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Fast Selective Black Blood MR Imaging[1]

To overcome the problems associated with gradient-echo (GRE) magnetic resonance (MR) angiography ("bright blood" imaging) and "black blood" imaging with presaturated spin-echo (SE) pulse sequences, the authors devised a new approach for black blood imaging. Their method, selective preinversion fast imaging with steady precession (turboFISP), uses a segmented GRE sequence for fast data acquisition. Nulling of vascular signal results, and stationary tissue appears bright. The method was compared with flow-compensated GRE imaging in a phantom and with GRE imaging and presaturated SE imaging in seven healthy volunteers and nine patients with various cardiac diseases. With phantoms, the selective preinversion turboFISP sequence produced better flow contrast than did GRE sequences. Selective preinversion turboFISP was often superior to SE imaging for depicting vessel lumina, particularly in patients with slowly flowing blood. Arteries appeared dark in selective black blood angiograms, but veins did not. Selective preinversion turboFISP can be used with bright blood GRE imaging to depict vessel lumina, and its capability for image acquisition within a breath hold and with cardiac gating minimizes artifacts from respiration and motion of the vessel wall.

Index terms: Aneurysm, aortic, 561.74, 981.731 • Blood vessels, MR studies, 17.1214, 90.1299, 94.1299 • Carotid arteries, stenosis or obstruction, 172.1214 • Lung, abnormalities, 60.145 • Magnetic resonance (MR), pulse sequences • Magnetic resonance (MR), vascular studies, 17.1214, 90.1299, 94.1299

Radiology 1991; 181:655–660

MAGNETIC resonance (MR) angiography, although only recently developed, has already come into widespread clinical use. It has been used to screen for intracranial aneurysms (1) and to evaluate stenoses of the extracranial carotid arteries (2). Other clinical applications of MR angiography such as evaluation of the portal venous system (3) are under development.

Phase-contrast and time-of-flight methods make flowing blood appear bright (4,5). These "bright blood" methods tend to result in overestimation of vascular stenoses because of turbulence-induced dephasing and/or saturation from stasis or recirculation (6). To overcome this problem, a "black blood" method that used thin-section spin-echo (SE) acquisitions and flow presaturation was proposed (7,8). Although the results to date have been promising, the method has several deficiencies. These include relatively long imaging times (typically 5–10 minutes), motion sensitivity, imperfect flow void in the setting of very slow flow, and inability to distinguish arteries from veins on the basis of vascular signal.

We have developed a new approach for flow imaging, which is a modification of a segmented ultrafast gradient-echo (GRE) sequence. The method, which we call selective preinversion fast imaging with steady precession (turboFISP), produces black blood images in a fraction of the time required by SE methods. To determine whether the method has advantages over other types of MR angiography, we compared the selective preinversion turboFISP sequence with flow-compensated GRE sequences in a flow phantom and with SE and GRE sequences in healthy subjects and patients with vascular disease.

SUBJECTS AND METHODS

Pulse Sequence

The purpose of the selective preinversion turboFISP method is to null vascular signal on the basis of blood T1 but not reduce the signal intensities of stationary tissues. To accomplish this, a 180° radiofrequency (RF) pulse is applied nonselectively to invert the longitudinal magnetization of all tissues. A section-selective 180° pulse is then immediately applied so that the longitudinal magnetization of in-plane tissues is returned to equilibrium. An inversion time (TI) is allowed to elapse prior to data acquisition. During this time interval, in-plane blood leaves and is replaced by blood from outside the section. The inflowing blood has only been affected by the first, nonselective 180° pulse; the longitudinal magnetization of these protons is therefore inverted, as with a standard inversion recovery sequence. If the correct TI is chosen, data (in particular, at the zero phase-encoding step) are acquired when the longitudinal magnetization of the inflowing blood is nearly zero, so that vascular signal is nulled.

For selective black blood images of arteries, the section-selective 180° pulse is applied over a much thicker volume that encompasses inflowing venous structures as well as the plane of section. As a result, inflowing venous blood as well as in-plane stationary tissues appear bright.

After TI, data are acquired by using a segmented ultrafast GRE sequence as previously described (9,10). A fast imaging with steady precession sequence is used (repetition time [TR], 8 msec; echo time, 5 msec). Data is acquired in eight segments of 32 phase-encoding steps each, with an

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Abbreviations: C/N = contrast-to-noise ratio, FISP = fast imaging with steady precession, GRE = gradient echo, RF = radio frequency, SE = spin echo, S/N = signal-to-noise ratio, TI = inversion time, TR = relaxation time, turboFISP = selective preinversion fast imaging with steady precession.

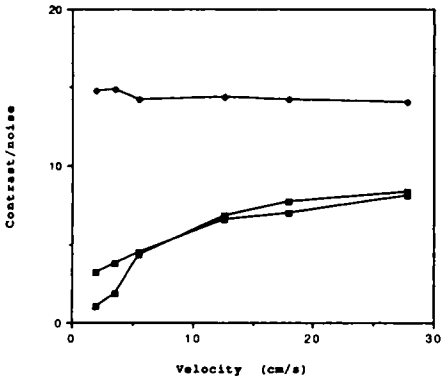
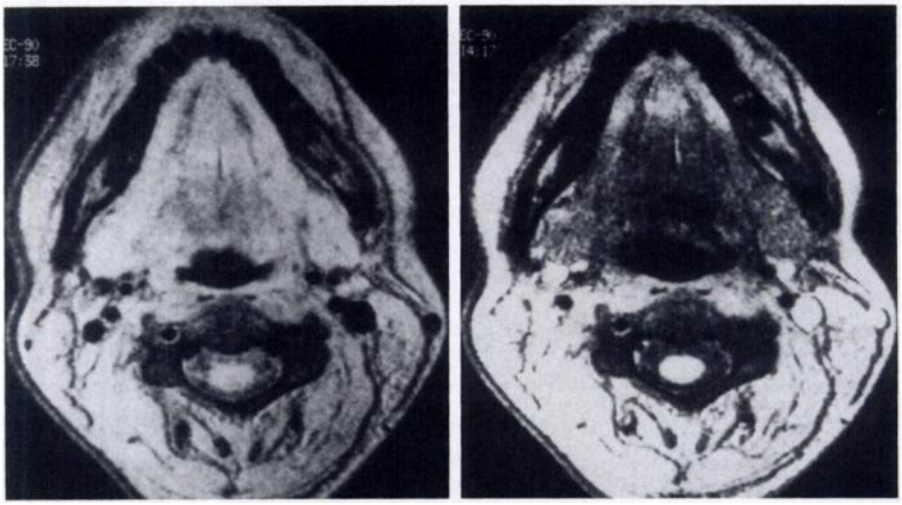


Figure 1. Absolute value of flow C/N versus velocity in phantom study for GRE (■), GRE with presaturation (⊡), and selective preinversion turboFISP (◆) sequences. Note that the flow C/N with preinversion turboFISP imaging is independent of velocity over the range tested.



a. **b.**

Figure 2. Axial 5-mm-thick sections through neck of healthy 25-year-old female volunteer. Imaging parameters include a 256 × 256 matrix, 21 × 21-cm field of view, 1,800-msec TR, and 475-msec TI. Total imaging time was 15 seconds. **(a)** Section-selective 180° pulse applied to plane of section results only in signal voids within all vessels. **(b)** Thick (50-mm) selective 180° pulse applied obliquely to include inflow from jugular veins and intracranial venous sinuses (but not from the carotid arteries) shows signal voids within arteries, whereas veins appear bright. Because the 180° pulse did not affect the anterior soft tissues, they appear dark.

operator-selected time delay between segments to permit T1 relaxation, which yields a 256 × 256 matrix. The selective preinversion turboFISP pulse sequence can be summarized as $180°_{t}$ (nonselective) — $180°_{-t}$ (section-selective) — TI — (excitation pulse — signal readout) $_{Np=32]Ns=8}$, where *Np* is the number of phase-encoding steps per segment and *Ns* is the number of segments.

A key feature of the method is that the excitation flip angle is incremented for each of the 32 phase-encoding steps within a segment (11). For our purposes, the goal is to maximize the flip angle at the zero phase-encoding step, which primarily determines signal-to-noise ratio (S/N) and contrast-to-noise ratio (C/N). A large, constant flip angle would quickly saturate the tissues well before the zero phase-encoding step; use of an incremented flip angle avoids this problem.

Phantom Study

The selective preinversion turboFISP method was tested in a flow phantom with circulating copper sulfate solution with a T1 of 820 msec. An infusion pump (Harvard Apparatus, South Natick, Mass) was used to circulate the fluid within polyvinyl chloride tubing (Norton Plastics, Akron, Ohio), and peak flow velocities were varied from 2 cm/sec to 30 cm/sec. The peak velocities were measured by means of a bolus tracking method (12). The tubing, coiled within the magnet bore to allow the circulating fluid to become equilibrated, was surrounded by stationary fluid with a T1 of 540 msec.

To minimize the signal from fluid within the tubing, TI was adjusted empirically by using no flow and a TR of 1 second. This value for TI was then used for all phantom experiments. The selective preinversion turboFISP method was compared with a flow-compensated GRE sequence (30/10; flip angle, 30°) with and without flow presaturation. Imaging was performed with a 1.5-T unit (Magnetom; Siemens, Iselin, NJ). Imaging parameters included a 3-mm section thickness, a 20-cm field of view, and 256 × 256 matrix. An axial plane of section perpendicular to the direction of flow was used. Signal intensities within the circulating fluid were determined by using standard region-of-interest measurements; the background was measured in air above the tubing along the phase-encoding direction. Flow C/N was calculated as | circulating fluid signal − stationary fluid signal | /1 standard deviation of the background signal.

Patient and Volunteer Studies

Seven healthy subjects and nine patients were studied (mean age, 62 years; age range, 32–80 years). Diagnoses in the nine patients included internal carotid artery stenosis ($n = 1$), type A and B dissecting aortic aneurysms ($n = 3$), atherosclerotic abdominal aortic aneurysms ($n = 3$), intracardiac thrombus ($n = 1$), and pulmonary sequestration ($n = 1$). The same sequence used in the phantom study was used in studies of patients and volunteers.

For studies of patients and most volunteers, a TR of 1,800 msec and TI of 475 msec were chosen for the selective preinversion turboFISP sequence. Fields of view were 20–42 cm and section thicknesses were 3–5 mm. A variety of flip angle series were tested in healthy volunteers. Images of the neck, chest, and abdomen were acquired during breath holding. Electrocardiographic gating was used during breath-hold cardiac imaging. The selective preinversion turboFISP technique differed slightly in that only 16 segments were acquired (one per R-R interval) with eight phase-encoding steps per segment, which yielded a matrix of 256 × 128. Imaging times were approximately 8–16 seconds.

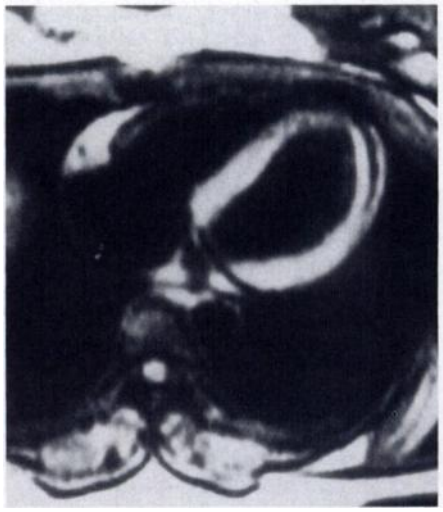
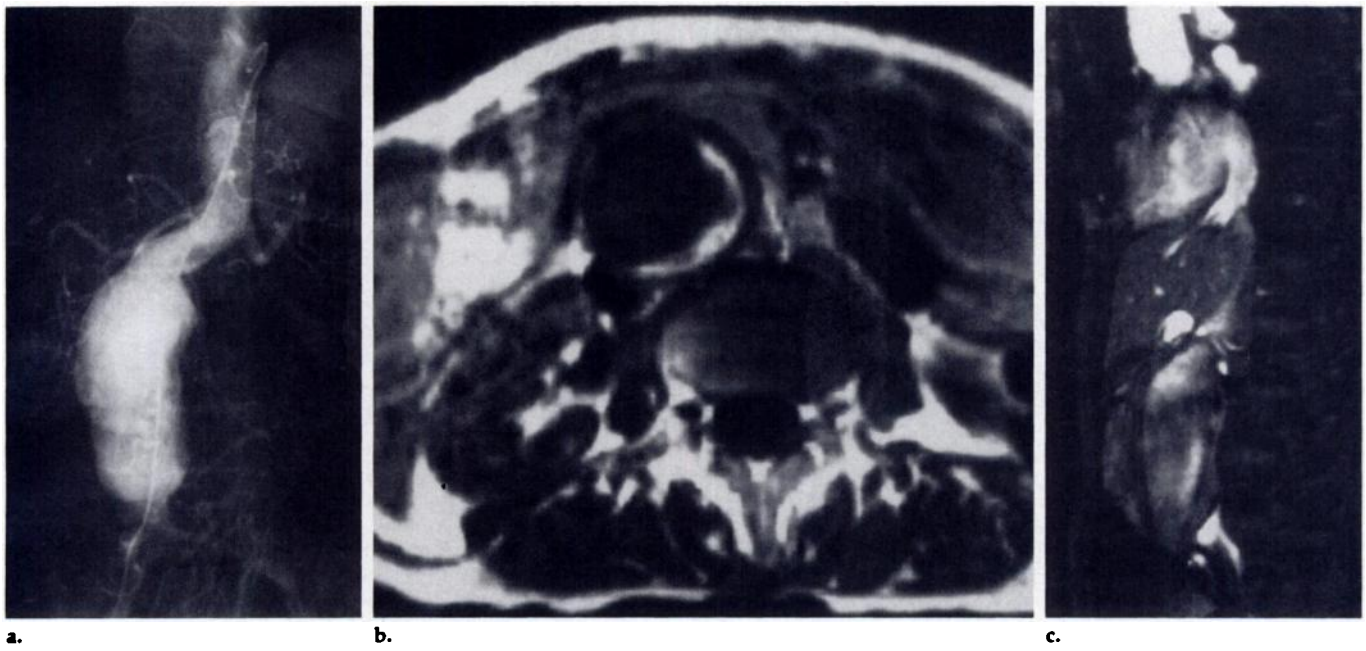
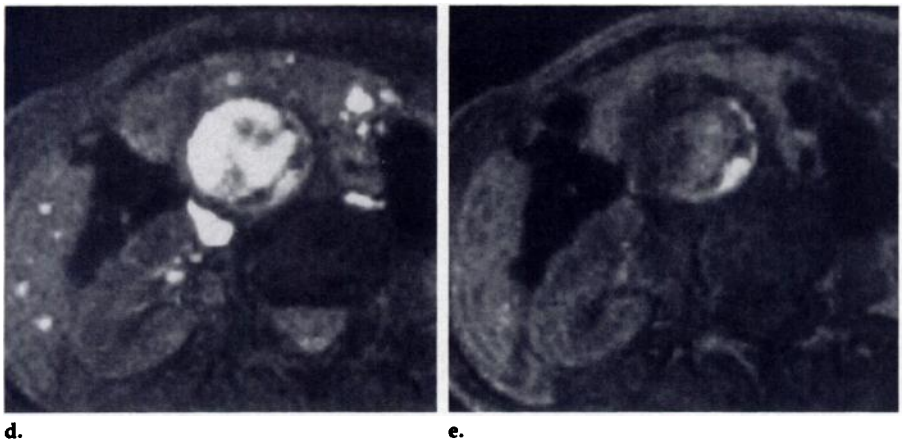


Figure 3. Selective preinversion turboFISP image obtained in a 32-year-old male volunteer. Image was obtained during 14-second breath hold with electrocardiographic gating (70 beats per minute), section thickness of 7 mm, 256 × 128 matrix, and a 40 × 40-cm field of view. Image was obtained at the midventricular level during diastole. Signal intensity of the cardiac chambers is low, but the signal intensity of myocardium is high.

SE images (500–1,000/15–20) were obtained by using a section thickness of 5 mm, two to four acquisitions with 256 × 128 or 256 × 256 matrix, a field of view of 38–44 cm, and parallel presaturation of inflowing blood. For presaturation, computer-optimized 2.56-msec RF pulses with rectangular section profiles and flip angles of 90° were applied. The presaturated regions were 50 mm thick; the edge of each





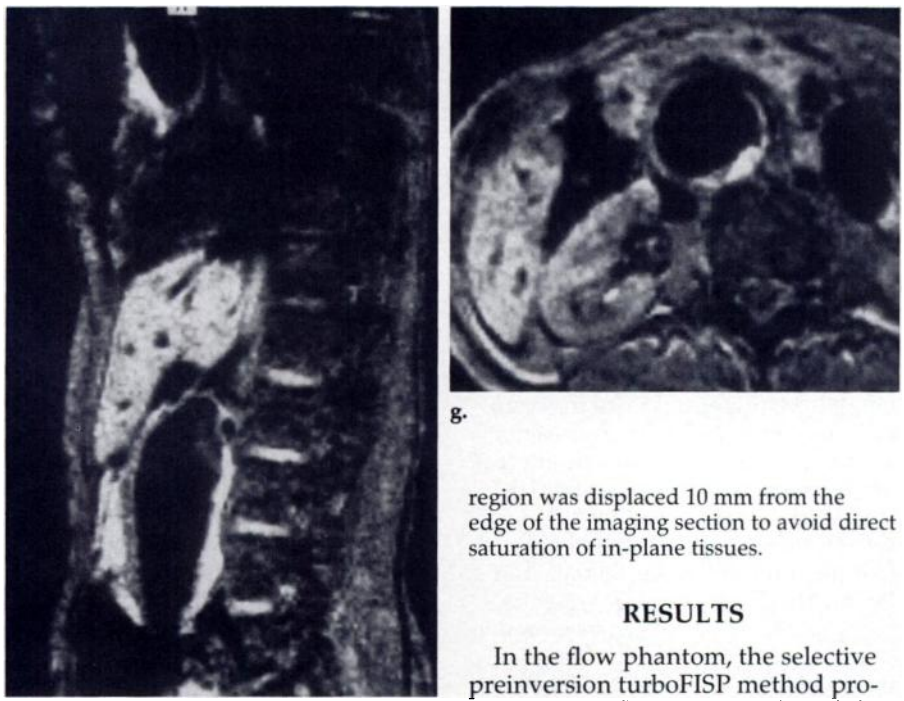


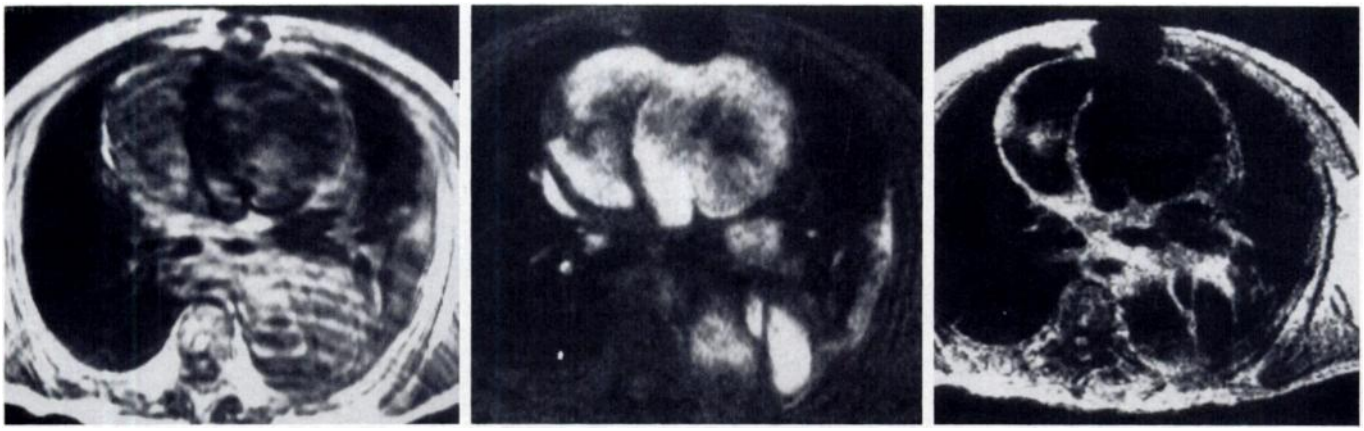
Figure 4. Images obtained in a 68-year-old female patient with saccular abdominal aortic aneurysm with slow, turbulent flow. **(a)** Conventional angiogram in frontal projection. **(b)** Axial SE image with parallel presaturation (400/15, 256 × 192 matrix, 44 × 44-cm field of view, 5-mm section thickness) obtained in approximately 4 minutes shows high signal intensity within mural thrombus but intermediate signal intensity within aneurysm lumen. **(c)** Sagittal breath-hold flow-compensated GRE image (25/8, 30° flip angle, 5-mm section thickness, 256 × 256 matrix, and 40 × 40-cm field of view) shows a confusing mixed signal intensity pattern within the aneurysm lumen, which is caused by a complex flow pattern. **(d)** Same parameters as in **c**, axial image. Persistent low-signal-intensity regions can be seen within the lumen. **(e)** Same parameters as in **d**. Parallel presaturation fails to eliminate signal intensity of flowing blood within the lumen. **(f)** Sagittal selective preinversion turboFISP image (256 × 256 matrix, 40 × 40-cm field of view, 1,800-msec TR, and 475-msec TI) shows nearly perfect signal void within the lumen of the aneurysm. Total imaging time was 15 msec. **(g)** Same parameters as in **f**, axial plane. Mural thrombus can be easily distinguished from flowing blood. Detail of the wall and thrombus is better than shown on GRE images.

region was displaced 10 mm from the edge of the imaging section to avoid direct saturation of in-plane tissues.

RESULTS

In the flow phantom, the selective preinversion turboFISP method produced better flow contrast than did the flow-compensated GRE sequences obtained with or without presaturation (Fig 1). This difference was most pronounced at low flow velocities. Flow contrast was independent of flow velocity from 2 to 30 cm/sec with the selective preinversion turboFISP method but was strongly velocity-dependent with use of GRE sequences.

The best results with selective preinversion turboFISP imaging were



a. b. c.

Figure 5. MR images obtained in a 73-year-old male patient with complex triple-barreled type A thoracic aortic dissection. **(a)** SE image with parallel presaturation (400/15, 256 × 192 matrix, 36 × 36-cm field of view, 5-mm section thickness) obtained in approximately 4 minutes is difficult to interpret due to persistent intravascular signal. Signal void from sternal wires is present anteriorly. **(b)** Axial breath-hold flow-compensated GRE image (25/8, 30° flip angle, 5-mm section thickness, 256 × 256 matrix, and 40 × 40-cm field of view) shows mixed signal intensity within ascending aorta and in one of two false lumina of the descending aorta due to extremely low flow velocity. **(c)** More precise evaluation is obtained with a breath-hold axial selective preinversion turboFISP image (256 × 256 matrix, 44 × 44-cm field of view, 1,800-msec TR, and 475-msec TI). Only a small persistent focus of signal intensity is seen within the lumen of the ascending aorta.

obtained by incrementing the flip angle by 2° from 10° to 68°. The S/N obtained with the incremented flip angle series was two to three times better than that achieved with a constant flip angle of 15°.

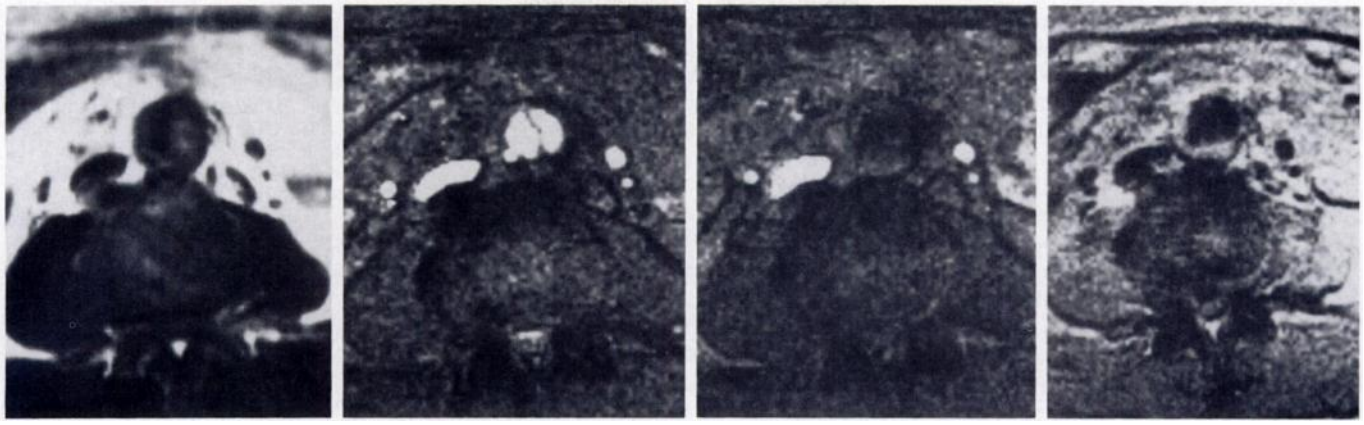
Selective preinversion turboFISP images obtained in healthy volunteers showed a uniform flow void and were free of respiratory artifacts. Selective preinversion turboFISP images of the neck could be obtained with all vessels dark or with veins bright and arteries dark, depending on whether the section-selective 180° pulse included inflowing venous blood (Fig 2). Selective preinversion turboFISP images of the heart obtained with electrocardiographic gating showed excellent contrast between bright myocardium and cavitary flow voids (Fig 3).

In patient studies, SE images were of variable quality because of ghost artifacts from respiratory motion and persistent intravascular signal on some sections despite the use of flow presaturation above and below the plane of section. On SE images obtained in patients with aortic dissection or aneurysm (Figs 4–6), blood flow could not be reliably differentiated from thrombus. On the other hand, good flow contrast was seen in all of these cases when selective preinversion turboFISP and flow-compensated GRE sequences were used. In one patient with a large dissection of the ascending aorta and one with an abdominal aortic aneurysm, differentiation of thrombus from regions of intermediate signal intensity resulting from slow flow was difficult with GRE images. This differentiation was easier with selective preinversion turboFISP images, which showed only minimal residual intravascular signal. In a patient with an angiographically proved pulmonary sequestration fed from the lower thoracic aorta, differentiation of flowing blood from high signal intensity areas of mucoid impaction was easier and more reliable with selective preinversion turboFISP images than with GRE images (Fig 7). Ghost artifacts from bowel peristalsis occasionally were seen on selective preinversion turboFISP images that included overlapping abdominal vessels, which caused substantial intraluminal signal intensity.

DISCUSSION

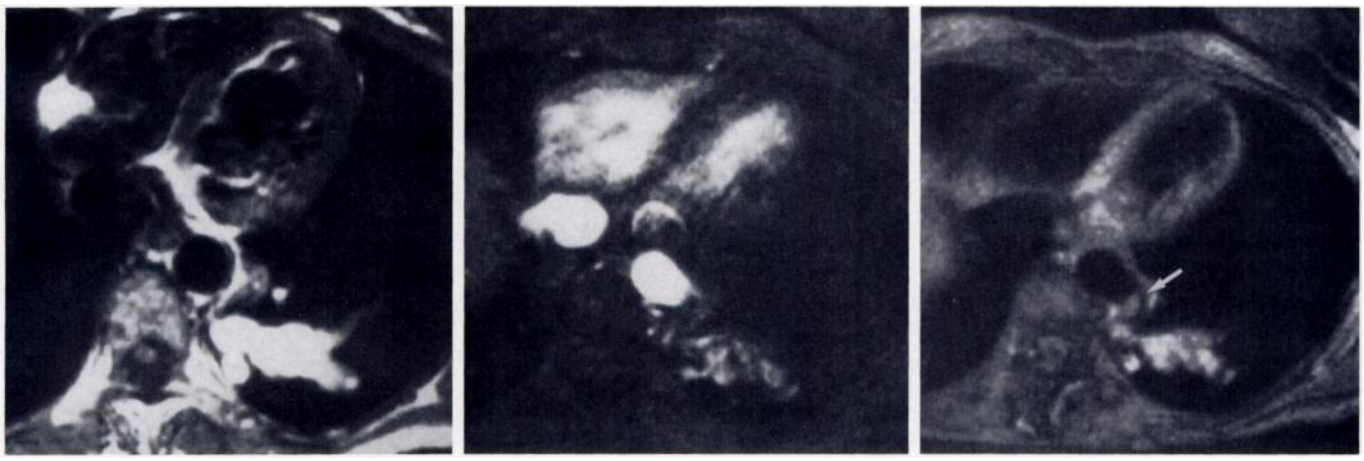
Our results indicate that the selective preinversion turboFISP method is a fast, effective means for creating black blood images and, compared with other methods, is less sensitive to motion artifacts and more effective for rendering a uniform flow void. The relative insensitivity of selective preinversion turboFISP to abnormal flow patterns is attributed to the prolonged period for inflow of inverted protons. For blood to produce signal with this sequence, it must be affected by the second, section-selective 180° pulse and remain within the plane of section for the entire TI period plus half the duration of data acquisition (ie, the time to the zero phase-encoding step). With a TI of 475 msec and 32 phase-encoding steps per segment, this total time is approximately 600 msec. For a section thickness of 5 mm and flow perpendicular to the plane of section, only blood flowing at less than approximately 1 cm/sec should produce any substantial signal. For a 3-mm section, the threshold velocity decreases to 5 mm/sec. Of course, with the segmented approach, not all the phase-encoding steps within a segment can be acquired when the signal intensity of blood is completely nulled. It is not necessary, however, to null the blood signal over the entire segment, since the zero phase-encoding step provides the dominant contribution to C/N and S/N.

Presaturation is a valuable method for decreasing vascular signal intensity in SE imaging, but it is substantially less reliable than selective preinversion turboFISP imaging. The signal intensity of presaturated blood recovers as it flows from the presaturated region into the imaging volume. A true flow void, therefore, may not be obtained, particularly in the setting of slow or recirculating flow that occurs distal to vascular stenoses or in patients with aortic aneurysms. With standard sequences, one may have difficulty distinguishing blood flow from thrombus (Fig 5a). Use of an inversion-recovery pulse sequence for eliminating vascular signal from the cardiac chambers has previously been described (13). With this method, however, stationary tissues such as muscle are also affected by the inversion pulse, which could cause contrast between blood and muscle to be relatively weak because of their similar T1s. This problem is not encountered with selective preinversion turboFISP, because the signal intensity of



a. b. c. d.

Figure 6. MR images obtained in a 64-year-old male patient with type B thoracic aortic dissection. **(a)** SE image (400/15, 256 × 192 matrix, 40 × 40-cm field of view, 5-mm section thickness) with parallel presaturation suggests a thrombosed false lumen on the left side. **(b)** Axial GRE image (25/8, 30° flip angle, 5-mm section thickness, 256 × 256 matrix, and 40 × 40-cm field of view) clearly shows patency of false lumen and ulceration on right posterior wall of aorta. Plaque along the aortic wall appears dark. **(c)** Parallel presaturation in same section as **b** fails to create a uniform flow void. **(d)** Selective preinversion turboFISP image (256 × 256 matrix, 44 × 44-cm field of view, 1,800-msec TR, 475-msec TI) similarly shows true and false lumina; plaque along the aortic wall appears bright.



a. b. c.

Figure 7. MR images obtained in a patient with pulmonary sequestration above the left diaphragm. **(a)** Axial electrocardiographically gated SE image shows high signal intensity from inspissated mucus within the lesion. **(b)** Axial GRE image (25/8, 30° flip angle, 5-mm section thickness, 256 × 256 matrix, and 40 × 40-cm field of view) presents confusing appearance; mucus and flowing blood both appear bright. **(c)** On the axial selective preinversion turboFISP image (256 × 256 matrix, 40 × 40-cm field of view, 1,800-msec TR, 475-msec TI), flowing blood is dark and mucus is bright. Note the small feeding vessel (arrow) arising from the aorta. This finding was confirmed with conventional angiography.

stationary tissues is not substantially altered by the technique.

The selective preinversion turboFISP sequence proved complementary to GRE sequences. Slow flow may have an intermediate signal intensity on GRE images, which could cause difficulty in differentiation from thrombus; this differentiation is easily made with selective preinversion turboFISP images, because flowing blood appears dark and thrombus appears bright. This differentiation can also be made by using phase-sensitive imaging methods, which were not evaluated during this study (14).

In one previously described approach for black blood imaging (7), thin-section SE acquisition with presaturation was used. Although that method is reasonably effective, relatively long imaging times are required, and it is not amenable to breath holding. In several patients evaluated with this approach, there was persistent signal within the lumen of an aortic aneurysm or dissection (Figs 4–6). Better results might have been obtained by modification of the imaging parameters (eg, changing the flip angle of the presaturation pulse or the delay between presaturation and RF excitation). Even with such modifications, however, the fundamental limitation remains: Slowly flowing blood exiting the presaturated region remagnetizes after moving just a few centimeters, so that intravascular signal is not suppressed further downstream.

Another problem with thin-section SE acquisition relates to the use of a minimum-intensity postprocessing method to create projection angiograms. Because arteries and veins appear dark on SE images, overlap may be difficult to avoid in a projection angiogram. On the other hand, one can render arteries as dark structures and other tissues including veins as bright by using selective preinversion turboFISP; in this case, only arteries would be included in the minimum-intensity projections.

The selective preinversion turboFISP method may also prove useful for cardiac imaging, since it can be difficult to obtain a uniform flow void within the cardiac blood pool by using SE sequences. One could null the

blood pool by using a standard inversion-recovery sequence with cardiac gating. Because myocardium and blood have similar T1s (on the order of 800–1,200 msec), however, a TI that nulls blood will also tend to result in poor myocardial signal and therefore poor flow contrast. Stimulated echo acquisitions can also be used to eliminate signal from the blood pool (15), but the method suffers from limited S/N.

The selective preinversion turboFISP method has potential limitations. If blood is flowing so slowly or recirculation is so severe that blood remains within or returns to the plane of section over periods of 600 msec or longer, signal-emitting blood will be imaged. As with GRE sequences, flow contrast will be best if the plane of section is perpendicular to the direction of flow. Apparent intravascular signal can also arise from nonvascular sources; bowel peristalsis in particular can create ghost artifacts that overlap the vessel lumen. One could apply the selective preinversion technique by using a single-shot approach to overcome this problem, at the expense of S/N and spatial resolution. In cardiac imaging, translation of myocardium originally within the section but out of the section during the time between the section-selective 180° RF pulse and the central phase-encoding step remains a problem. The use of k-space segmentation also requires good eddy current compensation and a stable RF transmitter to avoid image artifacts.

In conclusion, the selective preinversion turboFISP sequence is a new method for flow imaging that is much more effective than presaturation for creating flow voids. Motion artifact is minimal because of the fast data acquisition. The method may be particularly useful for evaluating vascular lesions that produce complex flow patterns, such as aortic aneurysms and dissections, and for distinguishing slow flow from vessel occlusion. The capability for creating selective black blood images of arteries may simplify image interpretation and postprocessing for black blood MR angiography. ■

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