AJNR

Aneurysm Clips: Evaluation of Magnetic Field Interactions and Translational Attraction by Use of ''Long-Bore'' and ''Short-Bore'' 3.0-T MR Imaging Systems

Frank G. Shellock, Jean A. Tkach, Paul M. Ruggieri, Thomas J. Masaryk and Peter A. Rasmussen

AJNR Am J Neuroradiol 2003, 24 (3) 463-471
http://www.ajnr.org/content/24/3/463

AJNR Am J Neuroradiol 24:463–471, March 2003

Aneurysm Clips: Evaluation of Magnetic Field Interactions and Translational Attraction by Use of "Long-Bore" and "Short-Bore" 3.0-T MR Imaging Systems

Frank G. Shellock, Jean A. Tkach, Paul M. Ruggieri,
Thomas J. Masaryk, and Peter A. Rasmussen

BACKGROUND AND PURPOSE: **The use of 3.0-T MR systems is increasing worldwide. We evaluated magnetic field interactions and translational attraction for 32 aneurysm clips in association with exposure to "long-bore" and "short-bore" 3.0-T MR imaging systems.**

METHODS: **Thirty-two different aneurysm clips were evaluated in this investigation. Each aneurysm clip was qualitatively evaluated for magnetic field interactions and quantitatively assessed for translational attraction by using the deflection angle test. The deflection angle tests were performed at the points of the highest spatial gradients for long-bore and short-bore 3.0-T MR imaging systems.**

RESULTS: **Seventeen of the 32 aneurysm clips showed positive magnetic field interactions. Deflection angles for the aneurysm clips were significantly ($P < .001$) higher on the short-bore (range, 0–18 degrees) compared with those recorded on the long-bore (range, 0–16 degrees) 3.0-T MR imaging system. Aneurysm clips made from commercially pure titanium and titanium alloy displayed no translational attraction (n = 15), whereas those made from stainless steel alloy, Phynox, and Elgiloy displayed positive deflection angles (n = 17).**

CONCLUSION: **The 32 different aneurysm clips passed (angle <45 degrees) the deflection angle test by using the long- and short-bore 3.0-T MR imaging systems, indicating that they are safe for patients and other persons in these MR environments (ie, immediate area of MR imaging systems). However, only clips made from the titanium and titanium alloy are entirely safe for patients undergoing MR imaging procedures because of the total lack of magnetic field interactions. The remaining clips require characterization of magnetic field–induced torque. Because of possible differences in the points of the highest spatial gradients for different 3.0-T MR imaging systems, the results are specific to the imaging units and bore designs used in this investigation.**

Neurosurgical management of an intracranial aneurysm or arteriovenous malformation by application of a temporary or permanent aneurysm clip is a well-established procedure (1–4). The presence of an intracranial aneurysm clip in a patient or other person in the MR environment may present a hazardous situation (5–10). Although certain aneurysm clips are a contraindication to the MR environment, others that are classified as "nonferromagnetic" or "weakly ferromagnetic" are deemed safe for patients or other persons exposed to MR imaging systems operating at 1.5 T or less (5–26).

The use of 3.0-T MR imaging systems for clinical applications is increasing worldwide. Importantly, most previous investigations conducted to assess MR imaging safety of aneurysm clips used MR imaging systems with static magnetic fields of 1.5 T or less (7, 11–25). In general, the increasing use of MR at 3.0 T requires additional studies to be performed to evaluate metallic implants and devices at this field strength. Thus, it is necessary to perform ex vivo testing at 3.0

Received April 25, 2002; accepted after revision July 2.

Supported by The Cleveland Clinic Foundation, Cleveland, OH, and the Institute for Magnetic Resonance Safety, Education, and Research, Los Angeles, CA.

From the University of Southern California, Los Angeles (F.G.S.), Keck School of Medicine and Institute for Magnetic Resonance, Safety, Education, and Research, Los Angeles, CA, and the Divisions of Radiology (J.A.T., P.M.R., T.J.M.), Neuroradiology Section, and Surgery (P.A.R.), Section of Neurosurgery, The Cleveland Clinic Foundation, Cleveland, OH.

Address reprint requests to Frank G. Shellock, PhD, 7511 McConnell Avenue, Los Angeles, CA 90045.

T to characterize magnetic field–related safety for aneurysm clips before allowing persons with these implants to enter this particular MR environment.

An important aspect of MR safety testing for metallic implants involves the determination of magnetic field interactions (ie, motion) and translational attraction (17, 18, 23–25). Translational attraction is typically assessed by using the deflection angle test originally described by New et al (17), modified and used by others (18, 23–25), and recommended by the American Society for Testing and Materials (27). According to this procedure, the deflection angle for an implant should be measured at the point of the highest spatial gradient for the specific MR imaging system used for testing (23–27). If the deflection angle from the vertical is less than 45 degrees, the implant passes the translational attraction test insofar as the magnetic force acting on the implant is less than the gravitational force (27).

Various types of magnets exist for commercially available 3.0-T MR imaging systems. The magnet configurations include conventional long- and short-bore imaging units used for head-only and whole-body clinical applications. Because of physical differences in the position and magnitude of the highest spatial gradient for different magnets, measurements of deflection angles for implants by using long- versus short-bore MR imaging systems may produce substantially different results. Therefore, the purpose of this investigation was to evaluate magnetic field interactions and translational attraction for 32 different aneurysm clips in association with exposure to long- and short-bore 3.0-T MR imaging systems. Implications of the results of this study for patients and other persons with aneurysm clips regarding the 3.0-T environment are discussed herein.

Methods

Aneurysm Clips

Thirty-two different aneurysm clips from various manufacturers were evaluated in this investigation. Each aneurysm clip was representative of the manufactured finished version and was not altered in any manner before testing. These aneurysm clips were selected for this study because they represent various types of clips made from nonferromagnetic or weakly ferromagnetic materials (eg, stainless steel alloy, Phynox, Elgiloy, commercially pure titanium, titanium alloy) used for temporary or permanent treatment of aneurysms or arteriovenous malformations. The Table lists specific information regarding the aneurysm clips (ie, the name, material, and manufacturer).

3.0-T MR Imaging Systems

According to the American Society for Testing and Materials (27), translational attraction should be assessed for implants at the point of the highest spatial gradient for the MR imaging system used for testing. This is done to evaluate the magnet-related force at an extreme or worst-case position for a metallic object. As previously stated, there are various types of magnets used for 3.0-T MR imaging systems, including long- and short-bore imaging units used for head-only and whole-body clinical applications. Because there are physical differences in the position and magnitude of the highest spatial gradient for a given magnet (based on a review of technical specifications provided by MR imaging system manufacturers), measurements of deflection angles may be substantially different. Therefore, in this study, long- and short-bore MR imaging systems were used to evaluate translational attraction for the aneurysm clips, as follows: long-bore MR system, actively shielded, head-only, MR imaging system (length, 248 cm; bore inner diameter, 55 cm; 3-T MR imaging system; General Electric Medical Systems, Milwaukee, WI); and short-bore MR system, actively shielded, head-only MR imaging system (length, 130 cm; bore inner diameter, 60 cm; MAGNETOM, Allegra 3-T Headscanner; Siemens Medical Systems, Erlangen, Germany).

Qualitative Evaluation of Magnetic Field Interaction

Each aneurysm clip was inspected at the entrance of the imaging system bore to determine the qualitative presence of magnetic field interactions with the 3.0-T MR imaging systems. This was defined as any visual observance of directional movement, rotation, or alignment to the magnetic field. The results were scored as either positive (observable motion, as described) or negative (absolutely no motion). The entrance of the MR imaging system bore was the position selected for this assessment because it provided an easy and rapid site for this evaluation and represented the closest position of the “MR environment” (ie, the immediate area relative to the MR imaging system).

Assessment of Translational Attraction

Translational attraction was assessed for each aneurysm clip by using a standardized procedure known as the *deflection angle test* according to guidelines provided by the American Society for Testing and Materials (27). The aneurysm clip was attached to a special test fixture to measure the deflection angle in the long- and short-bore MR imaging systems at the points of the highest spatial gradients (23–25, 27). The test fixture consists of a sturdy structure capable of holding the aneurysm clip in a proper position without deflection of the test fixture. The test fixture has a plastic protractor with 0-degree graduated markings. The protractor is rigidly mounted to the structure. The zero-degree indicator on the protractor was oriented vertically. The test fixture has a plastic bubble level permanently affixed to the top to ensure proper orientation in the MR imaging system during the test procedure.

The aneurysm clip was suspended from a thin, light-weight string (weight, $<1\%$ of the weight of the implant) that was attached at the 0-degree indicator position on the protractor. The length of the string was 20 cm, allowing the aneurysm clip to be suspended from the test fixture and to hang freely in space. Sources of forced air movement within the respective 3.0-T MR imaging system bores were shut off during the deflection angle measurements.

Measurements of deflection angles for the aneurysm clip were obtained at the positions in the 3.0-T MR imaging systems that produced the greatest magnetically induced deflections (ie, the points of the highest spatial gradients) (23–25, 27). This position was determined for each 3.0-T MR imaging system by using gauss line plots provided by the manufacturer, measurements, and visual inspection to identify the location where the spatial magnetic field gradient was the highest. For the long-bore 3.0-T MR imaging system, the highest spatial gradient occurs at a position that is 96 cm from isocenter. The magnetic spatial gradient at this position is 3.3 T/m. For the short-bore 3.0-T MR imaging system, the highest spatial gradient occurs at a position that is 78 cm from isocenter. The magnetic spatial gradient at this position is 5.25 T/m. The locations of the highest spatial gradients were marked by using tape to facilitate repeated measurements of deflection angles for the aneurysm clips.

Thus, the test fixture was placed at the point of the highest spatial gradient for the long- and short-bore 3.0-T MR imaging systems. The aneurysm clip was held on the test fixture so that

Aneurysm clips: evaluation of magnetic field interactions and translational attraction using "long-bore" and "short-bore" 3.0-T MR imaging systems

No.	Description	LB Mag. Field Interaction	LB MR System Deflection Angle	SB Mag. Field Interaction	SB MR System Deflection Angle
1	Perneczky; straight, 2-mm blade; stainless steel alloy; Zeppelin Chirugishe Instrumente, Pullach, Germany	Positive	8	Positive	15
2	Perneczky; straight, 6-mm blade; stainless steel alloy; Zeppelin Chirugishe Instrumente, Pullach, Germany	Positive	12	Positive	17
3	Perneczky; straight, 7-mm blade; stainless steel alloy; Zeppelin Chirugishe Instrumente, Pullach, Germany	Positive	12	Positive	17
4	Spetzler pure titanium aneurysm clip, model C-2200; straight, 5-mm blade; C.P. titanium; NMT Neurosciences, Duluth, Georgia	Negative	0	Negative	0
5	Spetzler pure titanium aneurysm clip, model C-2212; curved, 7-mm blade; C.P. titanium; NMT Neurosciences, Duluth, Georgia	Negative	0	Negative	0
6	Spetzler pure titanium aneurysm clip; straight, 9-mm blade; C.P. titanium; Elekta Instruments, Atlanta, Georgia	Negative	0	Negative	0
7	Spetzler pure titanium aneurysm clip, model C-2214; curved, 11-mm blade; C.P. titanium; NMT Neurosciences, Duluth, Georgia	Negative	0	Negative	0
8	Spetzler pure titanium aneurysm clip, model C-2203; straight, 11-mm blade; C.P. titanium; NMT Neurosciences, Duluth, Georgia	Negative	0	Negative	0
9	Spetzler pure titanium aneurysm clip, model C-2526; straight, 11-mm blade; C.P. titanium; NMT Neurosciences, Duluth, Georgia	Negative	0	Negative	0

Note.—LB indicates long-bore; Mag., magnetic; SB, short-bore; C.P., commercially pure.

Continued

No.	Description	LB Mag. Field Interaction	LB MR System Deflection Angle	SB Mag. Field Interaction	SB MR System Deflection Angle
10	Spetzler titanium pure aneurysm clip, model C-2224; straight, 11-mm/3.5-mm fenestrated blade; C.P. titanium; NMT Neurosciences, Duluth, Georgia	Negative	0	Negative	0
11	Spetzler titanium aneurysm clip; straight, 13-mm blade; C.P. titanium; Elekta Instruments, Atlanta, Georgia	Negative	0	Negative	0
12	Sugita fenestrated large clip; bent, 7.5-mm blade; Elgiloy; Mizuho America, Inc.; Beverly, Massachusetts	Positive	5	Positive	10
13	Sugita fenestrated large Fujita blade deflected type aneurysm clip for permanent occlusion; angled, 10-mm serrated blade; Elgiloy; Mizuho America, Inc.; Beverly, Massachusetts	Positive	8	Positive	10
14	Sugita large aneurysm clip for permanent occlusion; straight, 21-mm serrated blade; Elgiloy; Mizuho America, Inc.; Beverly, Massachusetts	Positive	9	Positive	12
15	Sugita long aneurysm clip for permanent occlusion; straight, 19-mm non-serrated blade; Elgiloy; Mizuho America, Inc.; Beverly, Massachusetts	Positive	9	Positive	12
16	Sugita standard clip; bent, 8-mm blade; Elgiloy; Mizuho America, Inc.; Beverly, Massachusetts	Positive	5	Positive	9
17	Sugita standard clip; curved, 6-mm blade; Elgiloy; Mizuho America, Inc.; Beverly, Massachusetts	Positive	5	Positive	9
18	Sugita temporary mini clip; bent, 7-mm blade; Elgiloy; Mizuho America, Inc.; Beverly, Massachusetts	Positive	3	Positive	4

Continued

No.	Description	LB Mag. Field Interaction	LB MR System Deflection Angle	SB Mag. Field Interaction	SB MR System Deflection Angle
19	Sugita temporary standard clip; straight, 7-mm blade; Elgiloy; Mizuho America, Inc.; Beverly, Massachusetts	Positive	5	Positive	9
20	Sugita titanium standard aneurysm clip for permanent occlusion; 45-degree angled, 19-mm serrated blade; titanium alloy; Mizuho America, Inc.; Beverly, Massachusetts	Negative	0	Negative	0
21	Yasargil mini clip, titanium model FT728T; bayonet, 7-mm blade; titanium alloy; Aesculap, Inc.; Center Valley, Pennsylvania	Negative	0	Negative	0
22	Yasargil standard aneurysm clip model FE750; straight, 9-mm blade; Phynox; Aesculap, Inc.; Center Valley, Pennsylvania	Positive	6	Positive	11
23	Yasargil standard aneurysm clip model FE780; straight, 14-mm blade; Phynox; Aesculap, Inc.; Center Valley, Pennsylvania	Positive	8	Positive	13
24	Yasargil standard aneurysm clip model FE786; curved, 15.3-mm blade; Phynox; Aesculap, Inc.; Center Valley, Pennsylvania	Positive	6	Positive	10
25	Yasargil standard aneurysm clip model FE790K; straight, 20-mm blade; Phynox; Aesculap, Inc.; Center Valley, Pennsylvania	Positive	16	Positive	18
26	Yasargil standard aneurysm clip model FE798; bayonet, 20-mm blade; Phynox; Aesculap, Inc.; Center Valley, Pennsylvania	Positive	6	Positive	10
27	Yasargil standard aneurysm clip model FE887; angled, 7-mm blade; Phynox; Aesculap, Inc.; Center Valley, Pennsylvania	Positive	5	Positive	9

Continued

No.	Description	LB Mag. Field Interaction	LB MR System Deflection Angle	SB Mag. Field Interaction	SB MR System Deflection Angle
28	Yasargil standard aneurysm clip titanium model FT740T; straight, 7-mm blade; titanium alloy; Aesculap, Inc.; Center Valley, Pennsylvania	Negative	0	Negative	0
29	Yasargil standard aneurysm clip titanium model FT750T; straight, 9-mm blade; titanium alloy; Aesculap, Inc.; Center Valley, Pennsylvania	Negative	0	Negative	0
30	Yasargil standard aneurysm clip titanium model FT758T; bayonet, 12-mm blade; titanium alloy; Aesculap, Inc.; Center Valley, Pennsylvania	Negative	0	Negative	0
31	Yasargil standard aneurysm clip titanium model FT760T; straight, 11-mm blade; titanium alloy; Aesculap, Inc.; Center Valley, Pennsylvania	Negative	0	Negative	0
32	Yasargil standard aneurysm clip titanium model FT790T; straight, 20-mm blade; titanium alloy; Aesculap, Inc.; Center Valley, Pennsylvania	Negative	0	Negative	0

the string was vertical and was then released. The deflection angle for the aneurysm clip from the vertical direction to the nearest 0.5 degree was measured three times and averaged (23–25, 27).

Statistical Analysis

Deflection angle measurements obtained for the aneurysm clips during exposure to the long-bore MR imaging system were compared with those recorded during exposure to the short-bore MR imaging system by using a Wilcoxon Signed Rank Test (StatView; SAS Institute, Inc., Cary, NC).

Results

The findings for magnetic field interactions and translational attraction for the aneurysm clips exposed to the long- and short-bore MR imaging systems are summarized in the Table. Seventeen of the 32 aneurysm clips showed positive magnetic field interactions. Deflection angles for the aneurysm clips were significantly ($P < .001$) higher on the short-bore 3.0-T MR imaging system compared with those recorded on the long-bore 3.0-T MR imaging system. On the long-bore MR imaging system, deflection angles ranged from 0 to 16 degrees. On the short-bore MR imaging system, deflection angles ranged from 0 to 18 degrees. Aneurysm clips made from commercially pure titanium and titanium alloy displayed no translational attraction ($n = 15$), whereas those made from stainless steel alloy, Phynox, and Elgiloy displayed positive deflection angles ($n = 17$).

Discussion

MR imaging procedures may be unsafe for patients with certain implants made from ferromagnetic or conductive materials because of problems associated with movement, heating, or induced electrical currents (5–8, 17, 30–36). Regarding aneurysm clips, heating and induced currents are not of concern because of the physical size and shape of these relatively small implants (17, 18, 30–35). Notably, MR imaging–related heating and induced currents have been reported for only those implants or devices that have elongated configurations or that are electronically activated (eg, neurostimulation systems, cardiac pacemakers, etc.) (6–8, 31–36). Therefore, from an MR safety consideration, it is primarily important to determine magnetic qualities for aneurysm clips before allowing patients or other persons with these objects into the MR environment. Because most previous testing of aneurysm clips was conducted at 1.5 T, as static magnetic fields of MR imaging systems increase above this level, further investigations are necessary to characterize MR safety for these implants.

From a magnetic field consideration, translational attraction or torque may cause movement or dislodgment of a ferromagnetic implant, resulting in injury (6–9, 15, 17, 18, 23–25, 29, 30). Translational attraction is proportional to the strength of the static magnetic field, the strength of the spatial gradient, the mass of the object, the shape of the object, and the magnetic susceptibility of the object (17, 23–25, 29, 30). The effects of translational attraction on ferromagnetic objects are predominantly responsible for possible hazards in the MR environment (ie, immediate area around MR imaging system) (5, 8, 30). The deflection angle test is commonly used to determine magnetic field–related translational attraction for implants, materials, and devices (17, 18, 23–25, 29).

The American Society for Testing and Materials guidelines for deflection angle testing of implants in the MR environment, indicate that, ". . . if the implant deflects less than 45 degrees, then the magnetically induced deflection force is less than the force on the implant due to gravity (its weight)" (27). For this condition, it is assumed that any risk imposed by the application of the magnetically induced force is no greater than any risk imposed by normal daily activity in the earth's gravitational field (27). Accordingly, findings from the deflection angle test permit implants and devices made from nonferromagnetic or weakly ferromagnetic materials that display deflection angles between 0 and 44 degrees to be present in patients or other persons in the MR environment (23–25, 27, 29).

Torque, which tends to align a ferromagnetic object parallel to the magnetic field, is dependent on the strength of the magnetic field, the dimensions of the object, and the initial angulation of the object relative to the static magnetic field (17, 23–25, 30). Torque effects on ferromagnetic objects are mainly responsible for possible hazards during an MR imaging procedure, when the patient is positioned at the center of the MR imaging system (ie, the position where torque effects are greatest) (30).

A variety of techniques have been used to qualitatively or quantitatively determine magnetic field-related torque for implants and devices (17, 23, 25, 29, 30). To date, a test procedure and acceptable measurement value for torque imposed on implants has not been defined by the American Society for Testing and Materials. However, according to the American Society for Testing and Materials (27), a torque value for an implant "that is less than that produced by normal daily activities (which might include rapidly accelerating vehicles or amusement park rides) is assumed to be safe." Notably, the amount of torque necessary to displace an aneurysm clip is unknown, particularly because counter forces (eg, related to the closing force of the clip, granulation of tissue, and other factors) may be present that require additional characterization, possibly by using in vivo techniques. Therefore, torque was not specifically determined for the aneurysm clips in this study because no standard currently exists for the quantification technique for torque and no measurement value is available for use to designate whether an aneurysm clip is unsafe. Therefore, only aneurysm clips that exhibit no magnetic field movements are considered to be safe from a torque consideration.

Aneurysm clips come in a wide variety of shapes and blade lengths and are made from different materials with varying magnetic susceptibilities. Each of these factors can influence the MR safety aspects of these implants. In the present study, aneurysm clips had shapes that included straight, bent, curved, and angled versions with blade lengths that ranged from 2 mm (Perneczky; Zeppelin Chirugishe Instrumente, Pullach, Germany) to 21 mm (Sugita, Large Aneurysm Clip for Permanent Occlusion; Mizuho America, Inc., Beverly, MA). Materials used to make these aneurysm clips included stainless steel alloy, Phynox, Elgiloy, commercially pure titanium, and titanium alloy.

Previous reports investigating magnetic qualities of aneurysm clips indicated that every aneurysm clip made from stainless steel alloy, Phynox, Elgiloy, commercially pure titanium, and titanium alloy was safe at 1.5 T (6–8, 11–14, 15–26). In consideration of the current knowledge pertaining to aneurysm clips at 1.5 T, the following guidelines have been recommended for careful consideration before performing MR imaging in a patient with an aneurysm clip and before allowing any person with an aneurysm clip into the MR environment (6–8, 23).

Guidelines Regarding Aneurysm Clips and the MR Environment

1. Specific information (ie, manufacturer, type or model, material, lot and serial numbers) regarding the aneurysm clip must be known, especially with respect to the material used to make the aneurysm clip, so that only patients or other persons with nonferromagnetic or weakly ferromagnetic clips are allowed into the MR environment. The manufacturer provides this information in the labeling of every aneurysm clip. The implanting surgeon is responsible for properly communicating this information in the patient's records.

2. An aneurysm clip that is in its original package and made from Phynox, Elgiloy, MP35N, titanium alloy, commercially pure titanium, or other material known to be nonferromagnetic or weakly ferromagnetic does not need to be evaluated for ferromagnetism. Aneurysm clips made from nonferromagnetic or weakly ferromagnetic materials in original packages do not require testing of ferromagnetism because the manufacturers ensure the pertinent MR safety aspects of these clips and, therefore, should be held responsible for the accuracy of the labeling.

3. If the aneurysm clip is not in its original package and properly labeled, it should undergo testing for magnetic field interactions.

4. The radiologist and implanting surgeon should be responsible for evaluating the available information pertaining to the aneurysm clip, verifying its accuracy, obtaining written documentation and deciding to perform the MR procedure after considering the risks versus the benefits of the examination.

Of note is that Brothers et al (37) evaluated patients after surgery for vertebrobasilar aneurysms with nonferromagnetic Sugita aneurysm clips at 1.5 T and reported that no ill effects occurred. In addition, Pride et al (26) conducted a study of patients with nonferromagnetic aneurysm clips who underwent MR imaging. No objective adverse outcome occurred in these patients, further confirming that MR imaging can be performed safely in patients with nonferromagnetic clips (26).

However, as previously discussed, few studies have been performed to evaluate magnetic field interactions of implants in association with MR imaging systems operating above 1.5 T (28, 29). A study conducted at 8.0 T by Kangarlu and Shellock (29) reported that all aneurysm clips, even those made from titanium or titanium alloy, displayed positive translational attractions (deflection angles ranged from 5 to 53 degrees). Importantly, several aneurysm clips reported to be safe at 1.5 T (6–8, 17, 18, 23) were found to be potentially unsafe at 8.0 T because they showed excessive deflection angles and relatively high qualitative torque values (29). In view of the findings at 8.0 T and because of the proliferation of 3.0-T MR imaging systems, it was considered important to determine magnetic field–related safety for comparable aneurysm clips.

Findings from the present study indicated that only the aneurysm clips made from commercially pure titanium or titanium alloy are definitely safe because they exhibit no magnet-related movements in association with exposure to 3.0-T MR imaging systems. Aneurysm clips made from stainless steel alloy, Phynox, and Elgiloy, while displaying acceptable deflection angles (<45 degrees) and thus considered safe for patients and other persons in the long- and short-bore MR environments (again, the immediate areas associated with the MR imaging systems up to and including the entrances of the magnet bores), require further characterization of torque effects to determine safety for patients who have these clips before allowing them to undergo MR imaging procedures.

Thus, from a practical consideration, the results of this investigation have implications for two different situations. First, regarding the long- and short-bore 3.0-T MR environments, all aneurysm clips that were assessed seem to be safe because of the relatively minor magnetic field-related translational attractions that were measured (deflection angles <45 degrees). Therefore, patients and other persons (eg, MR technologist, family member, etc.) with these specific aneurysm clips would be permitted into the respective 3.0-T MR environments. Second, for patients undergoing MR imaging procedures with the use of long- or short-bore 3.0-T MR imaging systems, only the aneurysm clips made from commercially pure titanium or titanium alloy seem to be entirely safe because of the total lack of magnet-related movements. The remaining aneurysm clips made from stainless steel alloy, Phynox, and Elgiloy require characterization of magnetic field-induced torque to determine whether they are safe for patients during MR imaging procedures. Notably, these results are specific to the 3.0-T MR imaging systems used for this evaluation or with comparable "highest spatial gradients."

Long-Bore versus Short-Bore Deflection Angle Measurements

An interesting finding of this study is that there were significantly ($P < .001$) higher deflection angles measured for the aneurysm clips during exposure to the short-bore versus the long-bore 3.0-T MR system. To our knowledge, this is the first description of such an important phenomenon that is obviously due to the higher spatial gradient associated with the short-bore imaging unit. Although this did not impact the MR imaging safety aspects of the aneurysm clips in this study, it is conceivable that other metallic implants may be found to be safe on the long-bore MR imaging system and unsafe on a short-bore MR imaging system. Therefore, further study of this issue is warranted.

Acknowledgments

Special thanks to Dr. Mark Cohen, Dr. Susan Bookheimer, and Dr. John Mazziotta at the University of California, Los Angeles Brain Mapping Division, Los Angeles, CA, for permitting use of the 3.0-T MR imaging system and, thus, facilitating the performance of this research project.

References

1. Yasargil MG. *Microsurgery Applied to Neurosurgery.* Stuttgart: Georg Thieme; 1969:126–130
2. Dujovny M, Kossovsky N, Kossovsky R, et al. **Intracranial clips: an examination of the devices used for aneurysm surgery**. *Neurosurgery* 1984;14:257–267
3. Dujovny M, Kossovsky, Kossowsky R, et al. **Vascular clips: an historic and biomedical perspective.** In: Fein JN, Flamm E, eds. *Cerebral Vascular Surgery.* New York: Springer-Verlag; 1985:997–1046
4. Mayfield FH, Kees G Jr. **A brief history of the development of the Mayfield clip: technical note.** *J Neurosurg* 1971;35:97–100
5. Sawyer-Glover A, Shellock FG. **Pre-MRI procedure screening: recommendations and safety considerations for biomedical implants and devices.** *J Magn Reson Imaging* 2000;12:92–106
6. Shellock FG. *Magnetic Resonance Procedures: Health Effects and Safety.* Boca Raton: CRC Press; 2001
7. Shellock FG. *Guide to MR Procedures and Metallic Objects: Update 2001.* 7th ed. Philadelphia: Lippincott Williams & Wilkins; 2001
8. Shellock FG. *Reference Manual for Magnetic Resonance Safety: 2003 Edition.* Salt Lake City: Amirsys, Inc.; 2003
9. Klucznik RP, Carrier DA, Pyka R, Haid RW. **Placement of a ferromagnetic intracerebral aneurysm clip in a magnetic field with a fatal outcome.** *Radiology* 1993;187:855–856
10. Johnson G. **Need for caution during MR imaging of patients with aneurysm clips.** *Radiology* 1993;188:287–288
11. Becker R, Norfray J, Teitelbaum G, Bradley WG Jr, Jacobs JB, Wacaser L, Rieman RL. **MR imaging in patients with intracranial aneurysm clips.** *AJNR Am J Neuroradiol* 1988;9:885–889
12. Dujovny M, Kossovsky N, Kossowsky R, et al. **Aneurysm clip motion during magnetic resonance imaging: in vivo experimental**

study with metallurgical factor analysis. *Neurosurgery* 1985;17:543–548

13. Dujovny M, Alp MS, Slavin KV, et al. **Magnetic characteristics of Yasargil aneurysm clips.** *Surg Neurol* 1997;47:547–550
14. Dujovny M, Gundamjaj NR, Misra M, Alp MS. **Aneurysm clips.** *Crit Rev Neurosurg* 1997;7:169–175
15. Kanal E, Shellock FG, Lewin JS. **Aneurysm clip testing for ferromagnetic properties: clip variability issues.** *Radiology* 1996;200:576–578
16. Romner B, Olsson M, Ljunggren B, et al. **Magnetic resonance imaging and aneurysm clips.** *J Neurosurg* 1989;70:426–431
17. New PF, Rosen BR, Brady TJ, et al. **Potential hazards and artifacts of ferromagnetic and non-ferromagnetic surgical and dental materials and aneurysm clips in nuclear magnetic resonance imaging.** *Radiology* 1983;147:139–148
18. Shellock FG, Crues J. **High-field strength MR imaging and metallic biomedical implants: an ex vivo evaluation of deflection forces.** *AJR Am J Roentgenol* 1988;151:389–392
19. Kato Y, Sano H, Katada K, et al. **Effects of new titanium cerebral aneurysm clips on MRI and CT images.** *Minim Invasive Neurosurg* 1996;39:82–85
20. Lawton MT, Heiserman JE, Prendergast VC, Zabramski JM, Spetzler RF. **Titanium aneurysm clips: part III. clinical application in 16 patients with subarachnoid hemorrhage.** *Neurosurgery* 1996;38:1170–1175
21. Piepgras A, Guckel F, Weik T, Schmiedek P. **Titanium aneurysm clips and their advantages in diagnostic imaging [in German].** *Radiologe* 1995;35:830–833
22. Wichmann W, Von Ammon K, Fink U, Weik T, Yasargil GM. **Aneurysm clips made of titanium: characteristics and artifacts in MR.** *AJNR Am J Neuroradiol* 1997;18:939–944
23. Shellock FG, Kanal E. **Yasargil aneurysm clips: evaluation of interactions with a 1.5-T MR system.** *Radiology* 1998;207:587–591
24. Kanal E, Shellock FG. **Aneurysm clips: effects of long-term and multiple exposures to a 1.5-T MR system.** *Radiology* 1999;210:563–565
25. Shellock FG, Shellock VJ. **Spetzler titanium aneurysm clips: compatibility at MR imaging.** *Radiology* 1998;206:838–841
26. Pride GL, Kowal J, Mendelsohn DB, Chason DP, Fleckenstein JL. **Safety of MR scanning in patients with nonferromagnetic aneurysm clips.** *J Magn Reson Imaging* 2000;12:198–200
27. American Society for Testing and Materials (ASTM) Designation: F 2052. Standard test method for measurement of magnetically induced displacement force on passive implants in the magnetic resonance environment. In: Annual Book of ASTM Standards, Section 13, Medical Devices and Services, Volume 13.01 Medical Devices, Emergency Medical Services. West Conshohocken, PA, 2002; pp 1576–1580.
28. Hennemeyer CT, Wicklow K, Feinberg DA, Derdeyn CP. **In vitro evaluation of platinum Guglielmi detachable coils at 3 T with a porcine model: safety issues and artifacts.** *Radiology* 2001;219:732–737
29. Kangarlu A, Shellock FG. **Aneurysm clips: evaluation of magnetic field interactions with an 8.0 T MR system.** *J Magn Reson Imaging* 2000;12:107–111
30. Schenck JF. **Health Effects and Safety of Static Magnetic Fields.** In: *Magnetic Resonance Procedures: Health Effects and Safety.* Boca Raton: CRC Press; 2001:1–31
31. Davis PL, Crooks L, Arakawa M, et al. **Potential hazards in NMR imaging: heating effects of changing magnetic fields and RF fields on small metallic implants.** *AJR Am J Roentgenol* 1981;137:857–860
32. Shellock FG. **Radiofrequency-induced heating during MR procedures: a review.** *J Magn Reson Imag* 2000;12:30–36
33. Smith CD, Kildishev AV, Nyenhuis JA, Foster KS, Bourland JD. **Interactions of MRI magnetic fields with elongated medical implants.** *J Appl Phys* 2000;87:6188–6190
34. Nyehnuis JA, Kildishev AV, Foster KS, Graber G, Athey W. **Heating near implanted medical devices by the MRI RF-magnetic field.** *IEEE Trans Magn* 1999;35:4133–4135
35. Smith CD, Nyenhuis JA, Kildishev AV. **Health effects of induced electrical currents: implications for implants.** In: Shellock FG, ed. *Magnetic Resonance: Health Effects and Safety.* Boca Raton: CRC Press; 2001:393–413
36. Rezai AR, Finelli D, Nyenhuis JA, et al. **Neurostimulator for deep brain stimulation: in vitro evaluation of magnetic resonance imaging-related heating at 1.5 tesla.** *J Magn Reson Imaging* 2002;15:141–150
37. Brothers MF, Fox AJ, Lee DH, Pelz DM, Deveikis JP. **MR imaging after surgery for vertebrobasilar aneurysm.** *AJNR Am J Neuroradiol* 1999;11:149–161