison with magnetic field measurements (Landwehr 1976, Bronson 1968).

Calculating the magnetic field of a single coil ends up in elliptic integrals that cannot be solved analytically (Jackson, 1962; p141 ff). Only special cases (on the z-axis) can be solved in a straightforward manner. Therefore we calculated numerically the magnetic field using a small computer (Elzet 80, ZB0-CPU with floating point processor, programming language Pascal under the CP/M operating system). According to the BIOT-SAVART law (Jackson, 1962; p134) in its differential form, the contribution of a differential current density ($\mathbf{I} \cdot \mathbf{dl}$) to the field ($\mathbf{dB}$) can be determined at an arbitrary point $\mathbf{X}$:

$$d\mathbf{B} = k \cdot I \cdot (d\mathbf{l} \times \mathbf{X}) / |\mathbf{X}|^3 \quad \text{(k: constant depending on units).}$$

A coil is divided into numerous parts and the contribution of each to the vector field in magnitude and direction is integrated. An additional integration over all coils yields the desired vector field.

For the field in Fig. 1 the magnet was approximated by 35 single coils with varying diameters to mimic the shape of the magnet. Field lines (dashed in fig. 1) are plotted in steps of about 1/1000 of the diameter of the magnet, beginning close at the magnet and following the direction of the calculated field. The gradient lines were obtained in a similar manner: Starting at the edge of the graph the direction of rising field strength is determined and then a tiny part of the gradient line in this direction is plotted, iterating until the magnet is reached. The accuracy of this simple method is sufficient, as demonstrated by identical plots when the precision was doubled.

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