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SAFETY

Drug eluting coronary stent: in vitro evaluation of magnet resonance safety at 3 Tesla

FRANK G. SHELLOCK, PH.D.[1,2,*] and JOHN R. FORDER, PH.D.[3]

[1]*Keck School of Medicine, University of Southern California, Los Angeles, California, USA*
[2]*Institute for Magnetic Resonance Safety, Education, and Research, Los Angeles, California, USA*
[3]*Division of Cardiovascular Medicine, University of Southern California, Los Angeles, California, USA*

Purpose. To evaluate MR safety at 3 Tesla for a drug eluting coronary stent. *Methods.* A drug eluting coronary stent (Endeavor, cobalt alloy, Medtronic Vascular, Santa Rosa, CA) was evaluated for magnetic field interactions, heating, and artifacts at 3 Tesla. MRI-related heating was assessed with the stent in a gelled saline-filled phantom using a transmit/received RF body coil with a whole body averaged SAR of 2.0 W/kg. Artifacts were characterized using T1-weighted, spin echo, and gradient echo pulse sequences. *Results.* The stent exhibited minor magnetic field interactions that will not cause migration. Heating was not substantial (+0.5°C). Artifacts may create a problem if the area of interest is in the same area or close to the stent (e.g., for a T1-weighted, spin echo pulse sequence, within approximately 16 mm; for a gradient echo pulse sequence, within approximately 23 mm). *Conclusion.* The findings indicated that it would be safe for a patient with this cobalt alloy-based, drug-eluting coronary stent to undergo MRI at 3 Tesla or less. Importantly, because of the relative lack of magnetic field interactions, MRI may be performed immediately after implantation.

Key Words: Magnetic resonance imaging: safety; MRI; Implants; Specific absorption rate; Artifacts; Coronary stent; Drug eluting stent (DES)

1. Introduction

There is considerable attention focused on the development of drug-eluting stents to prevent coronary artery restenosis that tends to occur in a substantial number of patients following stenting with "bare" devices (1–4). Recent studies have reported that drug-eluting stents reduce the incidence of target vessel failure compared to uncoated metallic stents (1–4). As such, drug-eluting stents are being used on a widespread basis in patients with coronary artery disease.

Magnetic resonance (MR) imaging is an important diagnostic modality utilized for a wide variety of clinical applications. The use of 3-Tesla MR systems is increasing worldwide. There are general safety concerns regarding performance of MR procedures in a patient with a metallic implant, including the possibility of displacement and excessive heating of the object (5–13). In fact, for coronary stents, it has been recommended that patients wait 6–8 weeks after implantation before undergoing MR imaging (11, 14). However, the rationale for this recommendation with regard to a coronary stent made from a nonmagnetic material is unknown.

Because of the increasing use of both drug-eluting coronary artery stents and the 3-Tesla MR system, there is a need to evaluate this implant for safety relative to the use of these powerful scanners. In general, at 3 Tesla, the magnetic field interactions posing a risk for an implant made from a given material cannot be assumed, especially for objects that display "weak" or minor magnetic qualities at 1.5 Tesla (11–13). In addition, for implants with an elongated shape (7, 10, 11), MRI-related heating may be problematic due to differences in resonating RF waves at 3 Tesla vs. 1.5 Tesla. Therefore, the purpose of this study was to assess magnetic field interactions, heating, and artifacts for a new drug-eluting coronary stent in association with a 3-Tesla MR system. To our knowledge, this is the first drug-eluting stent that has undergone comprehensive testing for MR safety at 3 Tesla.

2. Materials and methods

2.1. *Drug eluting coronary stent*

A drug-eluting stent (DES) (Endeavor™ Drug Eluting Stent, 40 mg; diameter, 3.5 mm; length, 30 mm; Medtronic Vascular, Santa Rosa, CA) was evaluated in association with

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*Address correspondence to Frank G. Shellock, Ph.D., Institute for Magnetic Resonance Safety, Education, and Research, 7511 McConnell Ave., Los Angeles, CA 90045, USA; Fax: (310) 417-8639; E-mail: frank.shellock@gte.net

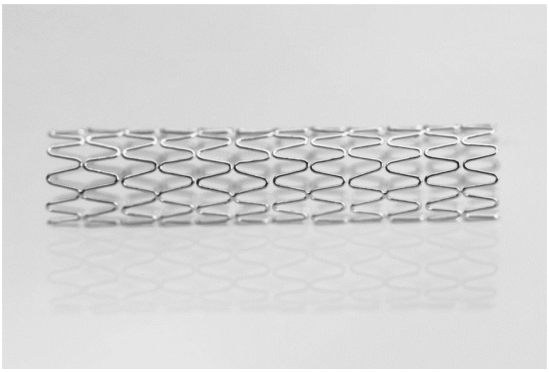

Figure 1. The drug-eluting coronary stent (Endeavor, cobalt alloy; mass, 40 mg; diameter, 3.5 mm; length, 30 mm; Medtronic Vascular, Santa Rosa, CA) that underwent testing for magnetic field interactions, heating, and artifacts at 3 Tesla.

the use of a 3-Tesla MR system. This implant is made from a cobalt alloy-based material and has a modular design that features 10 crowns (Fig. 1). It utilizes ABT-578 (Abbott Laboratories, Abbott Park, IL) to inhibit smooth muscle cell proliferation. (Note: ABT-578 is an investigational drug and is currently not approved by the Food and Drug Administration.) In addition, this coronary stent has a phosphorylcholine coating (PC Technology™, Biocompatibles UK Ltd., Surrey, UK). The PC coating is designed to reduce the body's response to an implanted device and serves as the "delivery matrix" to control the release of ABT-578 into the arterial wall. Currently, the Endeavor DES is an investigational device in the United States and is undergoing clinical trials throughout the world.

2.2. *Evaluation of magnetic field interactions*

The coronary stent was evaluated for translational attraction and torque in association with a shielded, 3-Tesla MR system (Allegra, Siemens Medical Solutions, Malvern, PA). This assessment was conducted on three randomly selected samples.

2.2.1. *Translational attraction*

To determine translational attraction for each stent, the deflection angle was measured, as previously described (7, 10, 12, 13, 15). Each stent was attached to a test fixture to measure the deflection angle in the 3-Tesla MR system. The test fixture consisted of a sturdy structure capable of holding the stent in a proper position and incorporated a protractor with 1-degree graduated markings (7, 10, 12, 13, 15). Each stent was suspended by a lightweight string (20 cm; weight, less than 1% of the weight of the stent) attached at the 0-degree indicator of the protractor. Deflection angle measurements were obtained at the position in the 3-Tesla MR system that produced the greatest magnetically induced deflection angle (10, 12, 13, 15). For the 3-Tesla scanner, the highest spatial gradient, 5.25 Tesla/meter, occurs 78 cm from isocenter (13). The deflection angle from the vertical direction to the nearest 1 degree was measured three times for each stent and an average value was calculated (16, 18, 19–21).

2.2.2. *Torque*

Magnetic field-induced torque was determined for each stent using a previously described qualitative methodology. This involved the use of a flat plastic device with a millimeter grid (10). Each stent was placed on the test apparatus in an orientation that was 45 degrees relative to the static magnetic field of the 3-Tesla MR system (10). The test apparatus with the stent was then positioned in the center of the scanner, where the effect of torque from the static magnetic field is the greatest (10). Each stent was observed for possible alignment or rotation relative to the static magnetic field. The stent was then moved 45 degrees relative to its previous position and again observed for alignment or rotation (10). This process was repeated to encompass a full 360 degrees rotation of positions for each stent. The following qualitative scale was applied to the results (10): 0, no torque; +1, mild or low torque, the implant slightly changed orientation but did not align to the magnetic field; +2, moderate torque, the implant aligned gradually to the magnetic field; +3, strong torque, the implant showed rapid and forceful alignment to the magnetic field; +4, very strong torque, the implant showed very rapid and very forceful alignment to the magnetic field (10).

2.3. *Evaluation of MRI-related heating*

2.3.1. *Phantom and experimental set-up*

An in vitro assessment of MRI-related heating at 3 Tesla was conducted on the drug-eluting coronary stent (one randomly selected sample). This procedure used a plastic phantom that approximated the size and shape of the human head and torso, with dimensions as follows (16, 17): head portion—width, 16.5 cm; length, 29.2 cm; height, 16.5 cm; torso portion—width, 43.2 cm; length, 61.0 cm; height, 16.5 cm. The phantom was filled with a gelling agent (hydroxyethylcellulose) in an aqueous solution (91.48% H_2O) along with 0.12% NaCl (16, 17). A plastic frame with small posts was placed at the bottom of the phantom to position the stent according to its intended in vivo use (i.e., coronary artery). Because this experimental set-up lacks "blood flow," it simulates an extreme condition used to assess MRI-related heating for the drug-eluting coronary stent.

2.3.2. *Temperature recording system and placement of thermometry probes*

Temperature measurements were obtained using an MR-compatible fluoroptic thermometry system (Model 3100, Luxtron, Santa Clara, CA). The fluoroptic thermometry probes (0.5 mm in diameter) were positioned on the stent to record sites that would generate the greatest heating during MR imaging (i.e., based on pilot experiments that were conducted), as follows: probe 1, placed in direct contact with

one end of the stent; probe 2, placed in direct contact with the contralateral end of the stent. In addition, a probe (#3) was placed in the gelled saline at a position approximately 30 cm from the stent to record a reference temperature. The positions of the thermometry probes were inspected and verified before and after the experiment.

2.3.3. *MRI conditions*

MR imaging was performed at 3 Tesla using a transmit RF body coil. (Note: For the heating experiment, a General Electric Medical Systems, 3-T scanner was used because the Siemens MR system was unavailable.) MRI parameters were applied to generate a relatively high level of radiofrequency (RF) energy (16, 17), producing a whole body averaged specific absorption rate (SAR) of 2.0 W/kg and spatial peak SAR of 4.0 W/kg. The landmarking position (i.e., the center position or anatomic region for the MR imaging procedure) and section locations were selected to encompass the entire area of the stent.

2.3.4. *Experimental protocol*

The stent was positioned on the plastic frame using the adjustable posts. The fluoroptic thermometry system was calibrated and the probes were positioned, as previously described. The phantom was filled with the gelled saline and allowed to equilibrate to the environmental temperature. The room temperature and the temperature of the bore of the MR system were at a constant level throughout the heating experiment. After recording baseline temperatures (5 min), MR imaging was performed for 20 min with temperatures recorded at 20-sec intervals.

2.4. *Evaluation of Artifacts*

Artifacts were determined by performing MR imaging of the drug-eluting coronary stent with the stent attached to a flat plastic frame and placed in a gadolinium-doped, saline-filled, phantom (10, 20). MR images were obtained using a 3-Tesla MR system (whole body gradients, peak amplitude, 40 mT/m; slew rate, 150 mT/m/msec; General Electric Medical Systems, Milwaukee, WI), a transmit/receive body RF coil, and the following parameters: T1-weighted, spin echo pulse sequence; repetition time, 500 msec; echo time, 20 msec; matrix size, 256 × 256; section thickness, 8 mm; field of view, 40 cm; number of excitations, 2; and gradient echo pulse sequence; repetition time, 100 msec; echo time, 15 msec; flip angle, 30 degrees; matrix size, 256 × 256; section thickness, 8 mm; field of view, 40 cm (i.e., selected for imaging of the thorax); number of excitations. Imaging planes were oriented to encompass the long axis and short axis of the stent. The frequency encoding direction was parallel to the plane of imaging for each imaging condition. Comparable pulse sequences have been utilized for the assessment of artifacts associated with metallic implants (10, 20). Planimetry software was used to measure (accuracy and resolution ±10%) the cross-sectional area of the largest artifact size for the drug-eluting coronary artery stent, for each pulse sequence, and for each orientation of the section location (10, 20). The image display parameters (i.e., window and level settings, magnification, etc.) were carefully selected and used in a consistent manner to facilitate valid measurements of artifact size.

Table 1. Artifact size for the drug-eluting coronary stent associated with MR imaging at 3 Tesla

Pulse sequence	Plane orientation	Signal void (mm^2)
T1-SE	Long axis	259
	Short axis	98
GRE	Long axis	535
	Short axis	141

Note: Imaging plane relative to the stent; T1-SE, T1-weighted spin echo; GRE, gradient echo.

3. Results

The average deflection angles and torque values associated with exposure to the 3-Tesla scanner were the same for the drug-eluting coronary stents (n = 3): 4 degrees and 0 (no torque), respectively. For the evaluation of MRI-related heating, the highest temperature change recorded by probe #1 and probe #2 was +0.5°C. The highest temperature change measured by the reference probe was +0.2°C. Artifact test results are summarized in Table 1. The artifacts were seen as signal voids that were slightly larger than the size and shape of the coronary stent, with the GRE pulse sequence producing larger artifacts than the T1-weighted, spin echo pulse sequence.

4. Discussion

Possible MR safety and other issues that exist for a patient undergoing an MRI procedure with a drug-eluting coronary artery stent include movement of the implant by magnetic field interactions, heating due to exposure to RF energy, and artifacts associated with this metallic object (5–12, 21). Because of the anticipated widespread use of drug-eluting coronary stents along with the growing utilization of 3-Tesla MR systems, there is an urgent need to evaluate these various factors because of their potential impact on patient management.

4.1. *Magnetic field interactions*

Measurements of translational attraction and torque for the drug-eluting coronary stent indicated a deflection angle of 4 degrees and a value of "no torque" in association with exposure to a 3-Tesla scanner. The guideline from the American Society for Testing and Materials (ASTM)

International for deflection angle testing of implants states that "...if the implant deflects less than 45°, then the magnetically induced deflection force is less than the force on the implant due to gravity (its weight)" (17). Accordingly, this drug-eluting coronary stent passes the ASTM International criterion and will not create a risk from translational attraction at 3 Tesla. Since there was no torque identified for the stent using the qualitative assessment technique, it was deemed unnecessary to perform a quantitative evaluation for this implant. The overall magnetic field interaction test results for this drug-eluting coronary stent are consistent with other reports that indicate there were no or only minimal magnetic field interactions at 3 Tesla for metallic implants made from cobalt alloys (11, 13). In consideration of the findings for magnetic field interactions, a patient with this particular drug-eluting coronary stent may undergo an MRI procedure at 3 Tesla or less without concerns of migration. Importantly, because of the relative lack of magnetic field interactions at 3 Tesla, MRI may be performed immediately after implantation.

4.2. *MRI-related heating*

MR imaging can generate substantial temperature increases in metallic implants that form a closed-loop as well as devices that have an elongated shape (7, 10, 11, 16, 18, 19–21). However, because of the small diameter (3.5 mm) and short length (30 mm) of the drug-eluting coronary stent that underwent assessment at 3 Tesla, only a minor temperature change (+ 0.5°C) occurred, despite the use of a relatively high level of RF energy (whole body averaged SAR, 2.0 W/kg). The fact that excessive heating does not occur in relatively small metallic objects has been reported by various investigators (7, 10, 21). Notably, this drug-eluting coronary stent is one of few implants that has been evaluated for heating in association with a 3-Tesla scanner.

4.3. *Artifacts*

During MR imaging, magnetic susceptibility-related signal loss seen with a metallic implant consists of a region of signal void that may appear larger than the size of the device (7, 22). The extent of the artifact is dependent on the magnetic susceptibility of the material used to make the implant as well as a variety of other factors including the field strength of the scanner used for MR imaging (7, 10, 22).

For the drug-eluting coronary stent, the size of the artifact at 3 Tesla may impair the ability to properly visualize anatomy that is located in the same area or near this implant. As expected, larger artifacts were seen with the use of the gradient echo pulse sequence compared to the T1-weighted pulse sequence, as was reported in investigations of stents and other implants performed at 1.5 Tesla (7, 10, 20). Of note is that the assessment of artifacts in this study did not entail the use of MR imaging techniques used for MR angiography procedures. Given the size of the artifacts seen for the drug-eluting coronary stent, and in consideration of the particular challenges associated with performing MR angiography of the coronary arteries at 3 Tesla, this was believed to be impractical.

In a study performed at 1.5 Tesla, Hug et al. (7) reported that coronary artery stents generate susceptibility artifacts that extend in excess of the true sizes of these devices and make imaging of the underlying structures impossible. In addition, artifact size differed according to the type and size of the stent and the MR imaging sequence used, with the larger artifacts observed for the larger and longer stents and with the use of gradient echo and echo-planar imaging sequences (7). Thus, the findings of the present study are compatible to those reported by Hug et al. (7).

4.4. *MR safety and other drug-eluting coronary stents*

Currently, two drug-eluting coronary stents are available for clinical use in the United States: the CYPHER stent (Cordis Corporation, Miami, FL, 2003) and the Taxus Express Stent (Boston Scientific Corporation, Natick, MA). Both of these implants have labeling relative to the use of MRI (14, 23). For the CYPHER stent, the instructions for use state: "An MRI scan should not be performed on a patient after stent implantation until there is adequate neointimal investment of the stent because of a potential for stent migration. For a conventional uncoated 316L stainless steel stent this period is usually considered to be eight weeks. Because of the reduced neointimal formation associated with the CYPHER Stent, the period of vulnerability may be longer, but there is currently insufficient information to provide a specific recommendation" (14). Interestingly, the static magnetic field strength for which this labeling applies is not indicated and there is no information with regard to the potential for MRI-related heating. To date, there has been no evaluation of MRI-related heating for this stent in association with the use of a 3-Tesla MR system.

Of note is that the labeling information for the CYPHER stent conflicts with MR safety findings for various implants made from 316L stainless steel (10–12), including recent work performed on coronary stents made from 316L stainless steel (7). To date, no stent made from 316L stainless steel has been observed to display magnetic field interactions at 1.5 Tesla. Furthermore, the forces applied to a stent implanted into the coronary arteries owing to rapid motion, with acceleration and deceleration of the heart during cardiac contraction and relaxation, are expected to be much higher than those caused by the magnetic field (7, 24). Therefore, there should be no concern for migration of a coronary artery stent related to exposure to a 1.5-Tesla MR system, regardless of whether or not it is a drug-eluting stent.

Regarding MR imaging and the Taxus Express Stent, the directions for use state: "Bench testing at field strengths of 3 Tesla (T) or less, and a maximum spatial gradient of

325 gauss/cm, showed that the TAXUS Express Stent should not migrate in this MR environment. This stent has not been evaluated to determine if it is safe in MRI systems with field strength greater than 3-T. This product has not been evaluated for heating in the MR environment. The effect of heating in the MR environment for overlapping stents or stents with fractured struts, or on the drug or polymer coating is not known. MR imaging quality may be compromised if the area of interest is in the exact same area or relatively close to the position of the stent" (23).

In summary, the findings of this in vitro investigation indicated that the cobalt alloy-based, drug-eluting coronary stent, Endeavor, exhibited only minor magnetic field interactions and minimal heating at 3 Tesla. Artifacts may only create a problem if the area of interest is in the same area or near the stent. Therefore, it would be safe for a patient with this particular drug-eluting coronary stent to undergo MR imaging using an MR system operating at 3 Tesla or less. Importantly, because of the relative lack of magnetic field interactions at 3 Tesla, MRI may be performed immediately after implantation.

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