Title

Magnetically Assisted Remote-controlled Endovascular Catheter for Interventional MR Imaging: In Vitro Navigation at 1.5 T versus X-ray Fluoroscopy

Journal

Radiology, 271(3)

ISSN

0033-8419

Authors

Losey, Aaron D
Lillaney, Prasheel
Martin, Alastair J
et al.

Publication Date

2014-06-01

DOI

10.1148/radiol.14132041

Peer reviewed

Magnetically Assisted Remote-controlled Endovascular Catheter for Interventional MR Imaging: In Vitro Navigation at 1.5 T versus X-ray Fluoroscopy[1]

Aaron D. Losey, MS
Prasheel Lillaney, PhD
Alastair J. Martin, PhD
Daniel L. Cooke, MD
Mark W. Wilson, MD
Bradford R. H. Thorne
Ryan S. Sincic, MS
Ronald L. Arenson, MD
Maythem Saeed, DVM, PhD
Steven W. Hetts, MD

Purpose: To compare in vitro navigation of a magnetically assisted remote-controlled (MARC) catheter under real-time magnetic resonance (MR) imaging with manual navigation under MR imaging and standard x-ray guidance in endovascular catheterization procedures in an abdominal aortic phantom.

Materials and Methods: The 2-mm-diameter custom clinical-grade microcatheter prototype with a solenoid coil at the distal tip was deflected with a foot pedal actuator used to deliver 300 mA of positive or negative current. Investigators navigated the catheter into branch vessels in a custom cryogel abdominal aortic phantom. This was repeated under MR imaging guidance without magnetic assistance and under conventional x-ray fluoroscopy. MR experiments were performed at 1.5 T by using a balanced steady-state free precession sequence. The mean procedure times and percentage success data were determined and analyzed with a linear mixed-effects regression analysis.

Results: The catheter was clearly visible under real-time MR imaging. One hundred ninety-two (80%) of 240 turns were successfully completed with magnetically assisted guidance versus 144 (60%) of 240 turns with nonassisted guidance ($P < .001$) and 119 (74%) of 160 turns with standard x-ray guidance ($P = .028$). Overall mean procedure time was shorter with magnetically assisted than with nonassisted guidance under MR imaging (37 seconds ± 6 [standard error of the mean] vs 55 seconds ± 3, $P < .001$), and time was comparable between magnetically assisted and standard x-ray guidance (37 seconds ± 6 vs 44 seconds ± 3, $P = .045$). When stratified by angle of branch vessel, magnetic assistance was faster than nonassisted MR guidance at turns of 45°, 60°, and 75°.

Conclusion: In this study, a MARC catheter for endovascular navigation under real-time MR imaging guidance was developed and tested. For catheterization of branch vessels arising at large angles, magnetically assisted catheterization was faster than manual catheterization under MR imaging guidance and was comparable to standard x-ray guidance.

Online supplemental material is available for this article.

[1] From the Department of Radiology and Biomedical Imaging, School of Medicine, University of California–San Francisco, 185 Berry St, Suite 350, Campus Box 0946, San Francisco, CA 94107-5705. From the 2013 RSNA Annual Meeting. Received August 28, 2013; revision requested October 15; final revision received November 29; final version accepted December 9. A.D.L. supported in part by an RSNA Research Medical Student Grant (2013–2014) **Address correspondence to** S.W.H. (e-mail: *steven.hetts@ucsf.edu*).

Magnetic resonance (MR) imaging guidance of endovascular interventions affords a wealth of physiologic and structural information and can be used for delivery of local therapy without the use of ionizing radiation (1–4). The promise of endovascular MR-guided procedures remains unrealized in part because of the lack of MR-compatible catheters and guidewires that the user can safely navigate and track efficiently in real time (1,3–5). Maneuverability and steering performance of an endovascular catheter from a remote access site to pathologic targets is of paramount importance because it affects procedural time and efficiency (6,7).

Design solutions for deflecting a catheter in the strong magnetic field of the MR imaging unit can be categorized into catheter tip microcoils, catheter tip ferromagnetic beads, pull-wire catheters, smart material actuators, and hydraulic catheters (6–13). The strengths and weaknesses, including function, cost, configuration in the operating room, and safety, have been reviewed previously (6,7). Whereas benchtop studies have characterized catheter functionality by the degree of rotation achievable, preclinical or clinical studies present case studies or case series performed in the interventional MR imaging environment (2,3,14). However, to our knowledge, no researchers in studies to date have tested the navigability of an endovascular catheter device in the MR imaging environment versus a control to investigate whether improvements in deflection result in increased efficacy versus nonassisted MR imaging guidance and standard x-ray fluoroscopic guidance.

Investigators have used an electromagnetic microcoil on the microcatheter tip to deflect the catheter and assist endovascular navigation (13). When energized inside the MR imaging unit bore, the magnetic moment created by the microcoil will align itself with the direction on B_0, causing the catheter tip to deflect. By controlling the direction of the current, the interventionalist can control the direction of deflection, thus allowing the catheter tip to be more easily steered into the desired vessel branch (13,15,16). The operating system, deflection capability, and safety of such a system with use of first-generation prototypes have been described (13,15–19). The aim of this study was to compare in vitro navigation in an abdominal aortic phantom of a magnetically assisted remote-controlled (MARC) catheter under real-time MR imaging guidance with manual navigation under MR imaging and x-ray guidance in endovascular catheterization procedures.

Advances in Knowledge

- In an abdominal aortic phantom, magnetically assisted endovascular catheter navigation under real-time MR imaging guidance is superior to manual catheter navigation (192 of 240 successful turns [80%] vs 144 of 240 successful turns [60%], $P < .001$; and mean procedure time, 37 seconds ± 6 [standard deviation] vs 55 seconds ± 3, $P < .001$).
- In the phantom, magnetically assisted endovascular catheter navigation under MR imaging guidance is comparable to catheter navigation under conventional x-ray guidance (192 of 240 successful turns [80%] vs 119 of 160 successful turns [74%], $P = .028$; and mean procedure time, 37 seconds ± 6 vs 44 seconds ± 3, $P = .045$).

Materials and Methods

Design of MARC Catheter

An in-kind donation of the catheter substrate was given by Penumbra (Alameda, Calif). The authors had control of the data and information submitted for publication. The MARC catheter prototype was constructed by using a 1500-mm-long 0.97-mm-diameter custom microcatheter that was based on the clinical slim catheter (PX Slim; Penumbra) but braided with nonmetallic polyether ether ketone fibers (Penumbra) instead of standard metallic fibers. Two 0.01-mm-diameter copper wires in the catheter lumen were connected to a hand-wound solenoid coil at the distal tip. The solenoid coil consisted of 30 turns of 0.02-mm-diameter copper wire (California Fine Wire, Grover Beach, Calif) wrapped around an alumina tube with a 1.20-mm outer diameter. The tip was covered with heat shrink tubing (Component Force, St Louis, Mo), resulting in a final distal tip outer diameter of approximately 2 mm (Fig 1). The copper wires were strung through the lumen and connected to a screened fully shielded twisted pair cable.

Design of Sham Catheter

The sham catheter used for the MR imaging–guided (not magnetically assisted) control arm was designed in a similar manner to the MARC catheter but without the solenoid coil at the tip. Magnetic coil-tipped catheters were difficult to visualize when no current was running through them; therefore, we used a passively marked catheter as a sham catheter. Gadolinium oxide powder (Sigma Chemical, St Louis, Mo) was coated over the heat shrink tubing (20). This small modification to the

Published online before print
10.1148/radiol.14132041 **Content codes:** MR IR VA

Radiology 2014; 271:862–869

Abbreviation:
MARC = magnetically assisted remote controlled

Author contributions:
Guarantors of integrity of entire study, A.D.L., P.L., D.L.C., S.W.H.; study concepts/study design or data acquisition or data analysis/interpretation, all authors; manuscript drafting or manuscript revision for important intellectual content, all authors; approval of final version of submitted manuscript, all authors; literature research, A.D.L., D.L.C., M.W.W., M.S., S.W.H.; experimental studies, A.D.L., P.L., A.J.M., M.W.W., B.R.H.T., R.S.S., R.L.A., M.S., S.W.H.; statistical analysis, A.D.L., P.L., M.S.; and manuscript editing, all authors

Funding:
This research was supported by the National Institute of Biomedical Imaging and Bioengineering (grant 1R01EB012031), the National Institute of Minority Health and Health Disparities (grant R25MD006832), and the National Center for Advancing Translational Sciences (grant UL1 TR000004), National Institutes of Health.

Conflicts of interest are listed at the end of this article.

sham control catheter led to increased visibility of the tip by creating an artifact (T2* effect) similar to one created by delivering 300 mA of current to the functional experimental catheters.

Operating System

The operating system consisted of a custom-hardware control board with direct communication to a computer (Latitude; Dell, Round Rock, Tex) via a Universal Serial Bus connection positioned outside the magnet room. The computer was running a custom software program designed in Laboratory Virtual Instrument Engineering Workbench (LabVIEW; National Instruments, Austin, Tex) to communicate with the control system. Both the catheter prototype and a row of mounted foot pedals (Aquiline; Linemaster Switch, Woodstock, Conn) in the interventional MR imaging suite were connected to the control board via 10-m screened fully shielded twisted pair cables to allow the user to deliver current and maintain free use of his or her hands while deflecting the catheter via foot pedal actuator. The foot pedal actuator was set to deliver 300 mA of positive or negative current to deflect the catheter superiorly or inferiorly in the MR imaging unit bore (ie, left or right with respect to the axis of the aortic phantom).

Magnetic Deflection

Using the MARC catheter prototype and operating system, current was delivered to the catheter tip. When excited inside the MR unit bore, the magnetic moment created by the microcoil will tend to align itself with the direction on B_0, causing the catheter tip to deflect. By controlling the direction of the current, the interventionalist can control the direction of deflection. The equation for predicting deflection as experimentally validated previously is as follows: $\tau_{mag} = \tau_{mech}$, where $\tau_{mag} = nIAB_0 \sin(\gamma - \theta)$ and $\tau_{mech} = (EI_A/L)\,\theta$. In this equation, the catheter was modeled as a cantilever beam, where a torque produced by the magnetic moment of the solenoid interacting with the magnetic field of the imaging unit, τ_{mag}, is balanced against the torque of the catheter attempting to restore to the initial state, τ_{mech}, where n is the number of turns in the solenoid, I is the current, A is the cross-sectional area of the solenoid, B_0 is the strength of the magnetic field of the MR imaging unit, γ is the initial angle of the catheter with respect to the direction of B_0, θ is the angle of catheter deflection from the initial angle, E is the elastic modulus of the catheter, I_A is the area moment of inertia of the catheter, and L is the unrestrained length of the distal end of the catheter (13,15,16).

Figure 1

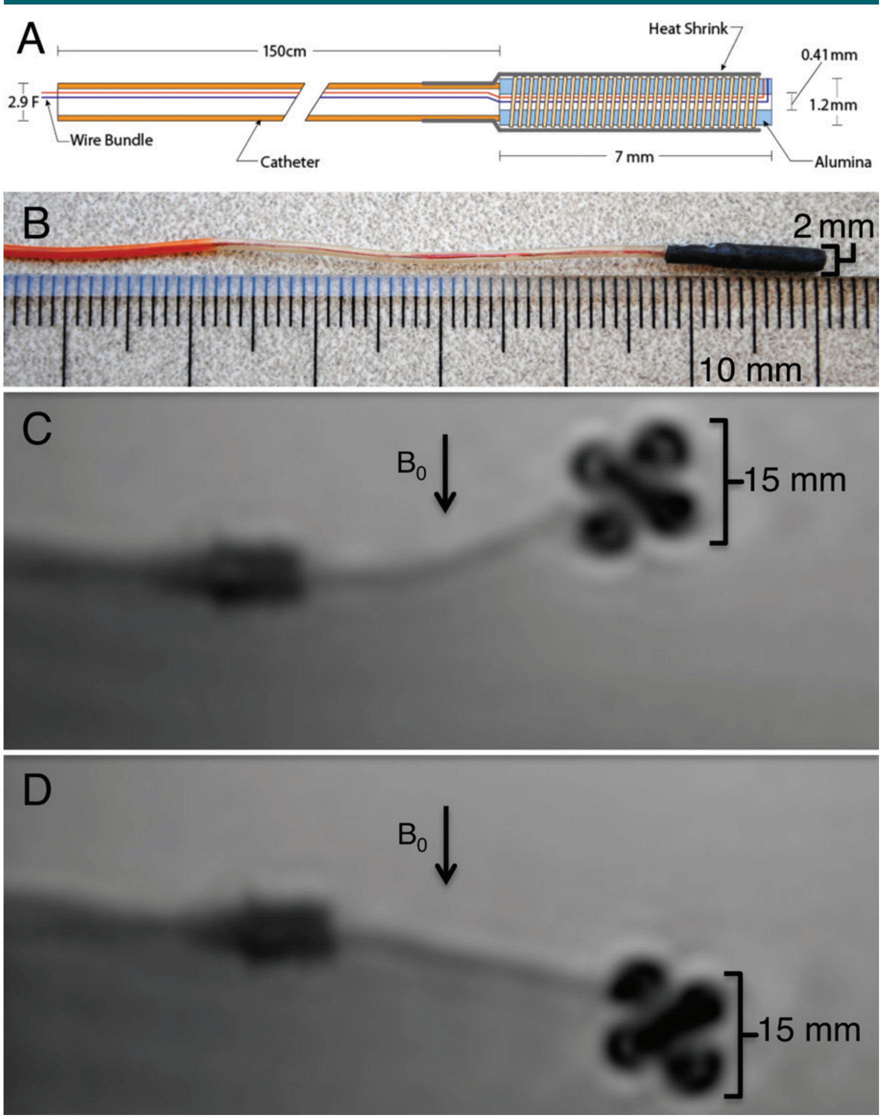

Figure 1: Images of catheter prototype. *A,* MARC catheter diagram. *B,* Distal end of MARC catheter prototype with solenoid covered by heat shrink tubing at the tip. Coronal balanced steady-state free precession 1.5-T MR images (repetition time msec/echo time msec, 3.1/1.1) of MARC catheter prototype while activated with 300-mA of, *C,* positive current and, *D,* negative current.

Phantom Design

In vitro navigation was tested in a polyvinyl alcohol (Sevol Grade 165 PVA powder; Sekisui Specialty Chemicals America, Dallas, Tex) cryogel simplified abdominal aortic vascular phantom (Fig 2),

Figure 2

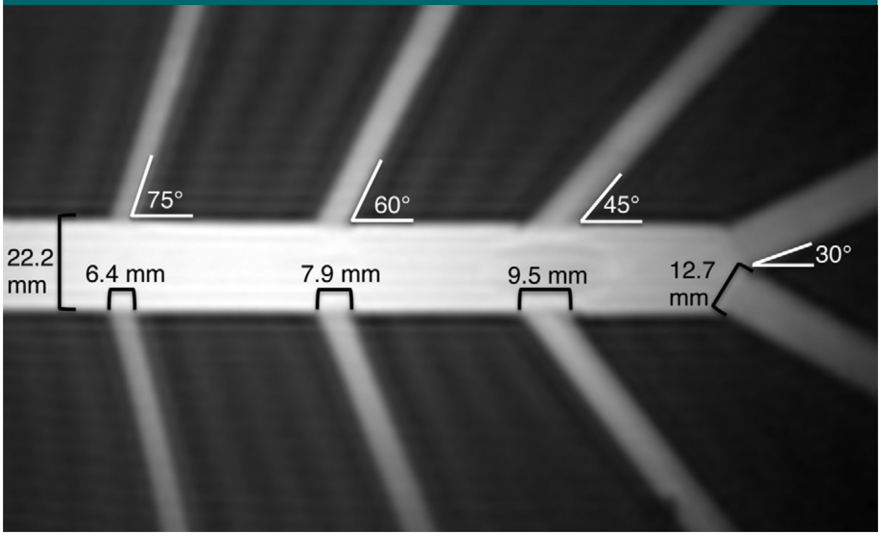

Figure 2: Coronal MR image (3.1/1.1) of phantom. White areas = water in the vessel lumens, dark areas = polyvinyl alcohol cryogel phantom material.

created by using a process previously outlined by Surry et al (21). The phantom provided slippery walls and physiologically relevant vessel trajectories with multiple symmetric angles (30°–75°) and diameters (6.4–22.2 mm). The phantom was placed in distilled water in a plastic bin with one-half–inch vinyl tubing connected to the bin, and a 5.3-mm introducer sheath (Check-Flo Performance Introducer; Cook , Bloomington, Ind) was inserted into the tubing to mimic the size of a typical vascular access, although as if coming from an upper extremity access site to the abdominal aorta (antegrade) as opposed to from the femoral artery (retrograde).

Experimental Design

A total of 240 turns were attempted with magnetic assistance and without assistance, and 160 turns were attempted by using x-ray guidance. Four interventionalists (S.W.H. with 11 years, D.L.C. with 7 years, and M.W.W., with >15 years of experience with conventional endovascular procedures and A.D.L., a medical student with no previous experience with conventional endovascular procedures) attempted navigation of the catheter into each blood vessel with magnetic assistance, starting at 30° and alternating sides (right and then left) until navigation of all branches had been attempted. For the navigation with magnetic assistance and without assistance, three interventionalists (two with experience [S.W.H., D.L.C.]), one without experience [A .D.L.]) attempted 80 trials each. For x-ray guidance, four interventionalists (three with experience [S.W.H., D.L.C., M.W.W.], one without experience [A.D.L.]) attempted 40 trials each. The guide catheter was parked at the origin of the next most distal branch point (ie, the guide catheter tip was at the level of the 45° origins for attempts to catheterize the 30° branches with the MARC catheter) for each attempt, and the phantom was oriented perpendicular to B_0 to maximize potential magnetically assisted catheter tip deflections. A trial attempting every branch was repeated 10 times. The end point for each navigation was successful completion of turning into the branch and advancement to the edge of the phantom within 90 seconds. For successful attempts, the time was stopped once the catheter was advanced past the edge of the phantom (6 cm laterally to the main branch). If the catheter tip did not reach the edge of the branch vessel within 90 seconds, the trial was scored as a failure. The MR imaging–guided experiment was then repeated with the sham control catheter, without magnetic assistance, and a phantom oriented parallel to B_0 so that no magnetic torque was imparted on the catheter. All MR imaging experiments were performed while viewing an in-room monitor that displayed real-time imaging by using a balanced steady state free precession sequence and a 1.5-T clinical MR imaging unit (Achieva; Philips, Cleveland, Ohio). The pulse sequence parameters were 3.1/1.1; field of view, 280 × 190 mm^2; acquisition time, 590 milliseconds; temporal resolution, 1.7 seconds; matrix, 224 × 224 pixels; section thickness, 15 mm; bandwidth, 160 kHz; and average specific absorption rate, 2.8 W/kg.

The experiment was then repeated by using x-ray fluoroscopic guidance (OEC 9600; GE Medical Systems, Milwaukee, Wis) with a 1300-mm-long 0.93-mm-diameter coaxial microcatheter system (2.4-F Progreat Omega; Terumo, Somerset, NJ) and an 1800-mm-long 0.46-mm-diameter shapeable-type guidewire (Glidewire GT; Terumo). The guidewire was manually curved into a *C* shape before the start of the experiments. End points were the same as for the MR imaging–guided experiments.

Statistics

The mean procedure times were determined and presented as means ± standard errors of the means, and the percentage success data were presented as percentages. A linear mixed-effects regression analysis (xtmixed) was used to compare mean procedure times and percentage success data. The model included a random effect for interventionalist. A *P* value of less than .05 indicated a significant difference. Statistical analyses were performed by using software (Stata, version 12, StataCorp, College Station, Tex; and MatLab, MathWorks, Natick, Mass). To explore the learning curve of using the catheter system with and without magnetic assistance, a graph with the total time per trial for experienced interventionalists and the inexperienced interventionalist was constructed, with a best fit line marking the slope.

Results

Catheter Visualization

The MARC catheter was visible in the phantom while activated under magnetic guidance (Fig 3) and nonassisted guidance (Fig 4). Visualization of the catheter allowed the users to navigate the catheter to targeted vessels.

Navigation Success

For all interventionalists combined, 192 (80%) of 240 turns were successfully completed within 90 seconds with magnetically assisted guidance versus 144 (60%) of 240 turns successfully completed with nonassisted guidance (P < .001) and 119 (74%) of 160 turns with x-ray guidance (P = .028). Overall mean procedure time was significantly different between magnetically assisted and nonassisted guidance (37 seconds ± 6 [standard error of the mean] vs 55 seconds ± 3, P < .001) and between magnetically assisted and x-ray guidance (37 seconds ± 6 vs 44 seconds ± 3, P = .045).

For the two experienced interventionalists, 141 (88%) of 160 selective catheterizations were successfully completed within 90 seconds with magnetically assisted guidance versus 114 (71%) of 160 turns successfully completed with nonassisted guidance (P < .001); and for the three experienced interventionalists, 98 (82%) of 120 turns were successfully completed with x-ray guidance (P = .223). Mean procedure time was significantly shorter by using magnetically assisted versus nonassisted guidance under MR imaging visualization (31 seconds ± 3 vs 49 seconds ± 3, P < .001). There was no difference in mean procedure time between magnetically assisted MR imaging guidance and x-ray fluoroscopic guidance (31 seconds ± 3 vs 37 seconds ± 4, P = .132).

For the one inexperienced interventionalist, 52 (65%) of 80 selective catheterizations were successfully completed with magnetically assisted guidance versus 30 (38%) of 80 turns successfully completed with nonassisted guidance (P < .001) and 21 (53%) of 40 turns with x-ray guidance (P = .186). Overall mean procedure time was significantly faster with magnetically assisted guidance than with nonassisted guidance under MR imaging visualization (49 seconds ± 4 vs 67 seconds ± 5, P = .002). There was no difference in mean procedure time between magnetically assisted and x-ray guidance (49 seconds ± 4 vs 57 seconds ± 7, P = .259).

Figure 3

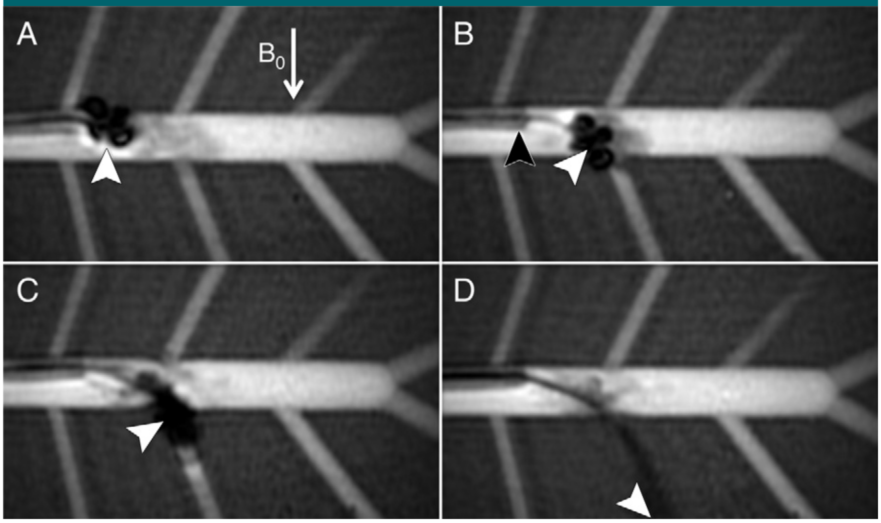

Figure 3: Coronal MR images (3.1/1.1) of catheter deflecting into branch vessel arising at 60° from the parent vessel. *A,* Catheter tip (white arrowhead) became visible by delivery of current to microcoil and, *B,* deflected instantaneously while the guide catheter (black arrowhead) remained stationary. *C,* Then the interventionalist advanced the catheter forward to enter a vascular branch angled 60° to the parent vessel, *D,* turning off the current once the tip was within the branch vessel and manually advancing the catheter in the branch vessel to the edge of the vascular phantom.

The results stratified by angle of vascular branch are presented in Table. Percentage success data and mean procedure times under MR imaging visualization were significantly higher and faster at turns of 45°, 60°, and 75° with magnetic assistance compared with nonassisted for both experienced and inexperienced interventionalists. Mean procedure time under MR imaging visualization with magnetic assistance was significantly faster at the turn of 45° when compared with x-ray guidance for both experienced and inexperienced interventionalists. Table E1 (online) presents results according to interventionalist.

Learning Curve

The learning curve of using the catheter system with and without magnetic assistance in a graph is presented for experienced interventionalists and the inexperienced interventionalist (Fig 5). Total time per trial does not change for guidance without magnetic assistance. By contrast, total time decreases per trial for catheter guidance with magnetic assistance for experienced and inexperienced interventionalists.

Figure 4

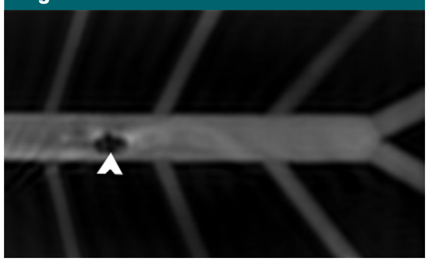

Figure 4: Coronal MR image (3.1/1.1) of control catheter with gadolinium powder at tip. Catheter tip = white arrowhead.

Discussion

The ability to navigate an endovascular catheter under MR imaging guidance to a specific target to deliver local therapy is a novel goal (6,7). A second-generation prototype endovascular MARC

Radiology

Percentage of Successful Turns and Mean Procedure Time in Vascular Phantom

Clinical Data	30°*	P Value	45°*	P Value	60°*	P Value	75°*	P Value
Percentage success data for all interventionalists†								
Magnetically assisted guidance	92 (55/62)	...	80 (48/60)	...	75 (45/60)	...	73 (44/60)	...
Nonmagnetically assisted guidance	97 (58/60)	.179	48 (29/60)	<.001	55 (33/60)	.011	38 (23/60)	<.001
Conventional x-ray guidance	100 (40/40)	.046	70 (28/40)	.089	68 (27/40)	.136	60 (24/40)	.064
Procedure time for all interventionalists‡								
Magnetically assisted guidance	20 (3)	...	35 (9)	...	24 (9)	...	53 (6)	...
Nonmagnetically assisted guidance	16 (4)	.204	66 (5)	<.001	64 (5)	<.001	75 (5)	<.001
Conventional x-ray guidance	14 (4)	.107	53 (6)	.001	49 (6)	.088	53 (6)	.781
Percentage success data for experienced interventionalists†								
Magnetically assisted guidance	95 (38/40)	...	90 (36/40)	...	85 (34/40)	...	80 (32/40)	...
Nonmagnetically assisted guidance	98 (39/40)	.495	68 (27/40)	.012	63 (25/40)	.016	55 (22/40)	.017
Conventional x-ray guidance	100 (10/10)	.207	80 (24/30)	.301	83 (25/30)	.869	63 (19/30)	.139
Procedure time for experienced interventionalists‡								
Magnetically assisted guidance	16 (3)	...	28 (5)	...	34 (4)	...	47 (5)	...
Nonmagnetically assisted guidance	15 (4)	.823	56 (6)	<.001	58 (6)	<.001	68 (7)	.002
Conventional x-ray guidance	13 (4)	.389	46 (7)	.007	40 (7)	.426	49 (7)	.809
Percentage success data for inexperienced interventionalist†								
Magnetically assisted guidance	85 (17/20)	...	60 (12/20)	...	55 (11/20)	...	60 (12/20)	...
Nonmagnetically assisted guidance	95 (19/20)	.252	10 (2/20)	<.001	40 (8/20)	.334	5 (1/20)	<.001
Conventional x-ray guidance	100 (10/10)	.175	40 (4/10)	.238	20 (2/10)	.066	50 (5/10)	.538
Procedure time for inexperienced interventionalist‡								
Magnetically assisted guidance	28 (5)	...	49 (6)	...	58 (6)	...	63 (6)	...
Nonmagnetically assisted guidance	17 (7)	.117	85 (9)	<.001	77 (9)	.033	88 (8)	.002
Conventional x-ray guidance	17 (9)	.235	72 (11)	.037	46 (11)	.107	63 (10)	.979

Note.—Reference group is magnetically assisted guidance. Percentage success data refers to the percentage of successful turns.

* Angle is the angle of the vascular branch.

† Numbers in parentheses were used to calculate the percentage success data.

‡ Procedure time data are presented in seconds as means; numbers in parentheses are the standard errors of the means.

catheter has been developed and tested under real time MR imaging guidance. The catheter navigation was faster and more accurate than without magnetic assistance and was comparable to conventional x-ray fluoroscopic guidance. The results indicate that when a vascular target arises at 45° or greater from the parent vessel, our magnetic navigation system can improve this process. In addition, a rapid learning curve was shown by interventionalists who were using the catheter system with magnetic assistance, but not without magnetic assistance, suggesting that our system would require a short training period. The similar times and success rates of magnetic assistance compared with x-ray guidance signify that our system already closely mimics current practice, with the additional benefit of MR imaging.

Technological and logistic challenges of implementing endovascular interventional MR imaging in the clinical setting include visualization of vascular wall and catheter tips, size of vessels and catheters, and training for catheter steering performance (1,4,5,7). A key to developing technology adaptable to the clinical setting is making it user friendly and intuitive to the interventionalist. Previous testing of another magnetic navigation system required up to 6 months of nonclinical training in magnetic navigation prior to participation in a validation study (22). In contrast, interventionalists in our study were allowed 5 minutes to work with the catheter system before they started the trial, yet catheterization times were comparable to times with conventional x-ray guidance with standard clinical microcatheters and guidewires that the experienced interventionalists use. Gaining more experience with the MARC catheter system resulted in higher success rates and shorter procedure times with magnetic assistance. Furthermore, in a prior study with another magnetic system, participants were required to have at least 5 years of experience in conventional procedures (22). We showed that both experienced and inexperienced interventionalists can benefit from using magnetically assisted guidance of the system. This is important because the range of level of training is broad in each practice setting, and any new system should be usable by interventionalists with varying experience.

The ability to visualize the catheter tip directly affects the capability of the

Figure 5

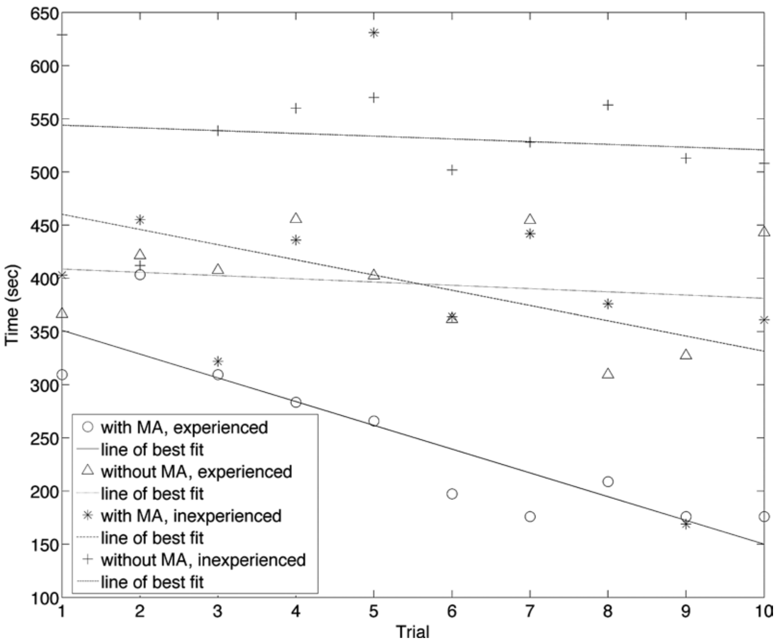

Figure 5: Average total time per trial with and without magnetic assisted guidance for experienced and inexperienced interventionalists at 1.5 T. *MA* = magnetic assistance.

interventionalist to reach the desired target (3,5). While our device uses the tip microcoil for simultaneous deflection and active tracking, and was clearly visible in all MR experiments, the artifact created by activation of the tip microcoil was several times the diameter of the actual device tip. Other groups have encountered this issue: for example, when ferromagnetic spheres are placed on a catheter tip, they create a large artifact, making it difficult to navigate into smaller branches (11,12). This artifact is inherent to the ferromagnetic material compromising the spheres. In our system, the artifact is present only when the microcoil is charged with current. A smaller current can be used to intentionally produce a smaller artifact when needed for visualization without deflection, or a passive catheter tip marker such as gadolinium or dysprosium can be used (as in the sham catheter in our control experiments).

Other groups have developed catheters by using pull-string technology and have made advances in the angle of deflection achievable (up to 150°). However, their catheter devices remain large (3–4 mm) because of the space required for suitable pull strings and are not useable in the smaller vasculature (8,10). Our device has a final tip diameter of 2 mm. While this is a welcome step toward miniaturization, there is still room for further improvement if the catheter is to be used in smaller cerebral and cardiac vessels to treat stroke and myocardial infarction. Future prototypes will use laser-lithographed coils with very thin heat shrink tubing, allowing for smaller coils coupled with greater deflection ability by increasing the number of coil turns per millimeter (23).

Steering performance is an important aspect of navigation in interventional MR imaging. While we showed superior performance with magnetic assistance versus without magnetic assistance and noninferior performance with magnetic assistance versus x-ray guidance, we tested only single turns in one plane up to 75°. While it is true that an angled guide catheter could decrease the x-ray guidance times, the same is true for using the MARC catheter with an angled guide catheter; hence, we used a straight guide catheter in both situations. One of the advantages of other designs, such as a pull-string apparatus or ferromagnetic spheres at the catheter tip, is the ability to achieve greater degrees of deflection in any direction independent of the MR imaging magnetic field (8,10–12).

The copper wires running down the catheter shaft and current delivered to the coil tip make the MARC catheter susceptible to radiofrequency and resistive heating, respectively. In in vitro studies (18,19) of our device, radiofrequency resulted in maximal temperature increases of 0.73°–1.91°C in air and 0.45°–0.55°C in saline. Researchers in an in vivo study (14) of the MARC catheter found that, for catheter tip coil activations, with current of 300 mA or less for 1 minute or less in normal carotid flow, zero of 43 samples had tissue damage.

Current limitations of the MARC catheter system are the ability to deflect in only two directions and relying on the orientation of the magnetic field of the bore. Future prototypes will focus on using laser-lithographed coils, with solenoid and Helmholtz coils layered on each other to maximize degree of bending and rotation achievable (23). Previous prototypes with use of this approach achieved a deflection angle of 50° in four planes in the 1.5-T environment when charged with 350 mA (16). Gudino et al (9) have proposed alternative designs by using an array of coils along the shaft of the catheter tip that can be independently controlled. While this has been shown to increase the deflection angle, it has the potential to limit torqueability of the catheter tip. In addition, this in vitro study does not assess variation provided by clinical physiology, including the effect of blood flow, viscosity, and vessel elasticity.

In conclusion, in the abdominal aortic phantom, the MARC catheter system was faster and more accurate than a similar nonmagnetic catheter under MR imaging guidance and was similar in catheterization efficiency to standard clinical microcatheterization under x-ray guidance. Future researchers in in vivo studies under MR imaging guidance will subsequently evaluate the MARC catheter system in a simulated clinical environment.

Acknowledgments: The authors thank Leland Evans, BS, Vincent Malba, PhD, and Anthony Bernhardt, PhD (all from University of California San Francisco, San Francisco, Calif), for their assistance in fabricating the catheter tips that were used in the prototype tested in this study; Nick Jeung (University of California San Francisco, San Francisco, Calif) for assistance with development of the imaging sequences; Kartiga Selvaganesan (University of California Berkeley, Berkeley, Calif) for assistance with computer programming of the control system; Erin J. Yee, BS (University of California San Francisco, San Francisco, Calif) for assistance with manufacturing of the vascular phantom; and David C. Berry and Cynthia Maskeny (both from Penumbra, Alameda, Calif) for fabrication of the catheter bodies that were used in the prototypes tested in this study.

Disclosures of Conflicts of Interest: **A.D.L.** No relevant conflicts of interest to disclose. **P.L.** No relevant conflicts of interest to disclose. **A.J.M.** No relevant conflicts of interest to disclose. **D.L.C.** No relevant conflicts of interest to disclose. **M.W.W.** No relevant conflicts of interest to disclose. **B.R.H.T.** No relevant conflicts of interest to disclose. **R.S.S.** No relevant conflicts of interest to disclose. **R.L.A.** Financial activities related to the present article: none to disclose. Financial activities not related to the present article: receives payment for expenses as board chairman from RSNA, has U.S. patent issued, receives book royalties from Charles Thomas Publisher. Other relationships: none to disclose. **M.S.** No relevant conflicts of interest to disclose. **S.W.H.** Financial activities related to the present article: received a Scholar Award to test endovascular remote controlled catheter from ASNR Foundation, in-kind donation of substrate catheter shafts onto which the lab placed navigation coils was received from Penumbra. Financial activities not related to the present article: author paid as Scientific Advisory Board Member by Medina, paid for consulting on design of stroke treatment device by Silk Road Medical, paid as Data Safety and Monitoring Board Member for DAWN stroke treatment trial and as Core Angiographic Laboratory Member for MAPS brain aneurysm treatment trial by Stryker Neurovascular, paid as Chief Medical Officer of a startup company to develop a technology developed in UCSF laboratory by ChemoFilter, paid for occasional consulting on medical malpractice cases by law firms; institution received grants for ChemoFilter application for testing of a chemotherapy filter device by NIH-STTR; author received payment for training lectures to company employees on basic neurovascular anatomy and diseases by Penumbra and Stryker Neurovascular; institution received payment for licensing of ChemoFilter patient from UCSF by ChemoFilter; author received founder stock from ChemoFilter and stock options from Medina. Other relationships: none to disclose.

References

1. Bock M, Wacker FK. MR-guided intravascular interventions: techniques and applications. J Magn Reson Imaging 2008;27(2):326–338.
2. Saeed M, Hetts SW, English J, Wilson M. MR fluoroscopy in vascular and cardiac interventions (review). Int J Cardiovasc Imaging 2012;28(1):117–137.
3. Kos S, Huegli R, Bongartz GM, Jacob AL, Bilecen D. MR-guided endovascular interventions: a comprehensive review on techniques and applications. Eur Radiol 2008;18(4):645–657.
4. Ratnayaka K, Faranesh AZ, Guttman MA, Kocaturk O, Saikus CE, Lederman RJ. Interventional cardiovascular magnetic resonance: still tantalizing. J Cardiovasc Magn Reson 2008;10:62.
5. Henk CB, Higgins CB, Saeed M. Endovascular interventional MRI. J Magn Reson Imaging 2005;22(4):451–460.
6. Fu Y, Liu H, Huang W, Wang S, Liang Z. Steerable catheters in minimally invasive vascular surgery. Int J Med Robot 2009;5(4):381–391.
7. Muller L, Saeed M, Wilson MW, Hetts SW. Remote control catheter navigation: options for guidance under MRI. J Cardiovasc Magn Reson 2012;14(1):33. http://www.jcmr-online.com/content/14/1/33. Published 2012. Accessed 2013.
8. Bell JA, Saikus CE, Ratnayaka K, et al. A deflectable guiding catheter for real-time MRI-guided interventions. J Magn Reson Imaging 2012;35(4):908–915.
9. Gudino N, Heilman JA, Derakhshan JJ, Sunshine JL, Duerk JL, Griswold MA. Control of intravascular catheters using an array of active steering coils. Med Phys 2011;38(7): 4215–4224.
10. Karmarkar PV, Kraitchman DL, Izbudak I, et al. MR-trackable intramyocardial injection catheter. Magn Reson Med 2004;51(6): 1163–1172.
11. Gosselin FP, Lalande V, Martel S. Characterization of the deflections of a catheter steered using a magnetic resonance imaging system. Med Phys 2011;38(9):4994–5002.
12. Zhang K, Krafft AJ, Umathum R, Maier F, Semmler W, Bock M. Real-time MR navigation and localization of an intravascular catheter with ferromagnetic components. MAGMA 2010;23(3):153–163.
13. Roberts TP, Hassenzahl WV, Hetts SW, Arenson RL. Remote control of catheter tip deflection: an opportunity for interventional MRI. Magn Reson Med 2002;48(6):1091–1095.
14. Hetts SW, Saeed M, Martin AJ, et al. Endovascular catheter for magnetic navigation under MR imaging guidance: evaluation of safety in vivo at 1.5T. AJNR Am J Neuroradiol 2013;34(11):2083–2091.
15. Settecase F, Sussman MS, Wilson MW, et al. Magnetically-assisted remote control (MARC) steering of endovascular catheters for interventional MRI: a model for deflection and design implications. Med Phys 2007;34(8):3135–3142.
16. Wilson MW, Martin AB, Lillaney P, et al. Magnetic catheter manipulation in the interventional MR imaging environment. J Vasc Interv Radiol 2013;24(6):885–891.
17. Hetts SW, Saeed M, Martin A, et al. Magnetically-assisted remote controlled microcatheter tip deflection under magnetic resonance imaging. J Vis Exp 2013;(74):e50299.
18. Settecase F, Hetts SW, Martin AJ, et al. RF heating of MRI-assisted catheter steering coils for interventional MRI. Acad Radiol 2011;18(3):277–285.
19. Bernhardt A, Wilson MW, Settecase F, et al. Steerable catheter microcoils for interventional MRI reducing resistive heating. Acad Radiol 2011;18(3):270–276.
20. Saeed M, Lee R, Martin A, et al. Transendocardial delivery of extracellular myocardial markers by using combination x-ray/MR fluoroscopic guidance: feasibility study in dogs. Radiology 2004;231(3):689–696.
21. Surry KJ, Austin HJ, Fenster A, Peters TM. Poly(vinyl alcohol) cryogel phantoms for use in ultrasound and MR imaging. Phys Med Biol 2004;49(24):5529–5546.
22. Schiemann M, Killmann R, Kleen M, Abolmaali N, Finney J, Vogl TJ. Vascular guide wire navigation with a magnetic guidance system: experimental results in a phantom. Radiology 2004;232(2):475–481.
23. Lillaney P, Malba V, Evans L, et al. Catheters for interventional MR: LaserLathe fabrication of micro-coils for remote catheter tip deflection. [abstr]. In: Proceedings of the Twenty-First Meeting of the International Society for Magnetic Resonance in Medicine. Berkeley, Calif: International Society for Magnetic Resonance in Medicine, 2013; 0472.