Magnets in living organisms

E. I. Volkov

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The influence of magnetic fields on living systems has long been the object of considerable attention. However, the studies were chiefly of physiological nature, and the physical basis of the effect of the field remained unclear. Studies devoted to the search for and measurement of magnetic components in the tissues of such living organisms as homing pigeons,[1] worker bees,[2] and certain species of bacteria have recently appeared.[3] There are at least three theoretical models that explain how animals detect magnetic fields.

The first model assumes that there is an electrical circuit in the tissues in which a readily measureable current is induced on rapid motion in the Earth's magnetic field. The lack of behavioral reactions of pigeons to magnetic stimuli under laboratory conditions[4] tends to favor this hypothesis. However, it encounters difficulties when it comes to explaining the following well-known experiment. Permanent magnets attached to the neck or head of a pigeon interfere with their ability to orient themselves in space. It is difficult to imagine why this should happen if the detector's principle is that of electric-current induction in a conducting circuit. Further, the recent observation[5] that slow-moving salamanders orient themselves in magnetic fields casts the inductive-orientation hypothesis even further in doubt.

The second model is based on the hypothesis that the magnetic-field detectors are of paramagnetic nature. In an external magnetic field, detector molecules generate their own magnetic field, which is somehow measured by the nervous system. This hypothesis is attractive in that many organic molecules have paramagnetic properties. Moreover, the construction of paramagnet-like detectors in the form of ferromagnetic particles, e.g., single domains, dispersed through a small volume of some tissue is theoretically possible. Detectors of this kind are called superparamagnetic.

The third magnetic-detector model consists of permanent magnets that are free to rotate on a change in magnetic-field direction, thereby creating a torque.

This last possibility is, to all appearances, realized in iron-containing bacteria. They behave like single-domain ferromagnetics in a magnetic field.[6] When such cells are cultured in a medium that contains enough iron (~29 μM) electron microscopy can detect chains of crystals with a total length of more than 1000 nm in which the size of a single crystal is of the order of magnitude of 50 nm. Study of the Mössbauer spectra of frozen and dried bacteria has shown that the iron-containing material of the magnetic cells is magnetite (Fe_3O_4). Each bacterium has a magnetic moment of $M = 1.3\times10^{-12}$ electromagnetic unit (10^{-3} emu $= 1\ A\cdot m^2$), which is sufficient for orientation in the geomagnetic field $H = 0.5G$ ($MH = 6.6\cdot10^{-13}$ erg, and $kT = 4.1\cdot10^{-14}$ erg at $T = 300$ K).

A search for magnetic tissues in homing pigeons and bees[1,2] showed that two detection mechanisms can, in principle, be in operation in these cases: permanent magnets and superparamagnetic regions. Below we present data on magnetic tissues in pigeons, mostly from Ref. 1. Bee magnetic detector studies have been made by practically the same methods.

To characterize the permanent magnets or superparamagnetic domains, a broth is prepared from small fragments of head and neck tissue and placed in a magnetometer. The residual magnetization induced at room temperature by a magnet of 700–2000 G and the magnetization that arises on cooling to -196°C (a test for superparamagnetic regions with sizes of 200–400 Å) were measured. When magnetization was detected, a search was made to identify the precise tissue fragments in the specimen that exhibited intrinsic magnetic activity.

A natural magnetic material was found in each pigeon. It was always single-layered and situated very close to the cranium in a small (1–2 mm) region of tissue. Only approximately 40% of the pigeons had natural magnetizations of 10^{-7}–10^{-6} electromagnetic unit, but they all showed induced magnetization. It amounted to 10^{-6}–10^{-5} emu (a measure of the total amount of magnetic material; this is equivalent to a field that could produce approximately 10^7 single domains in magnetite with sizes of the order of magnitude of 0.1 μm).

A 3000 G magnet was used to induce magnetization in magnetic tissues that had been frozen in liquid nitrogen, and they were then watched for a decrease in magnetization on warming to room temperature. The absence of sharp jumps on the declining magnetization curve indicates that the tissue contains few superparamagnetic domains.

Electron-microscope study of the magnetic tissue showed it to contain nerve fibers and connective tissue and a large number of clusters of electron-dense structures 0.8–0.15 μm long with a length-to-width ratio of 4:1, i.e., the dimensions characteristic for single domains consisting of magnetite or maghemite or for superparamagnetic domains formed by other naturally occurring magnetic substances, for example hematite. In the case of magnetite, the size of the crystals and the level of induced magnetization indicate the presence of 10^7–10^8 single-domain magnets.

Electron-probe analysis showed that the electron-dense particles are rich in iron—the principal component of all magnetic materials. They also contain small amounts of nickel, copper, zinc, and lead. The same elements are detected in trace amounts in magnetite

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crystals synthesized by marine animals—the Amphineuran mollusks (chitons).[7]

X-ray analysis confirmed the presence of iron. On the basis of the composition and quantitative proportions of the elements, the pigeon magnetic material should be magnetite or maghemite or a composite of these two materials. The results of Curie-temperature measurement (the magnetic tissues of five pigeons were combined for one determination), $570° \pm 10° C$, also favor magnetite as the principal component in the magnetic tissue of pigeons. It is known that the residual magnetization of maghemite vanishes between 300 and 400 °C, and that of magnetite at 580 °C.

Further data have been obtained using optical microscopy. Maghemite crystals are orange and magnetite crystals black under the optical microscope. This is because octahedral exchange coupling in magnetite absorbs photons at almost all frequencies. Although the crystals in the pigeon tissues are too small to speak of individual coloration, they are black in aggregates.

On the basis of the above data, therefore, we may conclude that magnetite is the primary magnetic component in pigeons. A similar conclusion was also drawn for bees.[2]

These results do not prove, however, that pigeons and bees are actually capable of detecting a magnetic field by means of an innervated, magnetite-rich natural magnetic structure situated in the immediate vicinity of the cranium in pigeons and in the upper third of the abdomen in bees. Only physiological and behavior experiments will aid us in determining whether these living organisms use the hypothetical detector in their "compass" and "map" systems, and, if so, how.

[1]C. Walcott, J. L. Gould, and J. L. Kirschvink, Science **205**, 1027 (1979).
[2]J. L. Gould, J. L. Kirschvink, and K. S. Deffeyes, Science **201**, 1026 (1979).
[3]R. B. Frankel, R. P. Blakemore, and R. S. Wolfe, Science **203**, 1355 (1979).
[4]M. L. Kreithen and W. T. Keeton, J. Comp. Physiol. **91**, 355 (1974).
[5]J. Phillips, *ibid.* **121**, 273 (1977).
[6]A. J. Kalmijn and R. P. Blakemore, Animal Migration, Navigation and Homing, Springer—Verlag, Berlin, Heidelberg, New York (1978), p. 344.
[7]H. A. Lowenstam, Bull. Geol. Soc. Am. **73**, 435 (1962).

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