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Cineangiography of the Heart in a Single Breath Hold with a Segmented TurboFLASH Sequence[1]

Six healthy volunteers and three patients with cardiac anomalies were studied in a comparison of segmented turboFLASH (fast low-angle shot) cine, a method of magnetic resonance imaging that permits an entire series of high-resolution cine images to be obtained in one breath hold, with standard cine. Segmented turboFLASH uses a gradient-echo sequence designed for short imaging times in combination with a segmented data acquisition method. Presaturation pulses were applied to eliminate the blood pool signal; the signal-to-noise ratio was assessed with a phantom. Standard hardware and image reconstruction methods were used. The breath-hold images consistently showed reduced ghosting and blurring from respiration. Because a very short echo time was used, segmented turboFLASH was relatively insensitive to dephasing caused by local field disturbances or flow. The authors conclude that, by reducing imaging times and eliminating respiratory artifact, segmented turboFLASH can be useful for performing cine studies of the heart and great vessels.

Index terms: Heart, MR studies, 51.1214 • Magnetic resonance (MR) cine study • Magnetic resonance (MR), technology, 51.1214

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OVER the past few years, considerable technical progress has been achieved in the field of cardiac magnetic resonance (MR) imaging. New features include multiphase/multisection cine capability (1,2), retrospective cine (3), and arbitrary angulation (4). Techniques such as ultrafast gradient-echo (eg, turbo-FLASH [fast low-angle shot]) (5,6) and echo-planar imaging (7) have progressed to the point that a cardiac image can be produced during one R-R interval. For cardiac imaging, single-shot turboFLASH has relatively poor temporal resolution (typically ≥ 300 msec per image on standard whole-body systems), and echo-planar imaging requires special hardware. Our goal was to develop an imaging technique that could produce a high-resolution cine series by using existing hardware within a single breath-hold period.

MATERIALS AND METHODS

Images were obtained with a 1.5-T whole-body system (Magnetom 63SP; Siemens Medical Systems, Iselin, NJ) with conventional gradients and a circularly polarized body coil. The standard cine used a velocity-compensated FLASH sequence with an echo time (TE) of 8 or 10 msec and a flip angle of 30°. Gating was performed prospectively with the R wave as the trigger signal. The minimum imaging time for the standard cine was 128 heartbeats for a 128 × 256 matrix; typically two signals were averaged because single-excitation images often showed prominent motion artifacts.

Standard and breath-hold studies were obtained in an axial or short axis orientation with a rectangular field of view (typically 320 × 450 mm or smaller). The in-plane resolution for these examinations was approximately 2.5 × 1.8 mm, or 4.4 mm^2 for a 256 × 128 matrix. For both sequences, the section thickness was 8-10 mm.

To increase the amount of data that could be obtained during each R-R interval, a segmented k-space approach was used, as has been described recently (8).

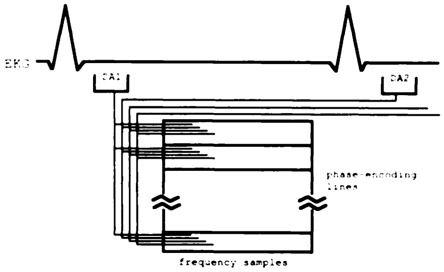

Figure 1. Map of k-space demonstrates the process of segmented data acquisition for two of 16 segments. Each segment has a 50-msec acquisition window (*DA1* for segment 1, *DA2* for segment 2), with eight phase-encoding steps. For each segment, every 16th line is acquired sequentially. The acquisition shown is for one phase; up to 20 phases can be acquired for an R-R interval of 1 second.

The data were acquired with a FLASH sequence (repetition time [TR] msec/TE msec = 6.2/3.6). The acquisition was divided into 16 segments; each segment consisted of eight phase-encoding steps. Every 16th step of k-space was filled in sequence; thus, the first segment consisted of lines 1, 17, 33, and so on; the second segment of lines, 2, 18, 34, and so forth. By interleaving the raw data sets from these segments (Fig 1), a 128 × 256 matrix required only 16 heartbeats. The acquisition window per segment was 50 msec. For a single section position, up to 20 cardiac phases were possible within a 1,000-msec R-R interval. The data were reconstructed with standard two-dimensional Fourier transform methods to produce the images; reconstruction time was 1 second per image. No filtering, radio-frequency (RF) prepulses, or spoiling was applied. For the initial optimization study, 10°, 20°, 30°, and 50° flip angles were tested. A flip angle of 10° or 11° was then used for all studies. For presaturation, an additional 90° RF pulse was applied at the beginning of each segment, followed by an 8-mT/m spoiler gradient of 2-msec duration.

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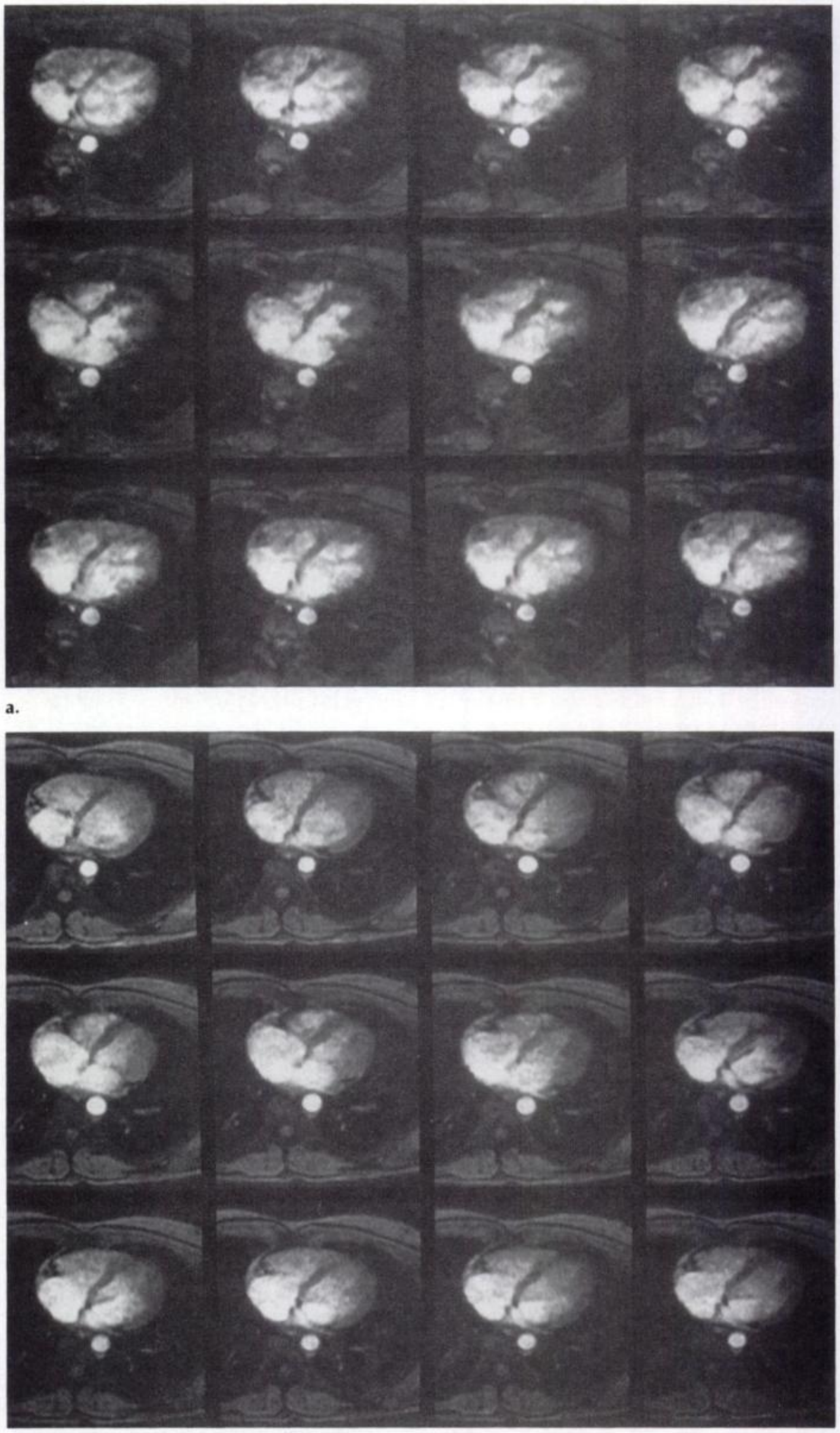
Abbreviations: FLASH = fast low-angle shot, RF = radio frequency, S/N = signal-to-noise ratio, TE = echo time, TR = repetition time.

Figure 2. Images of a healthy subject. All electrocardiogram-gated cine studies used 12 phases (R-R = 750 msec), one signal average, 256 × 128 acquisition matrix, and 10-mm section thickness. **(a)** Standard axial cine examination obtained during quiet breathing with a flow-compensated gradient-echo sequence (flip angle = 30°, TE = 8 msec, imaging time = 96 seconds). **(b)** Breath-hold axial cine examination (6.2/3.6; flip angle = 11°; eight phase-encoding steps per segment; imaging time = 12 sec). The images appear similar to **a** but show less blurring (*Fig 2 continues*).



Signal-to-noise ratio (S/N) was assessed in a phantom constructed from tubes filled with various concentrations of copper sulfate. T1 relaxation times ranged from 85 to 2,175 msec, and T2 relaxation times ranged from 54 to 529 msec. With the use of standard region-of-interest measurements, S/N was calculated as follows: S/N = signal intensity of phantom/standard deviation over air above the phantom.

Six healthy volunteers were imaged with a standard MR cine study as well as with a breath-hold study. The average resting heart rates for these subjects ranged from 48 to 82 beats per minute. Imaging was also performed in three clinical cases. One patient had undergone coronary bypass surgery and had sternal sutures, one had a pericardial cyst, and the third had a dissecting aortic aneurysm.

RESULTS

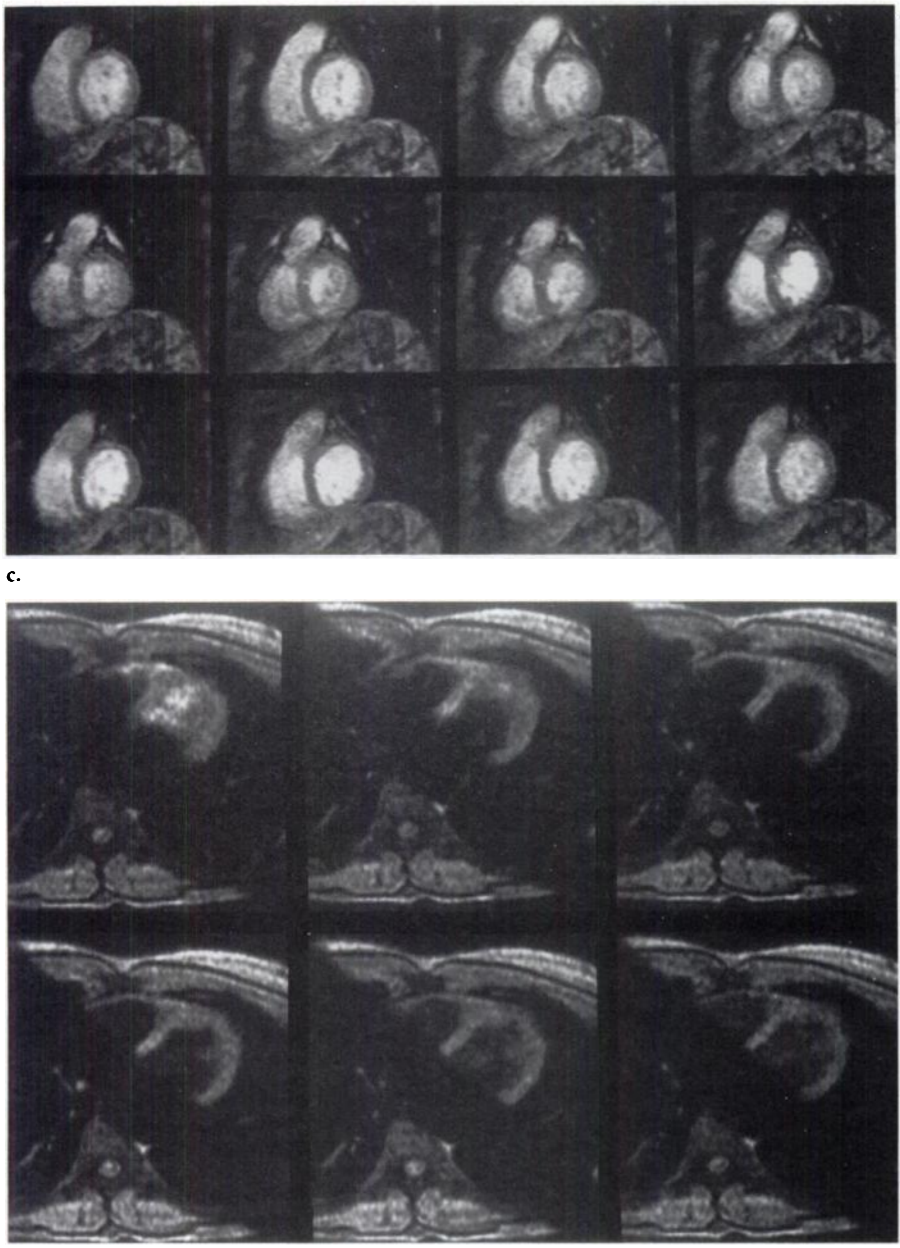
Standard cine studies were of good quality. Single-excitation studies showed respiratory ghosting (Fig 2); with two excitations, respiratory ghosting was reduced. Breath-hold cine studies showed no respiratory ghosting. In addition, blurring of cardiac structures was less apparent than with standard cine studies.

In a study of the effect of flip angle changes with the segmented turbo-FLASH cine method, a severe striping artifact was noted with increased (>30°) flip angles (Fig 3). In the raw data from these images, spurious echoes are apparent with the larger flip angles. The smaller flip angles showed no evidence for this in the raw data, nor were there striping artifacts on the images.

S/N measurements in the phantom for standard FLASH and segmented FLASH showed similar S/N for small flip angles (eg, 5°), but the segmented FLASH was significantly worse for larger flip angles (eg, 20°). For instance, with a 5° flip angle and T1/T2 equal to 1,075/406 msec, S/N was 137 for segmented FLASH and 165 for standard FLASH; the corresponding S/N values for the phantom with T1/T2 equal to 153/100 msec were 147 and 158. With a flip angle of 20°, the S/N values were 259 versus 504 for T1/T2 equal to 1,075/406 msec and 317 versus 525 for T1/T2 equal to 153/100 msec.

In one volunteer, a normal cardiac rhythm was occasionally punctuated with periods of sinus arrhythmia. With the standard cine method, the arrhythmia introduced ghost artifacts that obscured cardiac details. The breath-hold method, by limiting the acquisition time to 16 heartbeats and the acquisition to one phase of the respiratory cycle, was better able to avoid these periods of abnormal rhythms, and therefore fewer artifacts were apparent. The application of presaturation caused the blood

Figure 2 (*continued*). **(c)** Breath-hold short axis cine study (same parameters as **b**). **(d)** Breath-hold axial cine examination (same parameters as **b** but with presaturation of the atria). A 90° pulse was applied prior to each segment of eight phase-encoding steps. Good delineation of the ventricular myocardium is seen during diastole.



pool to appear dark (Fig 2d).

In the patient with an aortic dissection, the breath-hold cine demonstrated high and low flow velocity regions marking the true and false lumina. A pericardial cyst had sharper boundaries on the breath-hold study than the standard study (Fig 4). Artifacts from implanted sternal sutures in another patient only minimally degraded the anterior aspect of the heart (Fig 5).

DISCUSSION

Our results demonstrate that a rapid imaging technique can produce high-resolution cine images within one breath-hold interval by use of standard MR hardware. The technique is a simple modification to the turboFLASH sequence and is amenable to modifications such as spatial presaturation to remove blood signal. It is also capable of higher spatial resolution when used with slightly longer (>50 msec) data acquisition windows. Conversely, if a 12–16-second breath hold is beyond the capability of the patient, one can use fewer phase-encoding steps. In combination with bolus tracking or phase imaging modifications, it could also be used for fast, time-resolved flow velocity quantification of arteries within the chest and abdomen, thereby avoiding degradation from respiratory artifacts. S/N was inferior with the breath-hold method but was adequate for image interpretation.

This method differs from standard cardiac imaging methods in two areas: (*a*) the number of phase-encoding lines taken per R-R interval and (*b*) the time required per phase-encoding step. For each section position or cardiac phase, standard methods acquire only one phase-encoding line per R-R interval. As a result, imaging times for high-resolution studies with a 256 × 128 matrix are several minutes. With the segmented turboFLASH method, imaging times are reduced by a factor of eight to about 16 seconds; moreover, signal averaging is unnecessary to reduce respiratory and flow artifacts. In our study, this resulted in consistently less ghost artifact and blurring of the cardiac structures than the standard cine technique. A drawback of our comparison of standard cine and breath-hold cine was that retrospective gating and respiratory compensation were not used for the standard cine studies. One would anticipate fewer artifacts with the combination of these techniques than with the prospective gating technique actually used.

There are alternative fast imaging techniques that enable overall imaging times to be reduced to less than one R-R interval. For instance, with existing whole-body MR systems, temporal resolution down to 125 msec per image for a single-shot turboFLASH sequence is possible by using small acquisition matrices (5,9,10). However, to accomplish high spatial resolution (128 × 256), we lengthen imaging times to 300 msec or more. This technique has proved useful for first-pass perfusion studies with contrast agents, but the temporal resolution is inadequate for high-quality heart studies. Echo-planar imaging reduces imaging times to less than 100 msec but requires special hardware. It permits a whole cine study to be completed in one R-R interval, which is not possible with other methods. However, one problem is the long, low bandwidth readout. As a result, local magnetic field inhomogeneities produce susceptibility artifacts (eg, from metallic sutures or the air–soft-tissue boundary at the lung–heart interface) that degrade image quality. This problem is particularly severe when the images are acquired in fast cine mode (ie, by use of a reduced flip angle and no RF refocusing). The segmented turboFLASH approach avoids these problems because very short, high bandwidth readouts are used for each echo.

In conclusion, we have demonstrated the feasibility of producing high-resolution cine studies in one breath hold. The method should help to reduce imaging times and improve the reliability of cine studies of the heart and great vessels. ■

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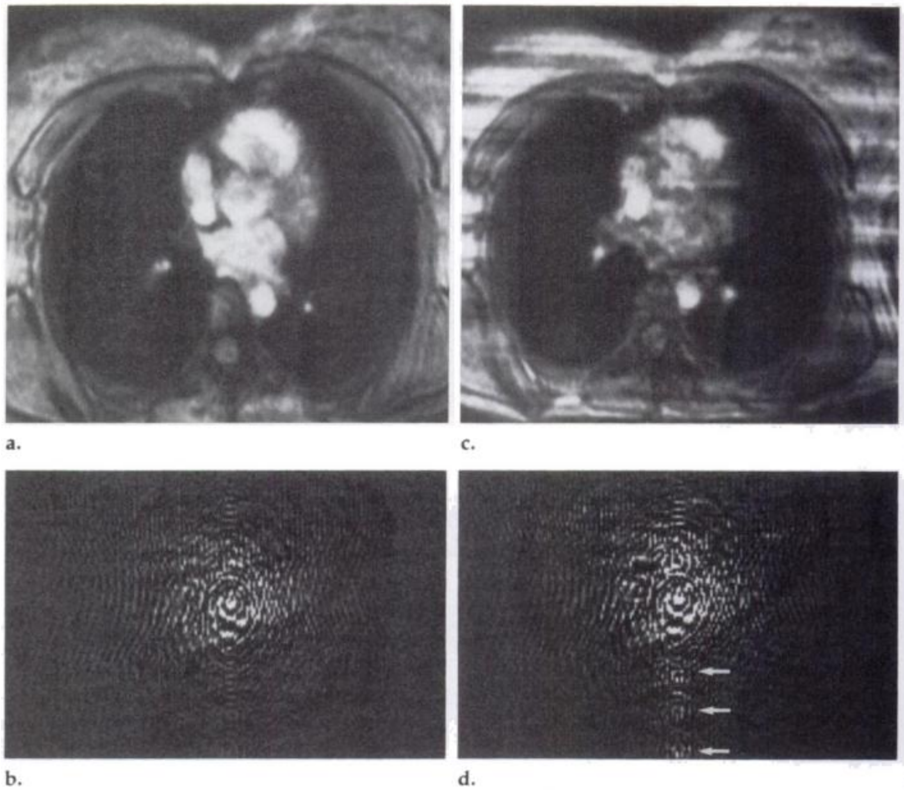

Figure 3. A comparison of the effect of increasing the RF flip angle. **(a, c)** Images demonstrate RF flip angles of 10° and 50°. **(b, d)** The associated raw data. As the flip angle is increased, image quality becomes degraded by striping artifacts. These artifacts represent refocusing of transverse coherences, resulting in spurious echoes (concentric bright and dark rings) as indicated by the arrows in the raw data in **d.**

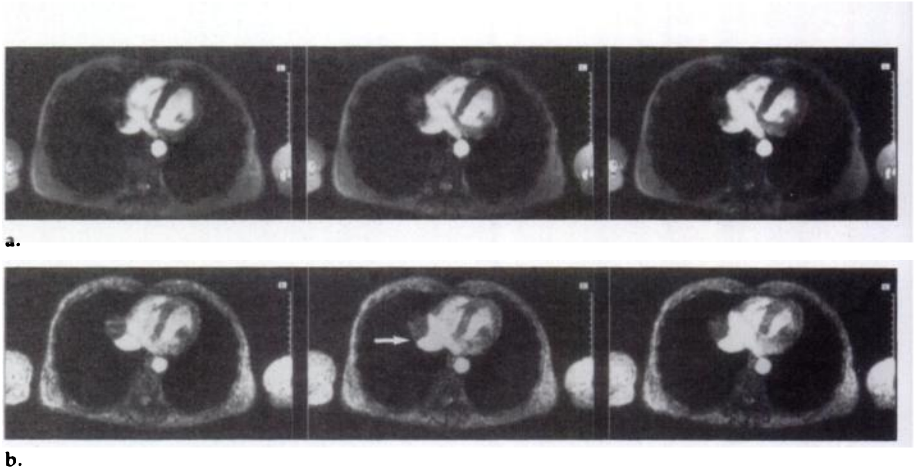

Figure 4. Pericardial cyst (12 phases, R-R = 1,100 msec). **(a)** Three phases from standard cine study with two excitations. **(b)** Corresponding phases from breath-hold cine study. Border of cyst (arrow) is better seen than in **a.**

Figure 5. Three phases from a breath-hold cine study in a patient with sternal sutures. Only a small susceptibility artifact is apparent near the sutures. *L* = left.