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A NEW MAGNET SYSTEM FOR 'INTRAVASCULAR NAVIGATION'*†

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Abstract—Channels such as blood vessels may provide a valuable means of access to parts of the body otherwise inaccessible except by major surgery. The system described here uses the field gradient to a large, movable electromagnet to propel and guide a small permanent magnet through such channels. The permanent magnet may incorporate or tow any of a number of minute diagnostic or therapeutic devices. A flexible catheter may be attached to conduct fluids to or from the tip and to provide additional control.

1. INTRODUCTION

ACCORDING to EQUEN (1957), the use of small, simple, permanent magnets in the removal of ferromagnetic foreign objects from the body has been practiced for some time. Yet only recently have magnets and magnetic devices begun to be developed with the power and sophistication necessary for more varied applications. The magnet system described here is designed for use in such areas as the treatment of intracranial aneurysms and other vascular malformations.

The system incorporates two basic concepts, 'intravascular access' and 'magnetic propulsion and guidance' of particles (necessarily ferromagnetic). LEUSSENHOP (1962), made use of intravascular access in demonstrating (without the aid of magnets) the feasibility of blocking the feeding vessels of certain intracranial vascular malformations with artificial emboli introduced via the carotid vessels in the neck. MEYERS *et al.* (1963), FREI *et al.* (1964), FINGERHUT and ALKSNE (1966), and POOL, ROSOMOFF, ROTH, and YASARGIL (1966), all made use of magnetic guidance in studies on animals. ALKSNE *et al.* (1966) and Rosomoff combined the concepts in attempts to thrombose intracranial aneurysms by attracting micron-sized iron particles into the aneurysmal fundus by stereotactically-placed small permanent magnets. Roth, also, has used iron particles and small permanent magnets in an attempt to thrombose an operatively-exposed superficial temporal artery aneurysm. To our knowledge, however, no complete and lasting thrombosis has yet been achieved, inadequate control of the iron particles—with the ensuing complications from stray particles—having been a major problem. Our magnet system has been designed to ensure much more adequate control.

The magnet system uses the field gradient of a large movable electromagnet to 'navigate' a single small platinum–cobalt (Pt–Co) permanent magnet. The Pt–Co magnet may incorporate or tow any of a number of minute devices. A very flexible Silastic¶ catheter may be attached to conduct fluids to or from the tip and to provide additional control by restraining the tip against too much pull from blood flow or from the external magnet. The catheter also permits the Pt–Co tip to be withdrawn rapidly, without manipulation of the electromagnet. The present system of electromagnet, mounting, tips, and

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¶ Silastic R Medical Grade Tubing, kindly donated by the Dow Corning Center for Aid to Medical Research.

catheters has been designed primarily for intracranial use, but modifications in design should be able to extend the applications to other areas of the body and, even, to industrial applications as well.

II. THE ELECTROMAGNET

A. *Construction*

The electromagnet and its mounting are pictured in Fig. 1. Each of the two energizing coils is 15 in. (38 cm) in diameter and 4½ in. (11 cm) long, and contains three hundred turns of aluminum tape wound around a 4 in. (10 cm) dia. soft iron core. The coils together consume a maximum of 5 kW of power (100 A at 50 V when connected in series), and are cooled by about 10 l/min of tap water. The coils and pole cores are inclined 60° with respect to each other to allow space for the patient's shoulders. The pole tips are low-carbon steel cones of 6 in. (15 cm) dia. base and 60° apex angle, one tip being rounded to ⅜ in. (0·95 cm) radius and the other to 1⅜ in. (3·5 cm) radius. The pole tip separation is 10 in. (25 cm). The mounting enables the entire assembly—coils, pole tips, and yoke—to be rotated about three axes and translated horizontally, thus allowing the magnetic field to be maneuvered about the patient's head.

B. *Performance*

The central field strength as a function of magnet current is shown in Fig. 2. The gradual drop in incremental G/A (from about 13 G/A for currents below 40 A to only 3 G/A at 100 A) is evidence of progressive saturation of the iron circuit. By increasing the cross sections of the pole cores and return yoke sufficiently to match the pole tip base, saturation could be postponed and somewhat higher fields attained—but at a price of greater weight and power consumption.

Figure 3 presents a map of the field pattern (at the maximum magnet current of 100 A) in the plane containing the intersecting axes of the two poles. As indicated, the field drops from several kG near the pole tips to about 820 G midway between them.

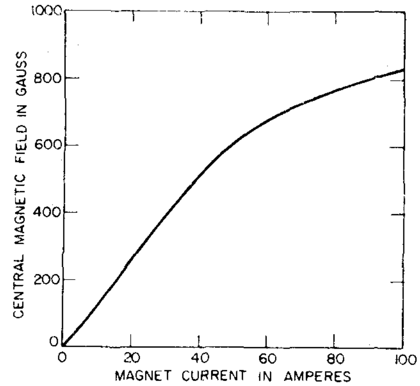

FIG. 2. Central magnetic field as a function of magnet current (coils connected in series).

III. THE CATHETER TIPS

A. *Construction*

Six tips were made, the first two of low-carbon steel and the last four (see Fig. 4) of platinum–cobalt, by far the best permanent magnet material available at the time.* The tips are bullet-shaped, 1–3 mm across, and of two types: non-detachable and detachable (see Fig. 5). The first type is machined to ensure a secure fit to the Silastic catheter and drilled longitudinally to allow fluids introduced into the catheter to be injected through the front of the tip. The second type of tip includes a cavity at the rear filled with paraffin wax in which is imbedded a minute heating coil of ten turns of 0·002 in. (0·5 mm) copper wire. The copper wires are lead through the catheter, which also is attached to the tip with paraffin. A current of about 400 mA passed through the coil suffices to melt the wax and detach the tip.

The permanent magnets are magnetized transversely. For tips whose transverse axis is shorter than the longitudinal axis, this results in a slightly lower level of magnetization (and hence a lower force per unit volume), but for the present electromagnet configuration this direction provides improved maneuverability.

* Anisotropic yttrium–cobalt, still a research laboratory material, is reported to be superior.

FIG. 1. Five kW electromagnet and mounting which permits horizontal translation and rotation about three axes.

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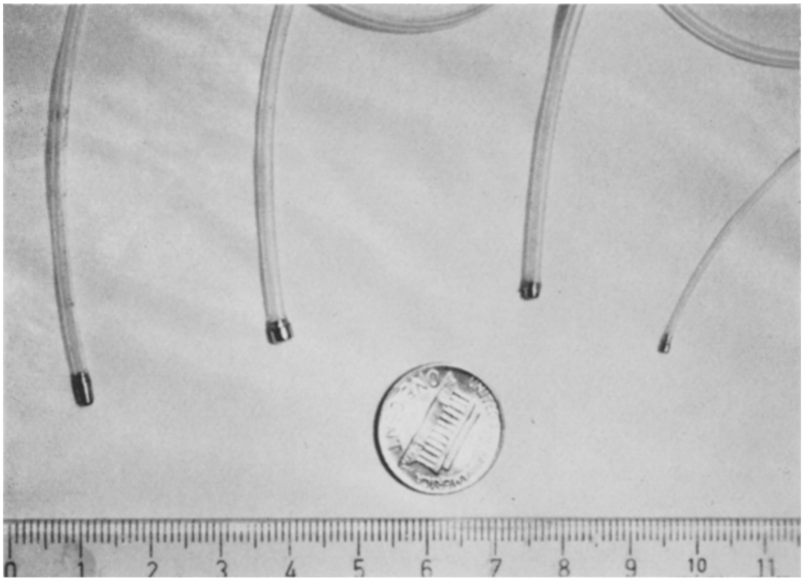

FIG. 4. Platinum–cobalt permanent magnet tips and attached catheters.

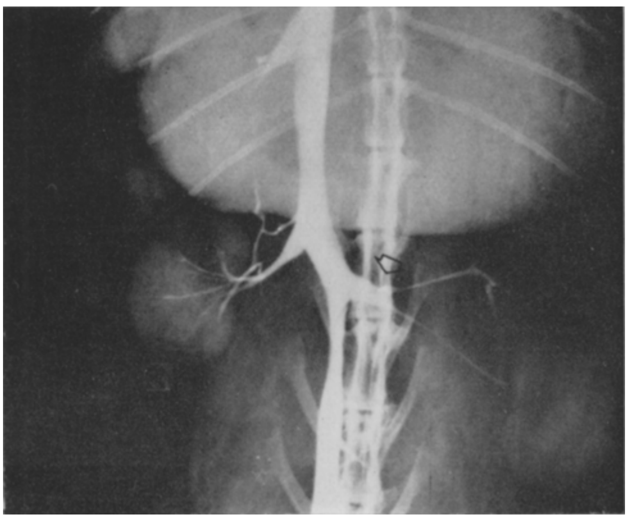

FIG. 7. Angiogram of the venous system of the rabbit: arrow points to the permanent magnet tip.

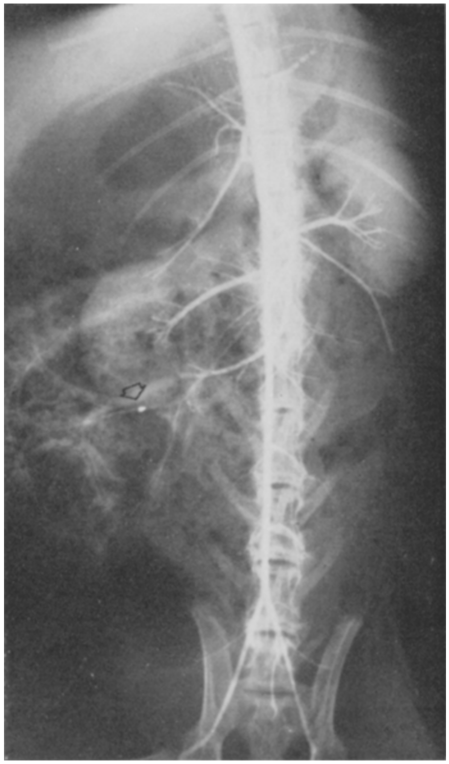

FIG. 8. Angiogram of the arterial system of the rabbit.

FIG. 9. Angiogram illustrating the selectivity achievable when the dye is injected through the catheter.

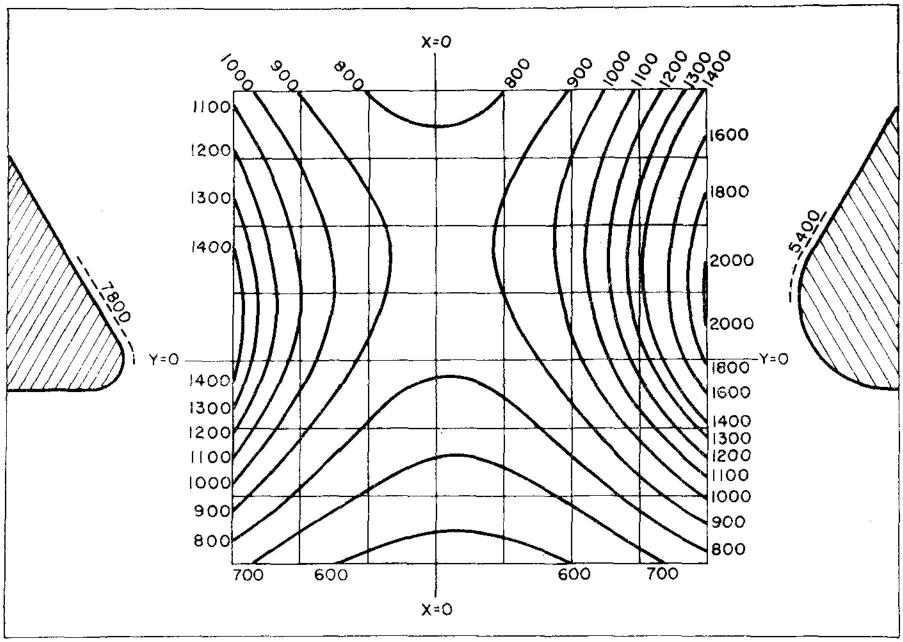

FIG. 3. Contour map of magnetic field in the plane defined by the intersecting axes of the poles (magnet current = 100 A).

The permanent magnet tips are unquestionably superior to those of steel. Not only is the level of magnetization higher (5000–6000 Oe compared with 2000–4000 for the steel), but also the permanence of the magnetic moment of the platinum–cobalt tips allows the external field to exert a torque even on spherical tips. With a proper sequence of orientations and magnitudes of the external magnetic field, the tips may literally be steered around corners.

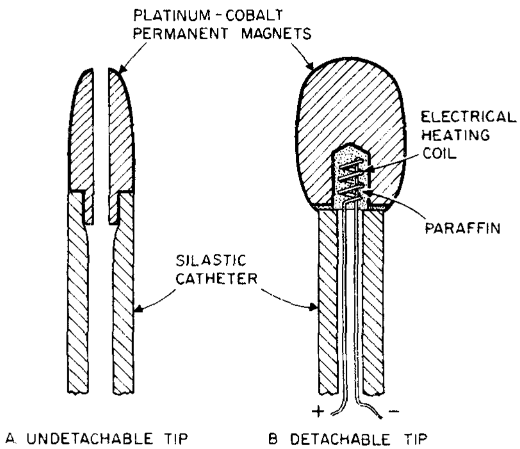

FIG. 5. Sketches of the two types of permanent magnet tips:
(A) non-detachable and
(B) detachable.

B. *Performance*

Qualitative evaluation of the various tips was made in a glass model of the main arteries of the brain, with running tap water to simulate blood flow. Quantitative evaluation of the system consisted in measuring the force on each tip at eight points along the $y = -1$ in. line of the field (see Fig. 6). To within the rather broad limits set by experimental error, the forces per unit volume appeared to be (as they should be) approximately proportional to the field gradient for Pt–Co tips, and proportional to the product of field and gradient for the steel tips. In every case, the force was greater than the weight of the tip, and hence could be made to levitate the tip. The force per unit weight generally was greater on the permanent magnets than on the steel tips, and the force per unit volume was

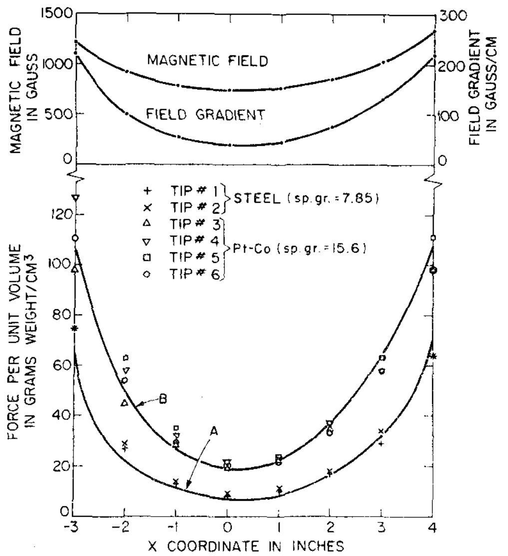

FIG. 6. Forces per unit volume on each of six tips at eight points along the $y = -1$ in. line of the field: (A) theoretical curve for spherical steel tips of high permeability
(B) theoretical curve for permanent magnet tips with magnetization level of 6000 Oe.

greater by a factor of two to three at the field used. Significant geometric differences among the Pt–Co tips cause only slight differences in the forces per unit volume.

The force exerted on a tip is in the direction of the gradient of the field of the external magnet, i.e. toward regions of higher magnetic field. Forces thus are perpendicular to the lines of constant field shown in Fig. 3. The axis of magnetization of a Pt–Co tip tends to remain aligned with the flux lines linking the pole tips of the external magnet. Manipulation of the electromagnet thus can impart to the Pt–Co tips a rotational *torque* as well as a simple pull.

IV. PRELIMINARY EXPERIMENTS

Preliminary experiments indicate that it is feasible to navigate a 0·050 in. (1·3 mm) Pt–Co tip and its attached catheter through the vascular system of a rabbit. Figure 7 shows the tip in the venous system. Note that in entering the left renal vein from the inferior vena cava, the tip and catheter have changed course by more than 90°. Figure 8 shows the tip in one of the several branches of the arterial system entered by suitable manipulation of the external magnet. Figure 9 illustrates the selectivity obtainable in an arteriogram by injecting the dye through the catheter. The three X-ray photographs shown here are typical of those used in these experiments to check periodically the position and orientation of the catheter tip and confirm its proper advance through the blood vessels. Future applications could employ continuous X-ray monitoring of the catheter tip position.

The special catheter-introducer developed in connection with these experiments will be reported in detail in the near future.

V. NEUROSURGICAL APPLICATIONS

The present magnet system has been developed for three primary uses:

(1), the blocking of the feeding vessels of certain intracranial vascular malformations by implanting the detachable tip or by injecting congealable plastic through the catheter,

(2) the thrombosis of certain intracranial aneurysms by injecting congealable plastic into them or by detaching a Pt-Co tip inside and then injecting through the catheter iron particles which should adhere to the Pt-Co tip, and

(3) the local injection of high concentrations of chemotherapeutic agents after precise placement of the catheter in the main artery supplying a glioma: the localization of the agent should decrease the side effects on the normal brain and may allow the use of otherwise toxic agents.

VI. OTHER MEDICAL APPLICATIONS

By appropriate design of the tips, the magnet system should be suitable for a wide variety of applications where remote guidance is useful. The medical applications include the exploration—for research, diagnosis, or therapy—of the circulatory, gastro-intestinal, genito-urinary, and respiratory systems. The exploration can be for X-ray contrast studies, the collection of samples for analysis, the precise injection of local drugs, chemotherapeutic agents, or tracer isotopes, the embolization and thrombosis of blood vessels, or the placement of special devices. In most cases, no surgery is required beyond the small incision which may be necessary to introduce the catheter.

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SYSTEME MAGNETIQUE POUR LA "NAVIGATION INTRAVASCULAIRE"

Sommaire—Les vaisseaux sanguins se présentent comme des voies d'accès possibles à certaines parties du corps inaccessibles autrement que par une intervention chirurgicale importante. Le système décrit ici utilise le champ d'un grand électro-aimant convenablement orienté, guidant un petit aimant permanent à travers les vaisseaux sanguines. L'aimant permanent peut être tracteur ou porteur d'un certain nombre d'éléments de diagnostic ou de thérapeutique. On peut y attacher un cathéter flexible qui facilite le guidage et permet l'injection de liquide.

NEUES MAGNETSYSTEM ZUR 'INTRAVASKULÄREN NAVIGATION'

Zusammenfassung—Kanäle wie die Blutgefäße können eine wertvolle Möglichkeit bieten, Körperteile zu erreichen, die sonst nur durch große Chirurgie zu erreichen sind. Das hier beschriebene System benutzt den Feldgradienten eines großen, geeignet befestigten Elektromagneten, un einen kleinen Dauermagneten duchr derartige Kanäle zu führen. Der Dauermagnet kann hinter sich (oder kann selbst eingebaut werden in) jede gewünschte Zahl kleinster diagnosticher oder therapeutischer Geräte tragen. Ein flexibler Katheter kann befestigt werden, wenn Flüssigkeiten an die Spitze geleitet werden sollen, und wenn zusätzliche Führung gewünscht ist.