Transesophageal Magnetic Resonance Imaging of the Aortic Arch and Descending Thoracic Aorta in Patients With Aortic Atherosclerosis

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OBJECTIVES We sought to determine the feasibility and potential of transesophageal magnetic resonance imaging (TEMRI) for quantifying atherosclerotic plaque burden in the aortic arch and descending thoracic aorta in comparison with transesophageal echocardiography (TEE).

BACKGROUND Improved morphologic assessment of atherosclerotic plaque features in vivo is of interest because of the potential for improved understanding of the pathophysiology of plaque vulnerability to rupture and progression to clinical events. Magnetic resonance imaging (MRI) is well suited for atherosclerotic plaque imaging. Performing MRI using a radio frequency (RF) receiver probe placed near the region of interest improves the signal-to-noise ratio (SNR).

METHODS High-resolution images of the thoracic aortic wall were obtained by TEMRI in 22 subjects (8 normals, 14 with aortic atherosclerosis). In nine subjects, we compared aortic wall thickness and circumferential extent of atherosclerotic plaque measured by TEMRI versus TEE using a Bland-Altman analysis. Additional studies were performed in a human cadaver with pathology as an independent gold standard for assessment of atherosclerosis.

RESULTS In clinical and experimental studies, we found similar measurements for aortic plaque thickness but a relative underestimation of circumferential extent of atherosclerosis by TEE (p = 0.001), due in large part to the lower SNR in the near field.

CONCLUSIONS Using TEMRI allows for quantitative assessment of thoracic aortic atherosclerotic plaque burden. This technique provides good SNR in the near field, which makes it a promising approach for detailed characterization of aortic plaque burden. (J Am Coll Cardiol 2001;37: 2031–5) © 2001 by the American College of Cardiology

Considerable interest has focused on factors influencing atherosclerotic plaque stability. Plaque composition influences plaque stability, and interventions that alter plaque composition may change the likelihood of plaque rupture and clinical events (1). The thoracic aorta represents a valuable window on atherosclerotic plaque burden and vulnerability. Atherosclerosis of the thoracic aorta predicts cerebrovascular events (1–3), coronary disease/events (4,5) and death (1,5). Transesophageal echocardiography (TEE), the current reference method for aortic plaque imaging, provides real-time images but often fails to delineate the entire thoracic aortic wall, particularly in the arch. Recently, surface-coil magnetic resonance imaging (MRI) has been proposed for atherosclerotic plaque imaging in the descending aorta (6). Use of MRI has a distinct advantage over TEE for tissue characterization (7,8). By performing MRI using an intravascular receiver, high-resolution imaging (9–11) can be achieved at the cost of invasiveness. In an effort to improve signal-to-noise ratio (SNR) without invading a vascular space, we developed transesophageal MRI (TEMRI) and demonstrated its use in animals (12). In this article, we describe the use of TEMRI for imaging the thoracic aorta in humans with and without aortic atherosclerosis and compare it to TEE.

METHODS

The TEMRI probe device. The antenna has been described previously (9,12). In brief, it consists of a flexible 1.2-mm-diameter loopless radio frequency (RF) receiver constructed from 50Ω coaxial cable with an extended inner conductor, housed inside an 8- or 12F Levin gastric tube and connected via tuning, matching and decoupling circuitry to the scanner (Fig. 1). The circuitry provides high-speed diode switching to decouple the antenna during external RF pulses and allows signal reception between pulses. A BALUN circuit is interposed to block the transmission of unbalanced currents. In theory, without the BALUN, if the MRI connector cable is inadvertently left in a loop configuration during scanning, induced currents might be transmitted to the patient as heat.

Subjects. From a cohort of patients referred for TEE to rule out a cardiac or aortic source of thromboemboli, 14 (7 women, mean age 65 ± 11 years) were identified with evidence of significant atherosclerotic plaques (≥2 mm thickness) in the distal aortic arch or descending thoracic aorta. The MRI was performed within one day after TEE. Eight normal controls (3 women, mean age 30 ± 8 years)

were also studied by TEMRI. None of the volunteers had a history of smoking, hypertension (HTN), hypercholesterolemia, diabetes or a familial history of premature coronary artery disease (CAD). The study was approved by the Johns Hopkins Committee on Clinical Investigation. Written informed consent was obtained from each subject. We performed additional studies in a formalin-fixed human male cadaver with diffuse aortic atherosclerosis. A vitamin E–filled balloon catheter was placed below the origin of the left subclavian artery under TEE guidance and sutured into position for cross-registration among TEE, TEMRI and histopathology.

Placement of the TEMRI probe. The probe was advanced through the nose into the stomach, using topical benzocaine spray when needed. Proper positioning was confirmed by aspiration and auscultation, and adjusted once after scout images when necessary. The distal extremity of the receiver was placed at the gastroesophageal junction. As shown previously (9,12), because the sensitivity of the TEMRI antenna is maintained over much (~20 cm) of its length, it was not necessary to reposition it to image the upper portion of the descending aorta or aortic arch (Fig. 2E).
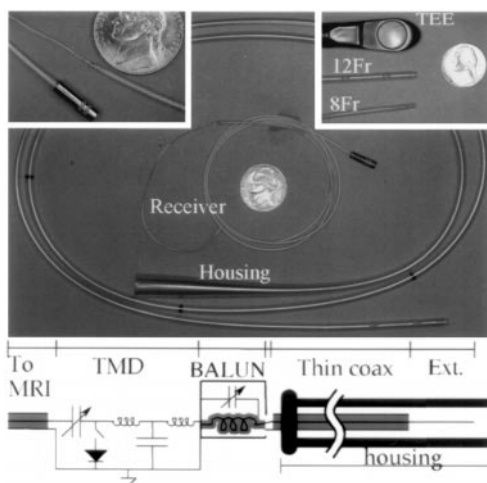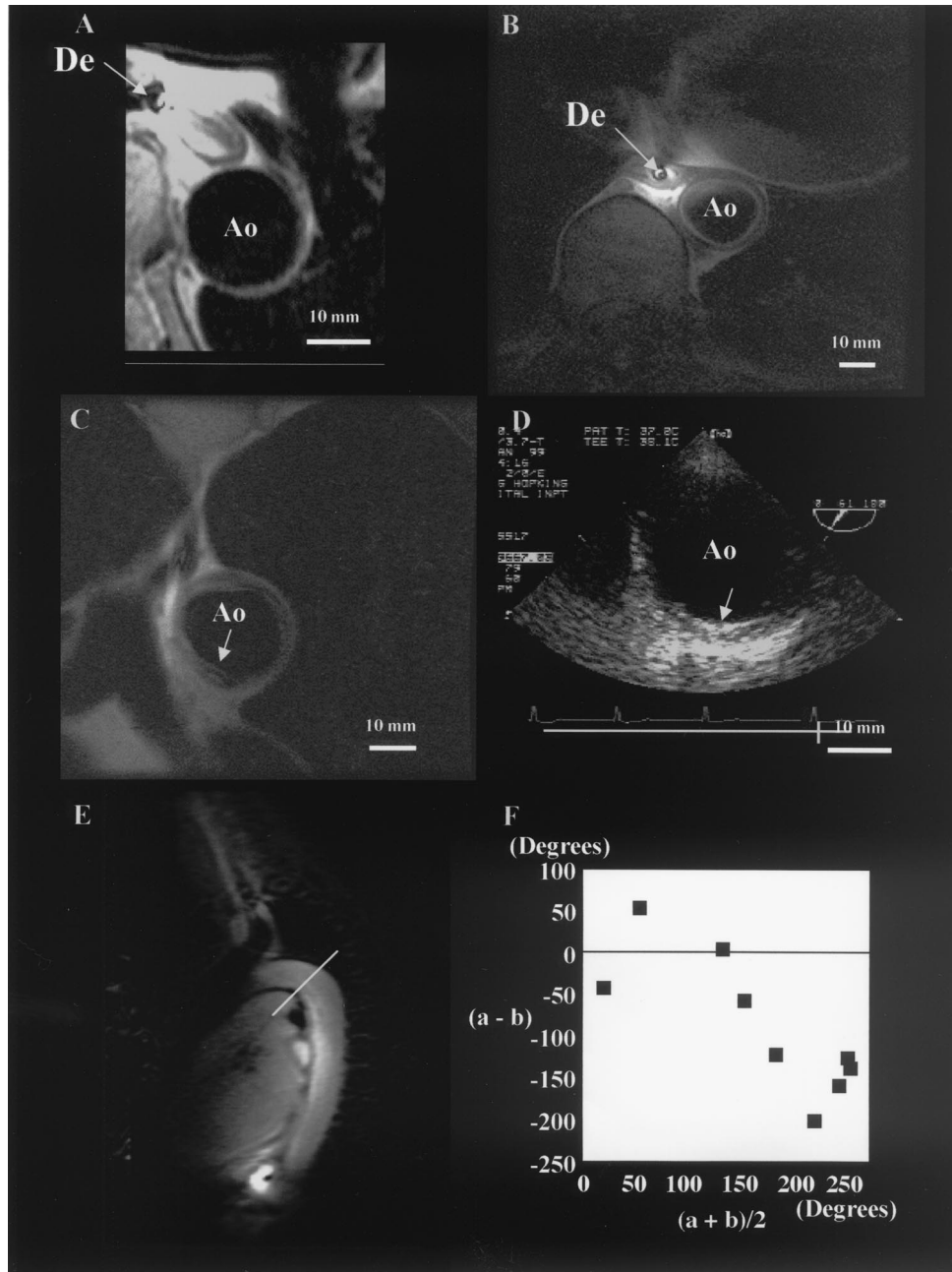

Figure 1. The transesophageal magnetic resonance imaging (TEMRI) device. The probe consists of a 1.2 mm-diameter loopless radiofrequency receiver and a modified Levin tube housing. A standard transesophageal echocardiography probe and a U.S. 5-cent coin are shown for size comparison. The TEMRI probe is connected via a BALUN circuit and a tuning, matching and decoupling circuit (TMD) to the scanner as described in the Methods section.

MRI. Studies were performed with a 1.5T (40 mT/m) Sigma (General Electric, Milwaukee, Wisconsin) magnet using the magnet coil as transmitter and the TEMRI device as receiver. The TEMRI device was arrayed with an anterior or posterior surface coil (FlexCoil, General Electric). Guided by scout images, oblique slices of the thoracic aorta perpendicular to blood flow were prescribed. We used a single breath-hold electrocardiographic-gated fast spin-echo imaging pulse sequence with an inversion-recovery RF pulse to obtain black blood (12 cm field of view; 4-mm-slice thickness, no gap, repetition time (TR) = 2 RR intervals; echo delay time (TE) 15 and 60 ms; image matrix 256×256, $\alpha=90°$, echo train length (ETL) 24, 1 NEX (number of excitations), no phase wrap, in-plane resolution 0.47×0.47 mm). The breath-hold duration varied from 18 to 28 heart beats/slice.

The TEE studies. The TEE studies were performed with conventional equipment (Hewlett Packard 5500) by an expert echocardiographer using an omniplane probe. The probe was advanced toward the level of the diaphragm and a gradual pullback was performed. Care was taken to obtain high-quality images by optimizing focal length, gain settings and the contact between the probe and the esophagus. Images were recorded on S-VHS videotapes. Horizontal-plane TEE images were compared with TEMRI.

The TEE/TEMRI comparison. In nine subjects with good-quality TEE images and for whom TEE and TEMRI images contained specific anatomic landmarks (origin of the left subclavian, pulmonary artery, carina, left main stem bronchus, crura of the diaphragm, left atrium), plaque thickness, and extent were analyzed independently by two observers (K.A.S., J.G.) (NIH Image 1.62, Frederick, Maryland). Maximum and minimum aortic wall thickness (WT), excluding adventitia, was measured in the visible circumference of the descending aorta. To establish a basis for an arbitrary definition of abnormal aortic WT, the TEMRI slices from normal subjects were obtained in similar anatomic locations. Allowing multiple measurements per individual, we generated 82 WT measurements from various independent sites in the normal aortic wall, with a mean value ($\pm$SD) of 1.03 ± 0.32 mm (Fig. 3). A WT ≥ 2.0 mm (mean + 3 SD) was defined as abnormal. Subsequently, we measured the circumferential extent of the plaque in patients as the number of radial degrees ≥ 2.0 mm WT, with good intraobserver ($r = 0.970$, $p < 0.0001$) and interobserver correlations ($r = 0.77$, $p = 0.0094$). Anatomic landmarks were used for cross-registration between TEE and TEMRI. Planimetry of aortic WT was performed on paired TEE images to determine maximum and minimum values and the extent of abnormal thickening. Comparisons were analyzed by the Bland-Altman method and significance determined by two-tailed paired *t* tests. The reproducibility of measurements was assessed by linear regression analysis.
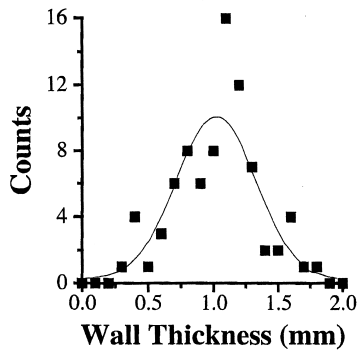
Figure 2. (A–F) Transesophageal magnetic resonance images in humans. **(A,B)** Descending thoracic aortae. **(A)** normal 33-year-old man and **(B)** 57-year-old woman with recent transient ischemic attack demonstrating diffuse and homogeneous thickening. **(C,D)** Distal aortic arch, 77-year-old man with remote stroke, showing heterogeneous **(arrows)** atherosclerotic thickening consistent with intraplaque calcification or hemorrhage. **(C)** Transesophageal magnetic resonance imaging (TEMRI) (repetition time/echo delay time [TR/TE] 1690/15 ms) and **(D)** corresponding transesophageal echocardiography (TEE). **(E)** Normal 33-year-old man. 10-mm-thick sagittal slice through the arch and descending thoracic aorta illustrating the longitudinal imaging range of the device (scout images, fast gradient echo [FGRE] sequence). **(F)** Bland-Altman plot of difference between circumferential extent of abnormal wall thickening assessed by TEE **(a)** and TEMRI **(b)**. Each point represents an individual study patient. The underestimation by TEE is significant by paired *t* test (p = 0.001). Ao = aorta; De = device.

RESULTS

Transesophageal MRI of human thoracic aortae demonstrate the feasibility of the technique in healthy volunteers (Fig. 2A) and among patients with aortic atherosclerosis (Fig. 2B–D). Figure 2C, D shows the corresponding TEMRI and TEE images of the distal aortic arch in a

77-year-old male patient with remote stroke, depicting heterogeneous atherosclerotic thickening, and this illustrates differences in circumferential plaque extent by the two methods. Figure 2E is a longitudinal slice through the descending thoracic aorta and a portion of the arch of a normal subject, demonstrating the nonuniform SNR of the device (9,12). The SNR decreases linearly with radial

Figure 3. Distribution of multiple measurements of aortic wall thickness in normal subjects by transesophageal magnetic resonance imaging. Aortic wall thickness (excluding adventitia) was measured in 82 locations in multiple transesophageal magnetic resonance images from normal subjects using National Institutes of Health Image 1.62 and allowing multiple measurements per individual. The distribution appears Gaussian, with mean = 1.03 mm; standard deviation (SD) = 0.32 mm; mean + 2 SD = 1.67 mm; mean + 3 SD = 1.99 mm. In subsequent subjects, abnormal thickness was arbitrarily defined as mean + 3 SD (i.e., ≥ 2.0 mm). The circumferential extent of disease was defined as the number of degrees (of 360) over which the wall thickness was abnormal.

distance from the probe, but substantially maintains its SNR along much of its length. In practical terms, this property allows TEMRI at multiple longitudinal locations over ~20 cm without the need for repositioning the device.

Maximum and minimum WTs were 3.5 ± 1.2 mm and 1.2 ± 0.8 mm by TEE, and 3.3 ± 1.5 mm and 1.0 ± 0.7 mm by TEMRI, respectively (NS), for the entire patient pool. Although the correlation was good between the two techniques for measurements of circumferential plaque extent (r = 0.77, p = 0.009), relative underestimation of the extent of disease was found by TEE, particularly at the higher range of values as reflected by the Bland-Altman analysis (Fig. 2F). Each point in Figure 2F represents an individual study patient.

The most important limitation of TEE in the quantification of aortic atherosclerosis is further demonstrated in Figure 4, which represents comparisons among TEE, TEMRI and pathology from a cadaver, using an intra-aortic vitamin E–filled balloon catheter as an artificial landmark for image registration. Figure 4 shows that TEMRI allows for evaluation of the aorta over its entire circumference, whereas TEE aortic imaging is hampered by near-field limitations inherent to the ultrasound method. These results further support the observation that TEMRI provides a more accurate measure of aortic circumferential plaque extent than TEE.

DISCUSSION

Feasibility of the TEMRI approach in patients. We have demonstrated the feasibility and potential of high-resolution TEMRI of the thoracic aortic wall and its atherosclerotic lesions in human subjects in vivo. The TEMRI method provided good SNR, allowing for detailed morphologic evaluation of aortic plaques in the descending thoracic aorta and the aortic arch. As opposed to TEE, this technique is not hampered by near-field limitations and artifacts, and it is therefore well suited for imaging the entire aortic wall circumference. The probe is small enough to be introduced transnasally in nonsedated patients. Once positioned, it provides multiple views without further manipulation. Because sedation is not required, the need for additional highly trained conscious-sedation personnel during imaging may prove unnecessary.

Limitations of TEE for aortic plaque imaging. Transesophaseal echocardiography is not ideal for aortic plaque imaging because the aortic wall is not visualized in its 360° entirely due to near-field signal losses. The probe is not a fixed reference point, making TEE an imperfect tool for
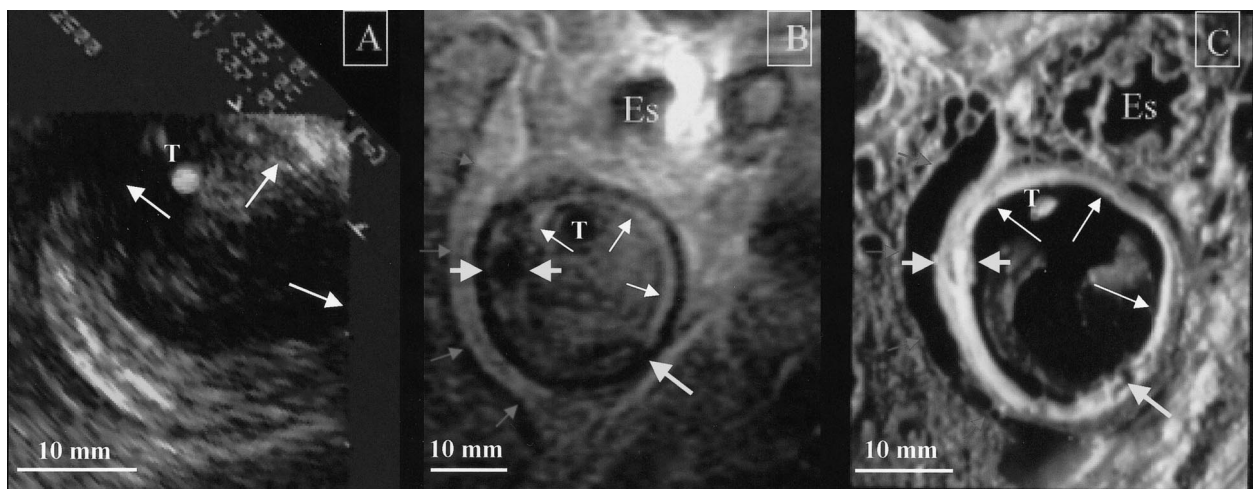
Figure 4. Descending thoracic aorta in a male cadaver with diffuse aortic atherosclerosis. **(A)** transesophageal echocardiography (TEE) (7 MHz) and **(B)** transesophageal magnetic resonance imaging (12-cm field of view, TR 1600 ms, TE 25 ms, 3-mm-slice thickness, 1 NEX, ETL 24) and **(C)** histopathology. The TEE fails to image the entire aortic cross section as demonstrated by the arrows in the three panels. **Small arrows** indicate the same blood vessel as well as other morphologic landmarks, confirming accuracy of the cross-registration protocol. Es = esophagus, T = tip of vitamin E-filled balloon for registration purposes.

plaque burden quantification, particularly in areas with many plaques and few anatomic landmarks. Finally, tissue characterization is poor. Despite these limitations, TEE has been used as a reference for aortic atherosclerosis quantification (6), and it has provided useful information about aortic atherosclerosis (13) and its relationship to cardiovascular clinical events (1–4). In addition, TEE provides readily available data about plaque mobility. In contrast, TEMRI may have several potential advantages over TEE for monitoring plaque behavior. First, it allows imaging in any plane with precise registration to a fixed reference frame. Second, TEMRI has potential for assessment of plaque composition (6–8).

Limitations of the TEMRI technique. The TEMRI technique does have limitations. As opposed to TEE, it is not portable to the patient's bedside and does not currently allow true real-time imaging. Also, if the center does not have an available MRI scanner, the acquisition cost of an MRI machine compared to a TEE probe and ultrasound machine is considerable. The nonuniformity of SNR is another limitation of TEMRI, but is a property shared by TEE. Compared to surface-coil MRI, TEMRI is slightly more invasive and, therefore, carries more potential risk. In principle, TEMRI can be combined with phased-array torso coil MR imaging to further enhance the SNR at the aortic wall. Studies are ongoing to rigorously compare the SNR obtainable at the aortic wall using TEMRI versus the best available phased-array torso coil to determine the incremental benefit of TEMRI over the more conventional MRI technique.

Conclusions. The TEMRI technique is a promising tool for quantification of atherosclerotic plaque extent in the aortic arch and the descending thoracic aorta. Because the entire circumference of the aorta can be visualized at any level and orientation, the relationship of individual plaques to structural landmarks is straightforward, making the technique ideal for serial studies. Its minimally invasive nature and lack of a requirement for sedation, which itself carries additional risks and costs, are additional advantages. Finally, the potential for detailed assessment of plaque composition makes TEMRI an important addition to cardiovascular medicine and clinical investigation.

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