Blood MR Signal Suppression by Preexcitation with Inverting Pulses[1]

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A cardiac-gated sequence has been developed for functional cardiac imaging. It uses a nonselective 180° preinverting pulse before a spin-echo (SE) readout sequence with an echo time (TE) of 28 msec. In seven healthy volunteers this sequence provided superior wall-to-chamber contrast in end diastole and end systole when compared with the following sequences: SE, TE = 28 msec; SE, TE = 28 msec with dephasing gradients; and SE, TE = 28 msec with presaturation bands.

Index terms: Blood, MR studies • Heart, MR studies, 51.1214 • Magnetic resonance (MR), contrast enhancement • Magnetic resonance (MR), pulse sequences

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FUNCTIONAL cardiac imaging relies on accurate assessment of chamber volumes in both end diastole and end systole. Unfortunately, at these two points in the cardiac cycle, spin-echo (SE) magnetic resonance (MR) images may contain a variable amount of signal intensity from captured intracavitary blood. This makes reliable differentiation of the interface between the chamber wall and blood difficult, if not impossible. In addition, motion artifacts arising from slowly flowing blood propagate in the phase-encoding direction and may significantly obscure other regions of the image. Thus, signal intensity from captured intracavitary blood is a major impediment to functional MR imaging of the heart (1).

The excellent wall-to-lumen contrast seen in SE cardiac images is caused by the familiar flow void. Although the intrinsic signal available from blood on SE images is high, much of this signal is lost in the presence of significant blood velocity (2). Therefore, we see flow voids in midsystolic images in which blood velocities are high. However, in end diastole or end systole, there is often slowly moving or stationary blood, which results in high signal intensity.

Previous attempts to augment the flow void have utilized presaturation of inflowing spins (3) and dephasing gradients. Alternately, second-echo refocusing (4) and phase maps (5) have been suggested as techniques to evaluate for the presence of slow flow, which is inadequate to create a flow void. All of these methods require a minimum flow velocity that may not be satisfied at either end diastole or end systole, when blood may be stationary. In addition, presaturation sequences are sensitive to the direction of flow. While this is useful in distinguishing arterial and venous flow peripherally, it is a major problem in the heart, where multidirectional flows occur.

For these reasons we have developed a new cardiac-gated pulse sequence that takes advantage of the difference in spin-lattice relaxation time (T1) between blood and chamber wall at 0.15 T. This new sequence generates low signal intensity from blood independent of flow velocity. This results in excellent contrast between the chamber wall and blood regardless of the phase of the cardiac cycle, and it will allow for more accurate evaluations of end diastole and end systole.

Materials and Methods

All studies were performed on a 0.15-T superconducting MR imaging system (Picker, Cleveland). After informed consent was obtained, seven healthy volunteers (mean age, 30 years; range, 22–42 years) were imaged in the transverse plane at the middle left ventricular level with a single section sequence. Sections were 1 cm thick and acquired on a 256 × 128 matrix with four averages and a 45-cm field of view. All sequences were cardiac gated, with the sequence initiated 16 msec after the R wave, corresponding to end diastole. Acquisition time per section was heart-rate dependent and ranged from 6.4 to 12.5 minutes. Three conventional sequences were performed; SE, echo time (TE) = 28 msec; SE, TE = 28 msec with balanced dephasing gradients (0.5 G/cm in three planes); and SE, TE = 28 msec with 4-cm-wide presaturation bands on either side of the imaging plane. A 16-msec delay after the R wave was necessary in the presaturation sequence to allow for the application of the presaturation bands. It is present in the other sequences to ensure that all the images were obtained at the same time. Since isovolumetric contraction lasts for approximately 50 msec after the R wave (6), all images were acquired in end diastole.

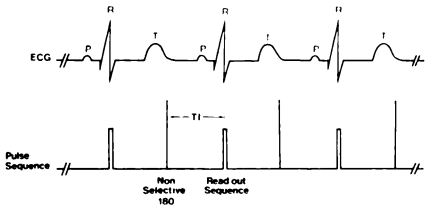

Figure 1. Timing diagram for the preinversion sequence shows the nonselective 180° pulse applied a time TI before the SE, TE = 28 msec readout sequence in an end-diastolic image. *ECG* = electrocardiogram.

A fourth experimental protocol (preinversion sequence) was also evaluated. In this sequence, a nonselective 180° preinversion pulse is applied approximately 500 msec before a conventional SE, TE = 28 msec readout sequence. The purpose of the preinversion pulse is to minimize the signal from blood while retaining signal from the wall. The SE, TE = 28 msec sequence is initiated 16 msec after the R wave (Fig 1), and the preinversion pulse is timed from the preceding R wave. For this reason the time (TI) between the preinversion pulse and the SE, TE = 28 msec readout sequence is heart-rate dependent. The sequence is designed to be modified at the time of imaging to accommodate different cardiac rates while keeping TI at approximately 500 msec. Small changes in the cardiac rate did not significantly affect image quality.

In all subjects at least two TIs were used. In one subject nine TIs ranging from 200 to 650 msec were used in two imaging sessions. Regions of interest from subcutaneous fat, cardiac muscle, and blood were measured in this subject as a function of TI. T1 relaxation times were then estimated by fitting to the relation $S(TI) = S_0(1 - 2e^{-TI/T1} +$

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$e^{-TR/T1}$), where S_0 was a fitted constant and TR was the repetition time (R-R interval) (7).

In two of the seven subjects systolic time intervals were calculated by means of echocardiography, and they were imaged on the same day with the sequence being placed accurately at end systole.

Captured intracavitary signal was evaluated by measuring a mean signal intensity from a large region of interest (349 pixels) within the left ventricle. An average value for cardiac muscle was obtained from three small regions (21 pixels each) taken in the septum, left ventricular apex, and free wall (variation of wall measurements, 10%–20% about the mean). The ratio of these two measurements (wall/chamber) was used as an index of wall-chamber differentiation for each of the different sequences. Motion-induced noise in the phase-encoding direction was assessed by using the ratio of intensities from a large region of interest above the heart (350 pixels) and a similar region above the right axilla (350 pixels) that was free of displaced signal.

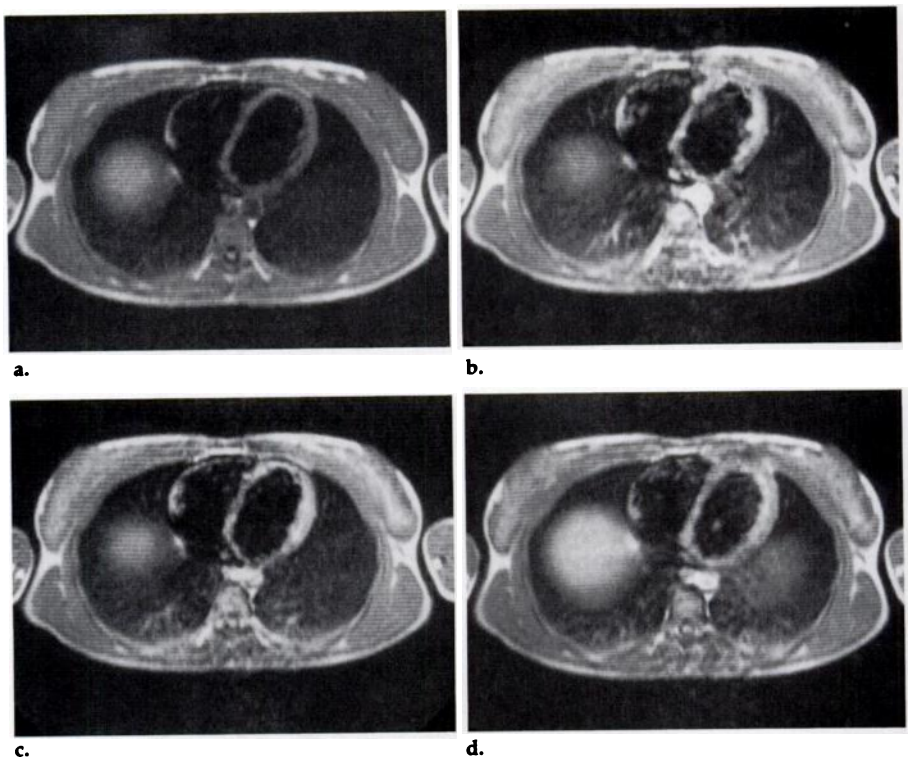


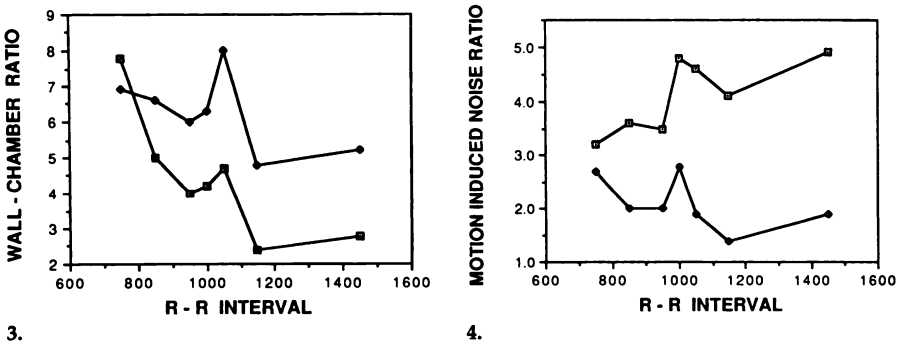
Figure 2. Transverse end-diastolic images demonstrate superior wall-chamber differentiation and less phase-induced noise for the preinversion sequence **(a)** compared with the SE, TE = 28 msec **(b)**, dephasing gradient **(c)**, and presaturation **(d)** sequences.

Results

In all cases, the preinversion sequence provided excellent wall-blood differentiation (Fig 2). The plot of the wall-chamber ratios as a function of the heart rate in each of the seven subjects (Fig 3) demonstrates that the preinversion sequence is clearly superior to the standard SE, TE = 28 msec sequence, especially for subjects with lower heart rates. Ratios for dephasing gradients and presaturation sequences were erratic and always lower than those obtained with the preinversion sequence. The preinversion sequence also has substantially less motion-induced noise at all heart rates (Fig 4). However, it also has the greatest attenuation of heart muscle signal, when all sequences are compared with those obtained with the standard SE, TE = 28 msec sequence.

Variation of the preinversion delay TI in the preinversion sequence provided T1 relaxation data for fat, cardiac muscle, and blood. The data for subcutaneous fat, which was relatively motionless and had high signal intensity, were fitted with a T1 of 163 msec. This is in good agreement with accepted values (8) and demonstrates that normal variations in the R-R interval over an imaging sequence do not have a large effect on the measured T1 values. The observed T1s of cardiac muscle (310 msec) and blood (640 msec) were also consistent with literature values at 0.15 T (8).

Images taken precisely at end systole showed similar results (Fig 5).



Figures 3, 4. **(3)** Graph of wall-chamber ratio as a function of heart rate shows superior wall-chamber differentiation for the preinversion sequence at lower heart rates. ⊡ = SE, TE = 28 msec sequence, ● = preinversion sequence. **(4)** Graph of the ratio of motion artifact in the phase-encoding direction above the heart to background above the axilla for different heart rates. This indicates less motion-induced noise for the preinversion sequence.

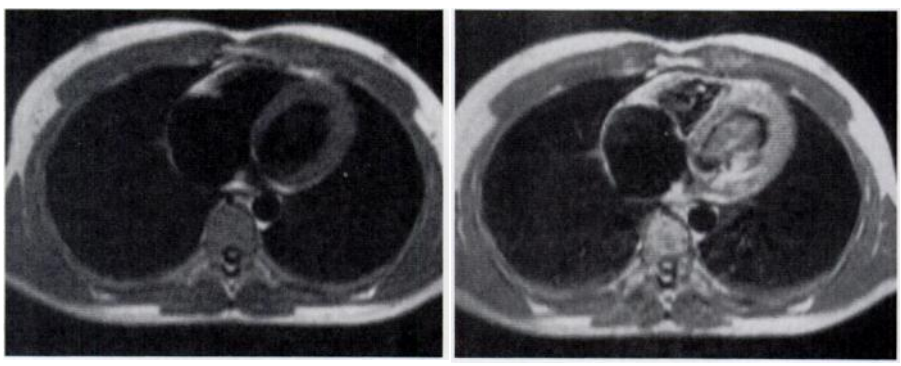


Figure 5. Superior wall-chamber differentiation of preinversion sequence **(a)** compared with SE, TE = 28 msec sequence **(b)** at end systole.

Discussion

Captured intracavitary blood signal has been a major impediment to cardiac imaging, especially in the functionally important phases of end diastole and end systole. The preinversion sequence resolves this problem by eliminating blood signal independent of blood velocity.

A variety of factors influence blood signal intensity in cardiac SE images: (*a*) signal attenuation due to flow out of the selected section, (*b*) signal attenuation due to motion-induced destructive phase interference within a voxel, (*c*) misregistration in the phase-encoding direction due to motion-induced phase shifts, and (*d*) signal enhancement due to unsaturated blood flowing into the image section. Turbulent and multidirectional flow in the heart chambers produce a complex combination of these factors in cardiac SE images. Dephasing gradients decrease signal from moving blood due to *b* but still cause motion-related noise in the phase-encoding direction due to *c* and are ineffective for stationary blood. Presaturation sequences attenuate signal from blood flowing into the section (per *d*) but have no effect on flow within the image plane or on stationary blood.

Our approach has been to employ a method that depends not on flow but rather on the different T1 relaxation times of cardiac muscle and blood at 0.15 T. The strategy of the preinversion sequence is to suppress the blood signal to a value below that of the wall by acquiring the image when the blood signal is close to a null following the preinversion 180° pulse. It can be shown that the optimum TI value for wall-to-chamber differentiation is 450–550 msec and is relatively independent of the R-R interval. The preinversion sequence is necessarily a compromise between nulling the signal from blood and retaining sufficient wall signal for chamber evaluation.

Although the optimal TI value for the preinversion sequence is, in principle, heart-rate independent, at short R-R intervals there may be insufficient time to apply the preinversion pulse. Fortunately, our data indicate that at high heart rates (>80 beats per minute) flow effects alone are sufficient to eliminate blood signal, making use of the preinversion sequence unnecessary (Fig 3).

In this pulse sequence development study we have limited ourselves to single-section techniques. However, this pulse sequence can be extended to limited multisectioning by taking advantage of the range of TI values (approximately 125 msec) in which there is adequate chamber-to-wall differentiation. Depending on the acquisition time per section of the imager, two or more sections could be obtained at multiple levels following a single leading preinverting pulse. Preliminary results on our system indicate that three 1-cm sections can be obtained within 120 msec of the R wave with good blood signal suppression. An additional constraint in multisection functional imaging is the approximately 50-msec isovolumetric period of end diastole and end systole (6).

In conclusion, the preinversion sequence is a useful addition to cardiac SE imaging, especially in the important phases of end diastole and end systole, and will result in more accurate functional quantification. ■

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