Real-Time Interactive Duplex MR Measurements: Application in Neurovascular Imaging

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OBJECTIVE. Real-time interactive duplex MR imaging is a new phase-contrast MR imaging technique that enables the quantification and display of flow velocities in real time without the need for cardiac gating. We investigated the feasibility and reliability of the technique to assess hemodynamic information both in vitro and in vivo in the carotid arteries and in the venous sinuses.

SUBJECTS AND METHODS. Real-time interactive duplex MR measurements (TR/TE, 53/27; flip angle, 90°; encoding velocity, 100 or 150 cm/sec) were performed in vitro with a steady-flow phantom and in 10 healthy volunteers in whom common and internal carotid artery velocities were measured. In eight volunteers, velocity measurements were also performed in the superior sagittal sinus during both normal breathing and hyperventilation. Time–velocity plots were analyzed qualitatively and quantitatively and compared with findings from conventional segmented k-space phase-contrast MR imaging and Doppler sonography.

RESULTS. Velocity determinations for real-time duplex MR and conventional phase-contrast MR imaging showed an in vitro correlation of 0.99 and an in vivo correlation of 0.83 (carotid arteries) and 0.76 (venous sinus). Velocity measurements in the carotid arteries with real-time MR imaging were significantly lower than those obtained with conventional phase-contrast MR (averaged, 7.8%; $p = 0.003$) or sonography (23.7%, $p < 0.001$), likely because of volume averaging. Small but significant velocity changes occurring in the venous sinus during hyperventilation were reliably identified with both MR techniques.

CONCLUSION. Real-time interactive duplex MR imaging can be effectively applied in neurovascular imaging to obtain hemodynamic information.

Phase-contrast MR imaging is based on the application of a bipolar gradient-pulse pair producing a phase shift that depends on the velocity component along the gradient. It has been shown that flow velocities can be accurately determined by this technique [1]. In neurovascular applications, MR flow-quantification techniques have most often been applied to evaluate the carotid arteries [2–6], intracranial arteries [7, 8], and venous sinuses [9, 10]. In routine clinical practice, however, MR flow quantification is rarely applied. Reasons for this omission include the need for cardiac gating and requirements for high temporal resolution to evaluate pulsatile flow patterns. These considerations lead to long measurement times, particularly when fast sequences with techniques such as segmented k-space or view-sharing [11] are not available. The long acquisition times of MR imaging have precluded interactive operation with online data evaluation, useful features of Doppler sonography.

Our study evaluated a new ungated real-time MR phase-contrast technique that quantifies and displays flow velocities in real times. The sequence uses a two-dimensional selective radiofrequency pulse followed by flow-sensitizing gradients with an echoplanar readout. It provides the simultaneous display in real time of both an anatomic image for positioning and the through-plane flow-velocity data. Flow velocities are displayed as time–velocity curves, closely resembling Doppler flow-velocity distribution plots. By controlling scan position and orientation interactively, one can optimize flow signal. This technique has been termed duplex MR imaging because of its similarities to sonography [12].

We have evaluated duplex MR imaging in vitro with a constant-velocity pump and then applied it in healthy volunteers to measure flow velocities and to evaluate velocity waveforms. Measurements in the common carotid artery and in the internal artery were correlated with conventional phase-contrast MR flow

Received January 26, 2001; accepted after revision March 14, 2001.

S. Wetzel was supported in part by Swiss National Science Foundation/Karger Stiftung and by Novartis Stiftung.

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AJR 2001;177:703–707

0361–803X/01/1773–703

measurements and Doppler sonographic measurements. Flow velocities in the superior sagittal sinus were measured by real-time duplex MR imaging and phase-contrast MR imaging during both normal breathing and hyperventilation to decrease blood flow velocity.

Subjects and Methods

Phantom Study

Velocity measurements were performed on a steady-flow phantom. The phantom consisted of a straight plastic tube of 0.7-cm inner diameter with circulating water maintained by a constant-rate flow pump. Using the quadrature head coil, we measured velocities with the conventional phase-contrast sequence and independently by two investigators with real-time duplex MR imaging. Image sequence details were identical to those used in volunteer subjects. Real-time duplex MR measurements were compared with conventional phase-contrast measurements over the range of constant flow velocities from 26 cm/sec to 108 cm/sec, with 108 cm/sec representing the maximum velocity reliably achievable by the pump system.

Study Subjects

Ten healthy volunteers (eight men, two women; 25–80 years old; mean age, 31.4 years) were examined with MR imaging and Doppler sonography to measure flow velocities in the carotid arteries within an hour. In eight subjects, MR flow velocities of the superior sagittal sinus were determined during normal breathing and after 3 min of hyperventilation of room air. Written informed consent was obtained from all volunteers, and the study was sanctioned by the institutional review board.

MR Imaging

All examinations were performed on a 1.5-T clinical imaging system (Quantum; Siemens, Erlangen, Germany), equipped with high-performance gradients (maximum gradient strength, 30 mT/m; rise time, 240 µsec). MR-compatible ECG leads were placed on the subject's back before the examination.

The imaging protocol followed by sequence details is described. For measurements of the carotid arteries, a four-element phased-array neck coil was used. Guided by localizer images, we scanned the carotid bifurcation with an axial two-dimensional time-of-flight MR angiography sequence. Conventional phase-contrast MR measurements were performed 2–3 cm below and above the carotid bifurcation in the common and internal carotid artery as seen on the time-of-flight MR source images. Acquisition was in the axial plane, which was perpendicular to the direction of blood flow. Only one coil element was activated for real-time interactive duplex MR measurements because processing and combining images from two or more elements significantly reduced temporal resolution. Duplex MR measurements were made as close as possible to the same position as the conventional phase-contrast measurements. For measurements of the superior sagittal sinus, the quadrature head coil was used. The sinus measurements were made just above the confluens sinuum, identified from conventional axial scout images, and orientated perpendicular to the blood-flow direction. Conventional phase-contrast MR and real-time interactive duplex MR measurements were first performed during normal breathing. Then volunteers were asked to hyperventilate room air for 3 min, after which conventional phase-contrast MR measurements were performed. After a break of a few minutes, hyperventilation was repeated for 3 min, and real-time interactive duplex MR measurements were performed.

Sequence parameters were as follows: axial two-dimensional time-of-flight MR angiography (TR/TE, 30/9.8; flip angle, 45°; field of view, 150 × 200; matrix, 146 × 256; matrix slice thickness, 3 mm; slices centered around the carotid bifurcation, 40) was performed with venous presaturation. With the ECG-triggered cine phase-contrast sequence (31.8/3.4; flip angle, 30°; field of view, 150 × 300 mm; matrix, 96 × 256: slice thickness, 8 mm; encoding velocity, 100 or 150 cm/sec), we measured 19–25 cardiac phases on the basis of each subject's heart rate, beginning immediately after the R wave. The real-time duplex MR imaging sequence (53/27; flip angle, 90°; slice thickness, 8 mm; field of view, 98 × 314 mm; matrix, 30 ×128; encoding velocity, 100 or 150 cm/sec perpendicular to the image plane; temporal resolution, 53 msec) consisted of a two-dimensional selective radiofrequency pulse followed by flow-sensitizing gradients and an echoplanar readout (Fig. 1). The two-dimensional excitation selected a rectangular column, 8 mm in the slice-select direction by 98 mm in the phase-encoding direction. This column can be phase-encoded with good spatial resolution and without aliasing, with relatively few phase-encoding lines. Data were processed and displayed on the console in real time in a two-part display, consisting of a magnitude image and the time–velocity plot (Fig. 2). The plot showed a total of the most recent 128 acquisitions and scrolled right with each scan. The scanning plane was positioned interactively with a six-degree-of-freedom input device (SpaceMouse; Logitech, Fremont, CA). Flow information was calculated from a 2 × 2 pixel region of interest at the image center, and velocity measurements were calculated and displayed for each of the four pixels. After the real-time duplex MR sequence was started, the target vessel was moved into the center of the region of interest with the input device. When the vessel was centered and the characteristic waveform was observed consistently over a few seconds, care was taken not to alter the scan position. On average, 400–800 acquisitions were obtained for measurement of a single vessel, resulting in acquisition times of 20–40 sec for a single vessel.

Sonography

Immediately after the MR examination, subjects underwent bilateral carotid sonography (Aspen; Acuson, Mountain View, CA) in the supine position, with a broadband (5–10 MHz) linear transducer. Gray-scale and Doppler color-flow examinations of the common carotid arteries and the internal carotid arteries were performed in all subjects. Doppler spectral waveforms were obtained in the distal common carotid artery and in the internal carotid artery beyond the bulb widening, approximately 2–3 cm below and above the carotid bifurcation. We performed the measurements using angle correction and the measured angle of insonation was kept less than 60º for all measurements. Absolute peak systolic velocities were recorded with the use of electronic calipers. The radiologist performing sonography was unaware of findings on MR imaging.

Image Analysis

The radiologist who performed the duplex MR study determined peak systolic velocities from real-time duplex MR imaging, using an electronic caliper at the MR console (Fig. 2). The radiologist was not aware of the results on sonography or on phase-contrast MR imaging. We analyzed conventional phase-contrast data on a Sparc 5 workstation (Sun Microsystems, Palo Alto, CA), using software developed in-house in the IDL programming language (Research Systems, Boulder, CO). The program identified the pixel with the maximum peak velocity in each vessel and plotted velocity values over the cardiac cycle.

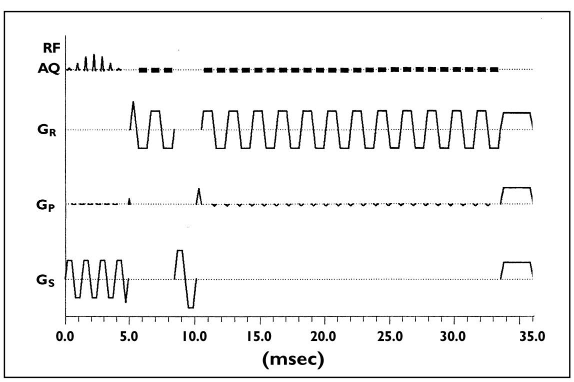
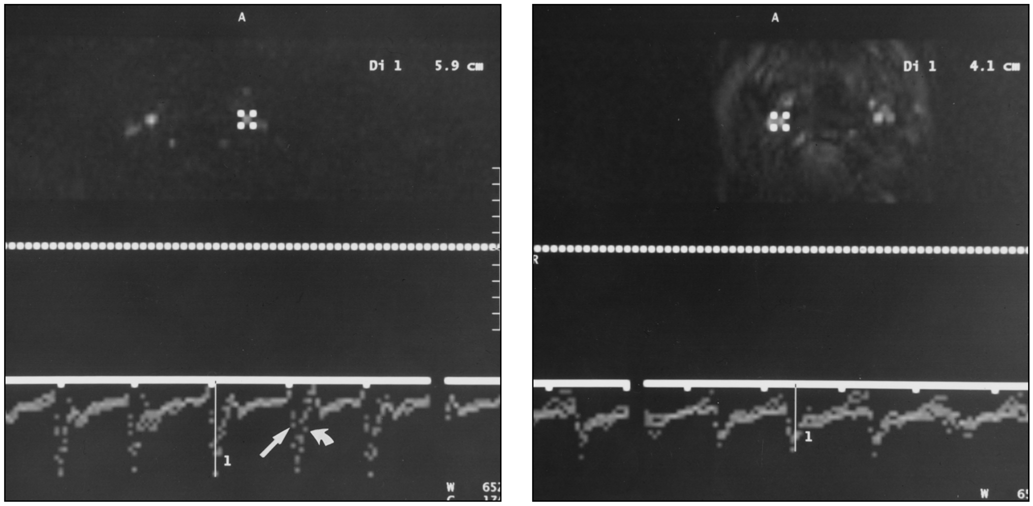


Fig. 1.—Line drawing shows real-time duplex flow-evaluation sequence, consisting of two-dimensional spatial radiofrequency (RF) excitation pulse, followed by bipolar flow-encoding and echoplanar readout gradient pulses. Note that during selective RF pulse, slice and phase-encoding gradients are applied to select column that subsequently can be encoded with few phase-encoding steps and without aliasing. AQ = Acquisition, G_R = readout gradient, G_p = phase-encoding gradient, G_S = slice select gradient.



A B

Fig. 2.—Normal duplex MR study of carotid arteries in 36-year-old healthy male volunteer.
A, MR image as displayed online by real-time duplex MR imaging (encoding velocity, 100 cm/sec) shows measurement of common carotid artery. At top, magnitude image is displayed. Four white circles indicate region of interest containing four voxels placed over left common carotid artery. Time–velocity plot at bottom reveals flow that is directed caudocranially below baseline. Baseline tick interval is 1 sec; gap on baseline indicates current point of measurement. Distance from baseline to systolic peak represents peak systolic velocity, depending on velocity encoding. Using encoding velocity of 100 cm/sec, we measured 5.9 cm with an electronic caliper (*vertical line*) that represents peak systolic velocity of 73.75 cm/sec. Note sharp systolic upstroke (*straight arrow*) and downstroke (*curved arrow*), characteristic of normal common carotid artery flow.
B, MR image shows measurement of right-sided internal carotid artery, for which vessel is shifted by input device under region of interest as marked by four white circles in center of image. Time–velocity plot shows less acute downstroke and persistent end-diastolic flow. Peak systolic velocity is slightly lower, with 4.1 cm (*vertical line*) representing 51.25 cm/sec.

Statistical Analysis

Velocity determinations in the phantom and in the superior sagittal sinus as measured by conventional phase-contrast MR imaging and real-time duplex MR imaging and velocity measurements in the phantom by two independent radiologists using real-time duplex MR imaging were compared with a paired two-tailed Student's *t* test. We applied a paired two-tailed Student's *t* test, using the Bonferroni adjustment, to evaluate differences in the peak systolic velocities between real-time duplex MR imaging, conventional phase-contrast MR measurements, and sonography for the carotid arteries.

The Bland-Altman method was used to describe quantitatively the agreement between the three techniques for velocity measurements. Linear regression analysis was also performed to compare velocities measured by real-time duplex MR imaging, phase-contrast MR imaging, and sonography and to compare in vitro real-time duplex MR velocity measurements made by two independent radiologists.

For the two-tailed paired Student's *t* test, *p* values of less than 0.05 were considered significant, and for the Bonferroni *t* method, *p* values of less than 0.01 were considered significant.

Results

Phantom Studies

For constant flow measurements in vitro, real-time MR velocities (v_{RT}) and conventional phase-contrast velocities (v_{PC}) were related linearly,

$$v_{RT} = 0.87\ v_{PC} + 7.25,$$

with $r = 0.99$. Real-time MR velocities over six velocity steps (range, 26–108 cm/sec) were on average (± SD) 2.37 ± 4.34 cm/sec lower than phase-contrast velocities ($p = 0.24$), whereby the difference increased with increasing velocities measured. When we considered interobserver variability, the mean difference between real-time MR velocities determined by two investigators was 1.05 cm/sec with a standard deviation of 2.19 cm/sec ($r = 0.99$; $y = 0.93x + 5.64$; $p = 0.30$).

Flow Evaluation in the Carotid Arteries

In all subjects, time-of-flight MR angiography and sonography showed normal-appearing carotid arteries. The time required for real-time duplex MR imaging was 30–40 min at the beginning of the study and dropped with experience to about 10 min.

The locations of velocity measurements in the common carotid artery with conventional phase-contrast MR and real-time duplex MR averaged 2.31 ± 0.8 cm and 2.22 ± 0.76 cm below the carotid bifurcation, respectively, and for the internal carotid artery, 2.59 ± 1.26 and 2.05 ± 0.8 cm above the bifurcation. The averaged difference between measurement positions was 0.1 ± 1.3 cm, indicating reasonably good agreement ($p = 0.79$).

Velocity waveforms depicted by real-time duplex MR imaging and Doppler sonography were qualitatively similar. In the common carotid artery, a sharp systolic upstroke and little end-diastolic flow was observed. In the internal carotid artery, the waveform resembled low resistance arterial flow with substantial persistent end-diastolic flow (Fig. 2). Doppler sonographic measurements of peak systolic velocities for the common and internal carotid artery were well correlated with both real-time duplex MR imaging ($r = 0.83$) and phase-contrast MR imaging ($r = 0.75$) (Fig. 3). However, compared with sonographic measurements, significantly lower velocity determinations were obtained with both real-time duplex MR imaging (mean difference, 19.8 ± 15.1 cm/sec, representing 23.7%; $p < 0.001$) and with phase-contrast MR measurements (mean difference, 14.5 ± 17.5 cm/sec, representing 18.3%; $p < 0.001$). The two MR measurements were well correlated, but flow velocities determined with duplex MR imaging were significantly lower ($r = 0.85$; mean difference 5.4 ± 10.8 cm/sec representing 7.8%; $p = 0.003$).

Flow Evaluation in the Superior Sagittal Sinus

Real-time duplex MR imaging showed a slow pulsatile flow pattern in the distal superior sagittal sinus in the craniocaudal direction (Fig. 4). Flow velocities measured by phase-contrast MR imaging and real-time duplex MR imaging showed a correlation of 0.76. Conventional phase-contrast MR measurements were on average 2.84 ± 5.1 cm/sec higher than real-time duplex MR velocity determinations ($p = 0.04$). Peak velocity for real-time duplex MR imaging determined during normal breathing in eight volunteers averaged 30.52 ± 6.81 cm/sec and dropped to 19.7 ± 2.8 cm/sec after 3 min of hyperventilation. The corresponding values for phase-contrast MR imaging were 32. 0 ± 8.0 cm/sec and 24.3 ±

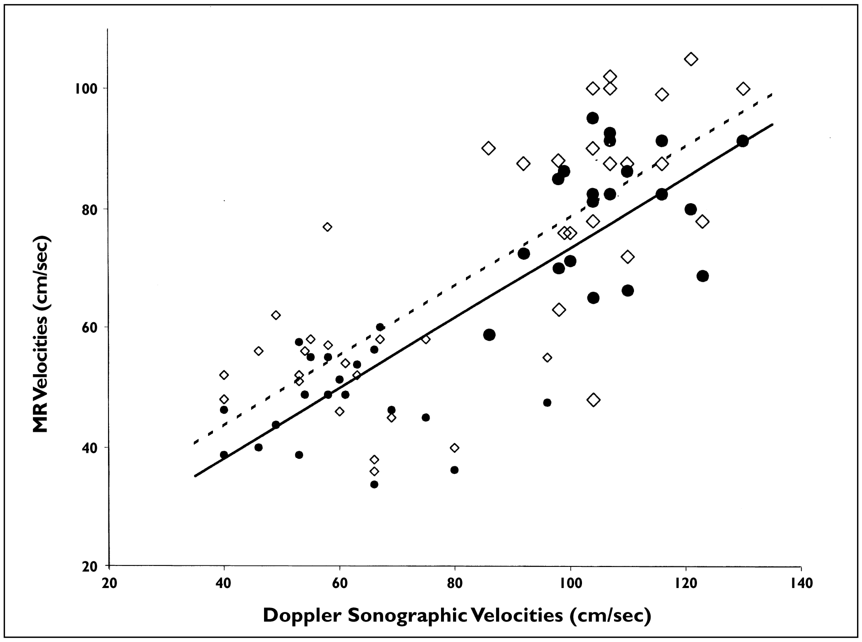


Fig. 3.—Graph shows correlation of Doppler sonography with duplex MR imaging (large ● = common carotid artery; small ● = internal carotid artery; solid line = regression line, with $y = 0.59x + 20.2$; $r = 0.83$) and phase-contrast MR imaging (large ◊ = common carotid artery; small ◊ = internal carotid artery; dashed line represents regression line with $y = 0.58x + 14.6$; $r = 0.75$) for measurements in carotid arteries. Note that velocities as determined by sonography (x-axis) are on average higher compared with both MR imaging methods (y-axis) and that conventional phase-contrast measurements are, on average, higher than duplex MR measurements.

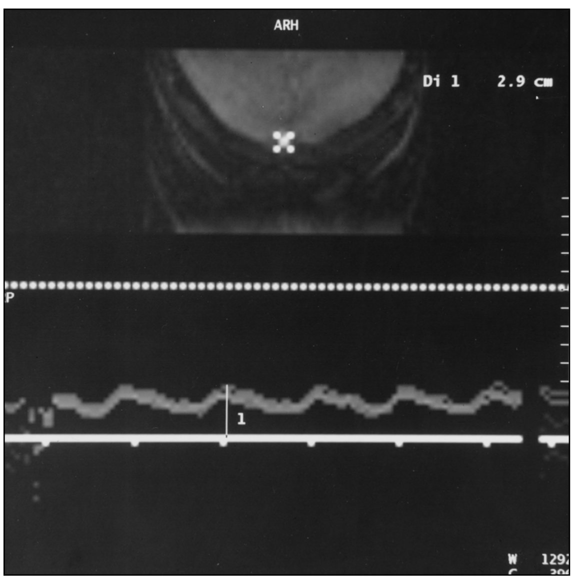


Fig. 4.—Normal duplex MR imaging of superior sagittal sinus in 34-year-old healthy female volunteer. Real-time duplex MR image (encoding velocity, 100 cm/sec) shows measurement of superior sagittal sinus (region of interest indicated by four white circles) during normal breathing. Note slow pulsatile flow with peak systolic velocity of 36.25 cm/sec. Craniocaudally directed flow is displayed above baseline.

5.3 cm/sec. For both methods, the drop in velocity was significant ($p < 0.01$).

Discussion

With practice, real-time duplex MR imaging proved a relatively simple and reliable method to obtain hemodynamic information from the carotid arteries and the superior sagittal sinus. It can be used to obtain directional flow information, to identify characteristic flow patterns over the cardiac cycle, and to quantify hemodynamic information, such as the peak systolic velocity.

Comparison with Conventional Phase-Contrast MR Imaging

Flow velocities determined by real-time duplex MR imaging showed an excellent correlation with phase-contrast measurements in a steady-state flow phantom and good correlation in in vivo measurements. The measurement of small velocity differences in the superior sagittal sinus before and after hyperventilation shows the high sensitivity of the technique in vivo. However, on average, real-time duplex MR velocity measurements were lower than those obtained with conventional phase-contrast MR imaging. This difference might, in part, be explained by the larger voxels used with real-time duplex MR imaging, leading to a greater averaging of flow velocities. This view is supported by the observation that the difference in flow velocities was more evident in higher velocities in which the effect of averaging between flow in the center of a vessel and at its margin is greater than that at slow velocities.

Our phase-contrast measurements of peak flow velocities in the common and internal carotid artery were in good accordance with findings reported by Vanninen et al. [2]. Our velocity determinations in the superior sagittal sinus were in good accordance with measurements of Mattle et al. [13], who used a bolus-tagging time-of-flight technique. However, Mehta et al. [10], who used a conventional phase-contrast technique, found velocities in the mid superior sagittal sinus for volunteers during normal breathing of about 15 cm/sec. These lower velocity determinations in the superior sagittal sinus might be explained because their velocity determinations were averaged over the entire vascular lumen. In our study, the phase-contrast data were postprocessed to identify the pixel with the highest velocity in the vessel area. Furthermore, our velocity determinations were performed in a more distal part of the sinus.

The real-time duplex MR sequence used in this study gives a temporal resolution of almost 20 velocity determinations per second, comparable to the temporal resolution of the conventional phase-contrast MR technique used.

However, with real-time duplex MR imaging, pulsatile flow patterns can be measured without cardiac gating. The application of the technique is, therefore, simplified, and hemodynamic information can be obtained in cases in which satisfactory cardiac gating is impossible, such as in patients with arrhythmias. The real-time display of velocity has two additional advantages: first, flow velocities can be measured instantly without postprocessing, unlike those required for conventional phase-contrast MR imaging. Second, adjustments in sampling or measurement location can be made in real-time as with Doppler sonography.

On the other hand, at the beginning of this study, the overall time needed to perform flow measurement was longer for real-time MR imaging than for phase-contrast MR measurements. The primary reason was the lack of experience in controlling the MR scanner interactively with a six-degree-of-freedom device. In our study population, the straight axial plane was almost perpendicular to the course of all vessels investigated. However, improved control of the scan orientation would be desirable for reliable flow measurements in tortuous vessels and in all vessels with an anatomic oblique flow direction. To have instantaneous feedback of the current scan position and orientation, it would probably be advantageous to see the current position on a three-dimensional MR angiography data set. We believe these changes would reduce examination time to a few minutes. The current real-time duplex MR imaging technique does not evaluate volumetric flow rates, although processing modifications may allow such measurements in the future. Finally, real-time duplex MR measurements can generate a large number of images, affecting storage capacity. To reduce this problem, images with cumulative data for over 100 acquisitions (as shown in the figures) could be selectively saved.

Comparison with Sonography

Real-time duplex MR imaging has several advantages over Doppler sonography in neurovascular applications. First, the absence of the sound propagation problems allow its use in cases in which the presence of bone or air cavities precludes the application of sonography. Although it is possible, for example, to insonate the rostral part of the superior sagittal sinus through a transtemporal window, the anterior and mid portions of the superior sagittal sinus cannot be assessed [14, 15]. Second, the free choice of scan-plane orientation eliminates angulation errors that are common in sonographic measurements. Finally, flow measurements can be made in conjunction with high-resolution anatomic MR imaging and MR angiography and do not require a second procedure.

Real-time duplex MR imaging represents a trade-off between the flow-sampling rate and the spatial resolution. This study was performed with a lower spatial resolution than that of the phase-contrast MR scans. This difference might be the major reason that velocity measurements were lower than those with the conventional phase-contrast MR imaging technique; this observation holds true, even to a higher degree, for the comparison with duplex sonography. The lower velocity measurements with phase-contrast MR imaging compared with sonographic measurements were also described by Vanninen et al. [2]. For accurate velocity measurements in stenotic arteries or smaller vessels with real-time duplex MR imaging, improved spatial resolution would be needed without loss of temporal resolution. This improvement might be accomplished by application of faster k-space encoding schemes (e.g., elliptic k-space acquisition schemes).

In conclusion, real-time duplex MR imaging can be considered a promising tool for assessment of flow velocities in the carotid arteries and venous sinuses. From a technical standpoint, further improvements in implementation of the technique are necessary. Studies should be performed to determine the utility of the technique in neurovascular diseases such as carotid stenosis and dural venous sinus thrombosis.

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