Transesophageal Magnetic Resonance Imaging

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The purpose of this study was to develop a non-invasive method of imaging the thoracic aorta that would provide both morphological detail within the aortic wall and information about regional aortic wall motion. An esophageal probe is described that allows transesophageal MR imaging (TEMRI) of the thoracic aorta and has several potential advantages over the competing non-vasculoinvasive techniques of transesophageal echocardiography (TEE) or standard MRI. The probe consists of a loopless antenna housed inside a modified Levin gastric tube, with external matching and tuning circuitry. Using this probe, the thoracic aorta has been imaged in longitudinal and cross-sectional views. Details of the aortic wall were readily seen. Tissue tagging for measurement of focal stress/strain relationships was demonstrated to be feasible. TEMRI avoids the risks inherent in intravascular MRI yet provides comparable image quality. Potential applications of the device are discussed. Magn Reson Med 41:722–726, 1999. © 1999 Wiley-Liss, Inc.

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Current standard techniques for imaging the thoracic aorta include computed tomography (CT), standard MRI, transesophageal echocardiography (TEE), and contrast aortography. Each of these techniques suffers from some important limitation in its ability to allow detailed mapping of the aortic wall and its anatomic and functional lesions. Standard MRI and CT lack adequate resolution of the aortic wall for precise characterization of aortic atheromata and are not able to provide measurements of focal variations in vessel wall compliance or distensibility. TEE allows real-time imaging but suffers both from an inability to image clearly the quadrant of the aortic wall that is directly against the esophagus and from an inability to register images to a fixed frame of reference, making precise mapping of aortic lesions problematic. Kasprzak et al (1) have attempted to circumvent this limitation using a technique to control movements of the probe while imaging in multiple planes with subsequent off-line three-dimensional (3D) image reconstruction, but the system is presently cumbersome and was not fully successful in obtaining "adequate" images in a select group of 21 patients. Montgomery and colleagues (2) have provided an example of a semi-quantitative atherosclerosis grading scheme that depends on orthogonal views to estimate the 3D characteristics of aortic lesions but does not circumvent the inherent advantage of MR over ultrasound imaging at defining atheroma structure (3).

Contrast aortography, which is often considered the gold standard for aortic imaging, is actually a misnomer since none of the tissues that make up the aortic wall are visualized directly. Only lesions that protrude into the lumen and focally displace the contrast agent can be "seen" as an absence of signal. Any inferences about the vessel wall depend on comparison of contrast displacement from the area of the lesion to the displacement around an adjacent "reference" segment of normal artery, which is often unavailable (4). Any statements about the thickness and stiffness of the vessel wall at the site of a contrast filling defect are purely conjectural. For these reasons, some investigators prefer the term lumenography (5) to describe standard contrast angiography.

Intravascular MR has overcome many of the limitations of CT and standard MRI, at the cost of invasiveness. Henkelman and colleagues (6) used an intraaortic catheter coil to image the aortic wall in a pig model, but the coil was relatively large and required ligation of the aorta. Recently, we developed a 9 French (3 mm diameter) catheter coil designed specifically for intravascular imaging and validated its ability to quantitate atherosclerotic plaque burden and intraplaque composition against histopathology in cadaveric human aortae (7). Intravascular MRI is emerging as a valuable tool for studying aortic disease, but in vivo human studies must await proper safety testing and regulatory approval. Without invading a vascular space, one may obtain similar information by receiving the signal from an adjacent body structure.

The concept of placing a radiofrequency (RF) receiver into a body cavity to image an adjacent structure by MR was reported simultaneously in August of 1989 by Nara]ayam et al (8), who demonstrated the use of an endorectal RF receiver coil to image the canine prostate, and by Schnall et al (9), who applied an expandable endorectal RF receiver coil to image the prostate in 15 humans with biopsy-proven prostate carcinoma and two normal volunteers. Schnall and others (10) later demonstrated the use of an endovaginal coil to image the vagina and adjacent structures. This concept was also exploited by Martin et al (11) for studies of the aorta using an expandable coil-type RF receiver in the inferior vena cava. While this approach avoids the need to invade the aorta, it necessitates placement of a large-caliber central venous catheter, with associated risks.

We describe here the use of a loopless RF receiver device designed for ease of placement into the esophagus for imaging of the adjacent aorta. Previously an intravascular version of this loopless catheter antenna was used for in vivo intravascular imaging of rabbit aortae (12). In brief, it is constructed from thin flexible coaxial cable with an extended inner conductor. The coaxial cable is connected to a tuning and matching circuit lying outside the study subject's body. The circuitry provides high-speed diode switching to decouple the antenna during external RF pulses, yet allows signal reception between pulses. We...
exploited the proximity of the esophagus and descending thoracic aorta. Our goal was to design and test in large animals a device that, in principle, could be passed down the esophagus of a non-sedated human patient and provide information comparable to that obtained with intravascular MRI and not obtainable by other non-invasive methods.

MATERIALS AND METHODS

Catheter Antenna

The design and construction of the MRI-compatible loopless RF receiver antenna have been described in detail previously (12). The current prototypes of our transesophageal MRI (TEMRI) antenna device are based on the same principles, but each is designed to fit and operate inside a modified Levin gastric tube (Sherwood Medical, St. Louis, MO), typically 8 or 12 French. In brief, a typical TEMRI antenna device consists of a thin coaxial cable \( \lambda/4 \) in length with a 10 cm extension of the inner conductor at the distal end. The distal portion of the antenna is housed inside a Levin gastric tube, which has been cut to adjust its length and marked to assist proper esophageal placement. The proximal end of the antenna protrudes from the proximal end of the Levin tube, at which point the two are secured together to prevent the antenna from migrating out the end of the Levin tube housing. The proximal end of the antenna is connected to an adjustable tuning and matching circuit, which in turn is connected via coaxial cable to the MRI scanner.

Animals

Two species were used for this study, the mini-swine (35–45 kg) and the New Zealand White rabbit (5 kg). All animals were handled according to the Johns Hopkins Animal Care and Use Committee guidelines (13), which ensure compliance with all relevant Federal regulations. Trans-nasal esophageal placement of the antenna device was confirmed by fluoroscopy in the case of the mini-swine. At the end of each study, the animal was sacrificed and the aorta and esophagus harvested en bloc for gross and microscopic histopathologic examination by an expert pathologist for evidence of tissue injury using standard hematoxylin and eosin stains.

MRI Imaging

Studies were performed using a GE 1.5 T MRI system. Tagged and non-tagged cine images were obtained as described previously (14,15). Specific imaging parameters are given in the legends to Figs. 2–4.

RESULTS

TEMRI devices were constructed in various sizes, as described in Materials and Methods, and used to image live animals. Figure 1 shows a prototypical 12 French device such as the one used to obtain images in the mini-swine model. An 8 French design was used for the rabbit studies.

Images of the thoracic aorta obtained by TEMRI in a living, anesthetized mini-pig are shown in Fig. 2. Adjusting the imaging parameters allows differentiation of the aortic wall from both surrounding tissues and intra-aortic blood. Images have also been obtained with tissue tagging (15) and electrocardiographic (ECG) gating at 5 frames per cardiac cycle to demonstrate focal movement of the aortic wall in response to pulsatile blood flow, which reflects focal stress/strain relationships. Figure 2a was obtained without tissue tagging. Figure 2b and 2c shows 159 msec delay images from tissue-tagged, ECG-gated cine-loops obtained at 44, 83, 121, 159, and 198 msec after detection of the QRS complex.

The indicated location of the TEMRI probe in each image is recognized by the characteristic appearance of a small dark region reflecting the actual silver and copper coaxial RF receiver within the brightest region of the image. In some cases, a target appearance of the probe is evident. We believe this represents the (dark) metallic conductor in the center, surrounded by gastric fluid (bright), surrounded by plastic (dark) from the modified Levin tube probe housing, all within the brightest region of the image. In practical terms, recognizing the location of the probe within the image is not difficult.

This technique was also applied to a smaller animal model. An 8 French version of the TEMRI device was constructed, as described in Materials and Methods, which was easily passed trans-nasally into the esophagus of a living anesthetized rabbit and allowed imaging of the rabbit aorta, including the aortic wall, which is \( \approx 0.2 \) mm
thick. ECG-gated TEMRI images from a rabbit obtained with a 61 msec delay from detection of the QRS complex are shown in Fig. 3.

The sensitivity of the TEMRI antenna decreases with the longitudinal distance from its receptive center and linearly with radial distance from the antenna (12) but is maintained at a reasonable level over a useful range. This can be seen qualitatively as the brightness of the images in both their longitudinal and radial dimensions (Figs. 2, 3). For applications in which the relative values of the signal intensities at two different locations are important, the image can be corrected after acquisition using an algorithm that accounts for this property of the antenna.

We also performed standard MRI while the TEMRI device was in the esophagus. The presence of the TEMRI device in the esophagus did not interfere with standard MRI, as demonstrated in Fig. 4. We have used this technique to verify proper positioning of the TEMRI probe within the distal esophagus.

At the termination of each experiment, the animal was sacrificed, and the aorta and esophagus were harvested en bloc. A trained pathologist examined the specimen grossly and by multiple level section sampling with microscopic hematoxylin and eosin staining for evidence of tissue injury. No evidence of esophageal injury was found, indicating that the use of this device is likely to be safe (data not shown).

**DISCUSSION**

We have demonstrated the principle of TEMRI and shown its potential application to the study of the thoracic aorta. This technique may have applications to studies of aortic atheroma size, morphology, and composition. While these properties have been studied ex vivo and by intravascular MR (3,6,16–19), they cannot be measured as well by competing non-invasive techniques. The current design using a loopless antenna has several advantages over other candidate TEMRI antenna designs incorporating coils. First, while the coil design theoretically has a higher signal-to-noise ratio (SNR), this advantage only persists in the region immediately adjacent to the probe (7,12). In practice, a small-caliber coil with a conductor separation of 1.5 mm will outperform a loopless receiver at <1 cm from the aorta.

**FIG. 2.** Transesophageal MR images from a mini-pig showing thoracic aorta. Imaging parameters (a–c): ECG-gated, segmented k-space, SPGR with HOT pulses (14,26) at 10 cm field of view, 256 × 140 matrix, flip angle–15°. a: Short-axis 7 mm slice obtained 7.7 cm proximal to the probe tip, 27 sec breath-hold, number of excitations 4, TR/TE 7.7/2.2 msec, 44 msec delay from QRS. Tissue-tagged images were obtained with ECG gating at 5 frames per cardiac cycle to allow direct visualization of aortic wall strain in response to pulsatile blood flow. b and c: Transverse and longitudinal images obtained using tissue tagging, which appears as transverse lines of voided signal. b: 7 mm thick, 7.7 cm proximal to the probe tip, 10 sec breath-hold, number of excitations 2, TR/TE 7.7/2.2 msec, 159 msec delay from QRS; c: 3 mm thick, 28 sec breath-hold, number of excitations 6, TR/TE 8.7/2.6 msec, 159 msec delay from QRS. Ao, aorta; Es, esophagus; De, TEMRI antenna device.

**FIG. 3.** Transesophageal MR images from a rabbit. Images are ECG gated with a 61 msec delay from detection of the QRS complex, fast spin-echo at 8 cm field of view, 256 × 256 matrix, flip angle 15°. a: A 3 mm longitudinal slice through the aorta from the arch to well below the diaphragm. Parameters: single breath-hold, number of excitations 8, TR/TE 600/19.6 msec. b–d: 3 mm short-axis slices at high, middle, and low positions within the descending thoracic aorta (7.8, 5.4, and 4.6 cm from the distal tip of the probe, respectively). Parameters: single breath-hold, number of excitations 8, TR/TE 600/11.8 msec. In d, the TEMRI antenna device can be seen in the esophagus at the gastroesophageal junction. In b and c, the aortic wall can be seen separating lung and aortic blood, demonstrating that this technique can resolve the aortic wall, which in a rabbit is <0.2 mm thick. Ao, aorta; Es, esophagus; De, TEMRI antenna device; GEJ, gastroesophageal junction.
number of excitations 2, TR 2000 msec.

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technique, i.e., measure the proper position externally, device in the esophagus by a standard nasogastric tube in terms of performance, yet it is simpler to construct and use. Thus, for imaging the human aorta, which is normally 2–3 cm in diameter and immediately adjacent to the esophagus, a loopless RF receiver sacrifices little if anything to the coil receiver in performance over time, reinforcing the current consensus view (for review, see ref. 5) that while atherosclerosis may be slowly progressive, it is so only because the sum of the activities in each individual lesion is slowly progressive. Many clinical events, in fact, probably result from a single plaque catastrophe. Tomochika et al (24) used TEE to image aortas in patients with familial hypercholesterolemia before and after a trial of strict cholesterol-lowering therapy, using biplane TEE and semiquantitative scores of both atheroma burden and circumferential aortic wall stiffness; they found a decrease in both parameters after therapy. For this important need to monitor response to anti-atherosclerotic therapy, TEMRI has several potential advantages over TEE. First, the probe is smaller and can be passed in the same manner as a standard nasogastric tube, i.e., by a well-trained nurse with neither sedation nor the additional monitoring mandated by conscious sedation. Second, MRI-based techniques more readily allow registration of images to a fixed frame of reference than does TEE, since the absolute position of each MRI slice is known and can be related to the locations of anatomic landmarks. Since TEE requires manual aiming of the ultrasound beam at an object

FIG. 4. Standard (body coil) MR images of a rabbit with a TEMRI device in position in the esophagus. While the TEMRI device was in place in the esophagus, standard MRI was performed. The presence of the TEMRI device in the esophagus did not interfere with standard MR imaging, which can be used to confirm proper placement in the distal esophagus. Imaging parameters: ECG-gated, fast spin-echo at 28 cm field of view, 256 × 256 matrix, 3 mm thick, single breath hold, number of excitations 2, TR 2000 msec.

the receiver; beyond 1 cm the loopless design affords a higher SNR. This is because the SNR for a receiver coil decreases with the inverse square of the distance from the coil, but the SNR for a loopless receiver decreases with the linear inverse of the distance.

This linear inhomogeneity of signal from a loopless receiver is quite predictable across the field of view and can be corrected to homogeneity after image acquisition with an appropriate algorithm, as described previously (12). In principle, this allows quantitative comparison of signal intensity between two pixels whose distances from the probe differ; however, as is the case with most diagnostic imaging modalities, limiting post-acquisition processing of the images may be preferable.

In addition, since coil receivers require capacitor components near the distal end of the device, a larger caliber is mandated and construction is more complex (7,12). Expandable coils can extend the range over which a coil design outperforms a loopless receiver by increasing the diameter of the coil (9–11); however, they add further to the complexity of device design and placement. Thus, for imaging the human aorta, which is normally 2–3 cm in diameter and immediately adjacent to the esophagus, a loopless RF receiver sacrifices little if anything to the coil receiver in terms of performance, yet it is simpler to construct and use.

For use in human subjects, we propose placement of the device in the esophagus by a standard nasogastric tube technique, i.e., measure the proper position externally, mark the device, and then pass it to the pre-marked level. Proper position could then be confirmed either by a rapid external body coil image such as we demonstrated in the rabbit model (Fig. 4) or by previously described MRI fluoroscopy techniques (20).

The advantage of a simple, small-caliber device such as the loopless TEMRI device we describe here may lie as much in practical issues as with theoretical concerns. In contrast to a TEE probe, an 8 or 12 French nasogastric tube is relatively small and can be passed transnasally into proper position in the esophagus of a cooperative conscious patient. Once the TEMRI device is in position, no further manipulation of the device is required to obtain different views. The net result is a decreased requirement for highly trained technical expertise to place the device and no need for sedation. This approach also avoids the need for a large-caliber central venous catheter, as is required by the transvenous approach (11).

Previous investigators have suggested that aortic atherosclerosis, as detected by TEE, can serve as a surrogate marker for coronary atherosclerosis (21–23). Fazio et al (23) used TEE to study a diverse group of 61 patients scheduled for coronary angiography; they found 95% and 82% positive and negative predictive values, respectively, for the ability of aortic atherosclerosis on TEE to predict a significant coronary lesion, i.e., 70% stenosis of a major coronary artery or 50% stenosis of the left main coronary artery. In more defined populations, two other groups (21,22) both found 93% sensitivities of TEE for predicting the presence of a ≥50% stenosis of a major coronary artery as determined at coronary angiography. The specificities were poor, however. In Matsumura’s study the specificities were only 55% and 10% in the subgroups under or over age 70, respectively; in Khoury’s study, the specificities were 77% and 40% in subgroups under or over age 64, respectively.

Montgomery et al (2) have used TEE to follow the natural history of aortic atheromatous disease and found that while the overall severity of atherosclerosis may not change significantly over time, individual lesions are sporadically active and have a high likelihood of worsening or regressing over time. In a large-caliber device such as the loopless TEMRI device we describe here may lie as much in practical issues as with theoretical concerns. In contrast to a TEE probe, an 8 or 12 French nasogastric tube is relatively small and can be passed transnasally into proper position in the esophagus of a cooperative conscious patient. Once the TEMRI device is in position, no further manipulation of the device is required to obtain different views. The net result is a decreased requirement for highly trained technical expertise to place the device and no need for sedation. This approach also avoids the need for a large-caliber central venous catheter, as is required by the transvenous approach (11).

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of interest, the probe position is not a fixed point of reference. Thus, unless two referenced landmarks are visible in the same TEE field of view as an object of interest, the object's position in space cannot be determined precisely. This makes TEE an imperfect tool for monitoring the fate of a particular atherosclerotic plaque over time, particularly in areas with many plaques and few landmarks. Third, MRI provides more lesion detail and information about plaque composition (3,6,16–19,25), which is a strong predictor of plaque stability and therefore clinical events. Finally, with the use of tissue tagging and ECG-gated cine-loop acquisition, TEMRI potentially provides a tool for measuring focal changes in wall stiffness, which we speculate may be the most sensitive indicator of preclinical disease or response to therapy.

In terms of safety, the potential for heating of the device is the primary concern. Whether the energy from the currents induced in the antenna is of sufficient magnitude to produce local temperature increases and subsequent thermal tissue injury depends on the switching, or “decoupling,” efficiency of our tuning, matching, and decoupling circuit (TMD box), which is designed to turn off RF reception during external RF pulses. Intrinsic to the MRI magnet is a feature that detects a change in the bias current used to decouple the antenna. If a change in this bias current is detected, the system will alarm and shut down the pulse sequence. While this safety feature has been triggered during deliberate attempts to operate the device in a phantom with the decoupling disabled, it has not triggered during any studies in which the decoupling feature of the TMD box was enabled. Furthermore, the absence of evidence of thermal injury to either pig or rabbit esophagus confirms that decoupling is efficient and provides a preliminary indication that TEMRI is likely to be safe.

In summary, TEMRI is feasible and provides information about the aorta that is potentially of clinical importance and otherwise unobtainable without invading a vascular space. Ongoing work addresses the use of TEMRI in visualizing lesions of the aorta.

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