THE AMERICAN JOURNAL OF OTOLOGY/VOLUME 16, NUMBER 5 September 1995

EFFECTS OF MAGNETIC RESONANCE IMAGING ON IMPLANTABLE PERMANENT MAGNETS

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ABSTRACT

Implantable permanent magnets are increasingly used in devices for otolaryngologic applications. It is likely that at least some of the patients with implanted magnets will be in need of magnetic resonance imaging (MRI). The effect of an MRI scan on the magnetic properties of implanted permanent magnets has not been previously demonstrated. Some of the basic concepts and descriptive terminology used in industry regarding permanent magnets are reviewed. Experiments presented show that the MRI scan is capable of demagnetizing permanent magnets. A case history is also presented that demonstrates demagnetizing of an implanted Audiant magnet by an MRI scan.

Permanent magnets are increasingly used in otolaryngologic applications for implantable devices. Currently they are used in the Xomed-Treace Audiant Bone Conductor device and in the Nucleus 22 cochlear implant device. Use of permanent magnets will probably be expanded into the middle ear with the development of implantable hearing aid devices (IHDs) using magnets. Magnetic resonance imaging (MRI) is the standard imaging method for multiple anatomic areas. Magnetic resonance imaging uses an extremely powerful supercooled magnet as part of the process to produce an image. It is probable that some future patients with implantable magnets will be in need of an MRI scan for diagnostic purposes. Thus the authors began to explore the effect of the MRI scan on permanent magnets.

It was discovered accidentally that magnets of IHD under development were demagnetized when placed on the ossicles of cadaver temporal bones and placed in an MRI scanner to see if the force produced adversely affected the ossicles. In addition, the authors were aware of at least one patient with an Audiant bone conductor whose device no longer functioned after an MRI scan. As a result of these findings a more thorough investigation of the effects of the MRI scan on permanent magnets was planned. This report addresses some of the pertinent basic science of these magnets, investigates the effect of the MRI scanner on their magnetic properties, and presents the case of a patient with an Audiant implant who had an MRI scan. This is the first published report on the effect of the MRI scan on implantable magnets, except for one report of questionable extrusion of an eye magnetic implant after MRI scan.[1]

DESCRIPTIVE TERMINOLOGY OF PERMANENT MAGNETS

Magnets may be either electromagnets or permanent magnets. A permanent magnet is usually initially magnetized with a coil with flowing electric current. If a substance such as soft iron is magnetized and removed from the coil it will lose its magnetism rapidly. Substances such as this are known as "soft" magnetic substances. Substances that are difficult to demagnetize once magnetized are known as "hard" magnetic substances. Various alloying agents (aluminum, copper, titanium, rare earths, and boron) alter the softness or hardness of the magnetic substance.

Some knowledge of terminology helps considerably in the understanding of the behavior of permanent magnets in clinical applications.[2–5] One of these terms is magnetomotive force (F). This term is basically one of potential strength. It is to magnetics what voltage is to electricity. Magnetomotive force in terms of definition and understanding is an ampere-turn (A-turn). A coil of wire with five turns and with 1 A of current flowing through it would produces 5 A-turns of magnetomotive force. To know the amount of magnetizing force, the magnetomotive force produces in terms of its ability to demagnetize or magnetize something (magnetizing force, represented by H), one must know the length of the core. If in the above example the five turns are wrapped around a core 1 m long, there would be 5 A-turns/m of magnetizing force. The oersted, another unit for measuring magnetizing force is used most commonly by magnet manufacturers, and is equal to $\pi \times 10^{-3} \times$ A-turns/m. The H alone does not describe how much

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attraction the magnetic field would have. The amount of attraction (magnetic flux density) a field has is identified by B (gauss or tesla, or lines of force) and is determined by the core of the electromagnet (i.e., what the coil is wrapped around). For example, the magnetic attraction would be much greater if a coil were wrapped around iron rather than copper. This characteristic of the core is called magnetic permeability (μ). The equation $H \times \mu = B$ relates magnetizing force to the amount of attraction.

There are two systems within the metric system for magnetic units. Electrical Engineering uses the International System (SI) or rationalized meter-kilogram-second system (RMKS). The standard units used for H are A-turns/m. Magnetic attraction (B) is measured in tesla. For a vacuum or air, μ is equal to $4\pi \times 10^{-7}$. These are not the standards used by the Magnetic Materials Producers Association. This organization uses the unrationalized centimeter-gram-second (CGS) system and the unit for magnetizing force (H) is the oersted. Magnetic attraction is measured in gauss. For a vacuum or air, μ is equal to 1 gauss (Table 1).

In processing, permanent magnets become magnetized by putting them in a coil with a high current flow (usually pulsed). If a magnetized permanent magnet is placed in the coil in reverse polarity, there is a certain amount of oersteds (H) or turns of wire carrying a certain current over a specific length, that will demagnetize the magnet on a permanent basis. In technical charts on magnets this is designated by H_{ci} (intrinsic coercive force) or coercivity and is the basic measure of how much a magnet resists demagnetization. The higher the H_{ci}, the harder it is to demagnetize the magnet. The magnetic strength or magnetic attraction a permanent magnet has after being removed from the electric magnetizing coil is termed B residual, and is measured in gauss or tesla (10,000 gauss = 1 tesla). Resistance to demagnetization (H_{ci}) and amount of attraction (B) the magnet has are somewhat independent qualities, and a permanent magnet can have a high B residual and a relatively low H_{ci}. In industry, there is a term called the BH product, which is simply magnetic strength (B residual) × coercivity (H_{ci}) and is intended to be a guide to the strength of magnets. It is a somewhat misleading term because the BH, or maximum energy product, could be the same in two magnets and the coercivity and magnetic strength could be proportionally quite different.

Table 1. Terminology and Units of Magnet Behaviour

Term	*CGS Unit*	*RMKS Unit*
Magnetizing force (H)	Oersted	Ampere turns per meter
Magnetomotive force (F)	Gilbert	Ampere turns
Magnetic flux density (B)	Gauss	Tesla (10,000 gauss = 1 tesla)
Magnetic permeability (μ)	1	1.257×10^{-6}

CGS = centimeter-gram-second system
RMKS = rationalized meter-kilogram-second system

The first Audiant magnets were $SmCo_5$ (1 atom samarium to 5 atoms of cobalt) and had a H_{ci} of >15,000 oersteds, which is high compared to most permanent magnets. In approximately 1989, the Audiant magnet was upgraded to neodymium-iron-boron (NdFeB), which had a H_{ci} of greater than 17,000 oersteds.

The basic question arose, "Does the MRI magnet have enough force to alter the permanent magnets used in the Audiant magnet and other implantable magnets?" The latest generation MRI magnet is basically a huge electromagnet that uses superconducting wires in which the current keeps flowing in a circle with almost no resistance. The core is the chamber for the patient. For a typical 1.5 tesla MRI magnet the demagnetizing force is 15,000 oersteds (assumes the core is air for which $\mu = 1$ gauss), which is close to the H_{ci} (demagnetizing force) of permanent magnets used in the Audiant and other magnets. This means that the MRI magnet would probably alter the magnetic strength of permanent magnets subjected to its field.

MATERIAL AND METHODS

Ten of the original style $SmCo_5$ Audiant implants, two of the newer NdFeB Audiant magnets, and three IHD magnets of a slightly different alloy (Sm_2Co_{17}) were subjected to an MRI field. The magnets were first placed in the "south" (opposite) pole of a GE Sigma (Sigma Chemical Co., St. Louis, Missouri) 1.5 tesla (15,000 oersteds) MRI magnet, to attempt demagnetization or reverse polarization of the magnets (Fig. 1). They were manually moved in and out of the magnetic field up to 40 times in an exploratory attempt to alter their magnetic strength. They were checked prior to and after with a Bell model 640 gaussmeter (F.W. Bell Inc., Orlando, Florida) to measure their residual magnetic strength. Finally, attempts were made to remagnetize them by placing them in the MRI magnet in the "correct" direction (same polarity).

RESULTS

Nine of the $SmCo_5$ magnets were totally unaffected by the MRI magnet (gauss measurements within 5% of original). One, however, suffered a total loss of magnetism, and then the polarity could be completely reversed to within 5% of original gauss readings. The two NdFeB magnets, despite publicized higher H_{ci} ratings, could be readily demagnetized to less than 10% of the original gauss readings. All three of the Sm_2Co_{17} magnets suffered a complete reversal of polarity. When an attempt was made to remagnetize the implants by placing them in the MRI

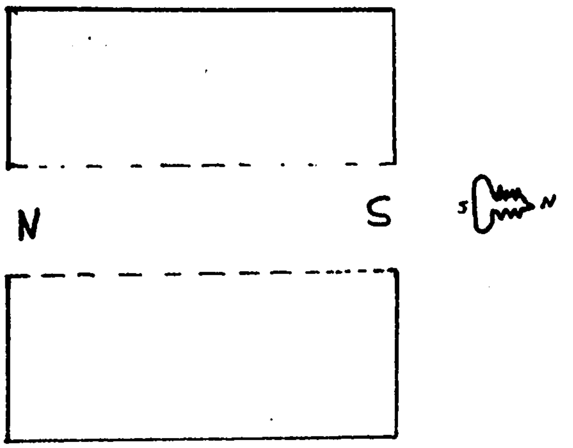

Figure 1. Positioning of magnets in MRI magnet, used to attempt demagnetization or reverse polarization of magnets.

field in the correct orientation, this could not be done successfully with the NdFeB magnets. It was fairly easy to correctly remagnetize the one $SmCo_5$ magnet that had been "reverse magnetized" as well as all three of the Sm_2Co_{17} magnets (gauss readings were within 5% of original).

CASE PRESENTATION

The patient was a 63-year-old white male with right neurosensory hearing loss secondary to an acoustic neuroma and its removal. He was originally implanted as part of the unilateral neurosensory hearing loss study group. Hearing in the left ear was normal. He achieved good results from the Audiant implant. Approximately a year after implantation he began having headaches, and after consideration and informing him that the risks were somewhat unknown, an MRI scan was done. It failed to reveal any pathology, but approximately a third of the head could not be visualized secondary to magnet artifact. After he had the MRI scan, the coil of the sound processor would no longer stay attached to the implant magnet, and sound quality was considerably less.

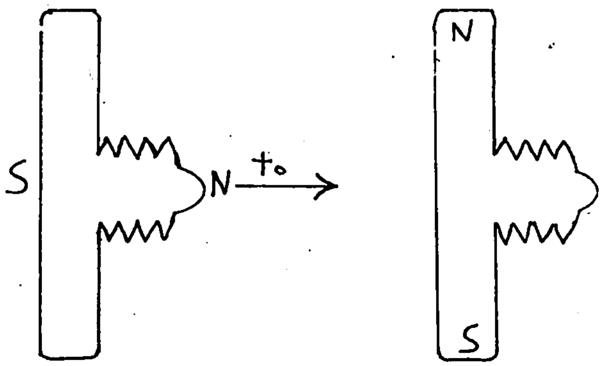

Figure 2. Illustration of magnet position within an MRI magnet with axis of poles of the magnet turned 90 degrees.

DISCUSSION

In prior studies by Hough Ear Institute on the Audiant, using goats, it has been demonstrated that particularly after osseointegration had occurred, there was little to no danger that the MRI magnet would dislodge the implant or cause significant heating of the implant. Earlier studies by the authors indicated that the ossicular chain would not be disrupted if the patient with the IHD underwent MRI scanning. There would be cases in which image quality would still be good enough that it still would be tempting to do an MRI scan (i.e., MRI of the trunk with an Audiant implant). However, if a patient was having an MRI scan of the trunk, a magnetic implant in the head would still be subjected to the full magnetic field. (The field through the MRI magnet is essentially uniform except for a 1-gauss/cm gradient field.) The fate of the implant itself and its usefulness afterwards has never been addressed.

If a patient with an Audiant magnet was placed in an MRI magnet, the tendency would be to change the axis of the poles of the magnet by 90 degrees (Fig. 2). This would markedly impair its effectiveness, and probably render it useless. The effect would be the same for the IHD magnets. The authors' experimental results and one case report have demonstrated this would occur at least some of the time. For some unknown reason the NdFeB magnets seemed to be more susceptible to alteration of their magnetic quality, despite having higher H_{ci} ratings. It also has been demonstrated that, at least in some situations with some alloys, it may be possible to remagnetize the magnets in vivo, using the MRI magnet. In fact, in future it may be better strategy to use softer magnets as implants and plan on remagnetizing them in vivo with the MRI magnet at the end of the procedure rather than to search for magnets with higher resistances to demagnetization. Currently used alloys have about the highest H_{ci} known. A high enough H_{ci} value could still be chosen to make the implantable magnet relatively resistant to ordinary magnetizing fields encountered.

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The authors thank Xomed-Treace Corporation, Jacksonville, Florida for providing technical help and also providing the NdFeB magnets.