Technical Note

Breath-Hold Signal-Loss Sequence for the Qualitative Assessment of Flow Disturbances in Cardiovascular MR

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Purpose: To develop a breath-hold segmented sequence which generates similar patterns of signal loss to a non-breath-hold, relatively long echo time, conventional gradient echo sequence for the qualitative assessment of valvular heart disease.

Materials and Methods: Both velocity-sensitized and acceleration-sensitized segmented sequences were developed. The sensitivities were empirically adjusted to give similar degrees of signal loss to a conventional sequence. These sequences were compared with a conventional sequence in eight patients with flow disturbances and in four healthy subjects.

Results: There was no significant difference in the extent of signal loss observed when using the breath-hold velocity- and acceleration-sensitized sequences developed and the conventional sequence (1862 mm², 1831 mm², and 1782 mm², respectively; P = ns). However, the image quality obtained was significantly better with the breath-hold sequences (both P < 0.01). Furthermore, the image quality achieved with the acceleration-sensitized sequence was significantly better than that achieved with the velocity-sensitized sequence (P < 0.01) where artifacts from beat-to-beat variations in blood-flow velocities were a frequent problem.

Conclusion: Signal loss in complex flow is best demonstrated using the breath-hold acceleration-sensitized sequence where the signal from both stationary and constant velocity material is rephased at the echo time.

Key Words: signal loss; breath-hold; blood flow; complex flow; valvular disease


Materials and Methods

This work was carried out on a Siemens Sonata scanner equipped with gradients having a peak strength of 40 mT/m and a peak slew rate of 200 mT/m/msec on each axis independently.

Two sequences were developed, both of which were based on a simple segmented gradient echo sequence with prospective electrocardiogram (ECG) triggering. The original sequence is shown in Figure 1a. In the first sequence developed (Fig. 1b), velocity sensitivity was...
introduced with the addition of a bipolar gradient in both the slice-select and frequency-encoding directions. Phantom and initial patient studies enabled the velocity sensitivity in both directions to be empirically adjusted to give a similar extent of signal loss as a conventional gradient echo sequence with a TE of 14 msec and velocity compensation in both slice-select and frequency encoding directions. The final sequence had a phase sensitivity of 1.08 and 0.99 cycles per m/sec in the frequency encoding and slice-select directions, respectively. In the second sequence developed (Fig. 1c), the gradient waveforms in the slice-select and frequency encoding directions were modified to give an acceleration sensitivity while maintaining velocity compensation at the center of the echo readout. This involved the addition of extra gradient lobes between the slice selection and signal readout (14), the timing and magnitude of which determined the phase sensitivity to acceleration. The sequence was initially designed to have the same phase sensitivity to acceleration as the conventional TE14 sequence (0.009 and 0.003 cycles per m/sec in the slice-select and frequency encoding directions, respectively). However, the comparatively high phase sensitivity required in the slice-select direction resulted in the sequence having a relatively long repeat time (TR), which would have a detrimental effect on the temporal resolution achievable when segmented for breath-hold acquisitions. Instead, the acceleration sensitivity was determined empirically, with the sensitivity in the slice-select direction being reduced while the sensitivity in the frequency encoding direction was increased until phantom and initial patient studies showed comparable signal losses. The final sequence had a phase sensitivity to acceleration of 0.004 cycles per m/sec² in both slice-select and frequency encoding directions. Table 1 shows the first three gradient moments for the slice-select and frequency encoding axes for the conventional TE14 sequence and for the velocity- and acceleration-sensitized sequences developed (Fig. 1b and c, respectively). The TEs of the sequences developed in Figure 1b and c were 6.9 msec and 8.2 msec, respectively, and the TRs for each view of data acquired were 11 msec and 12.4 msec, respectively. For each sequence, acquisitions were segmented with seven views of data acquired in each segment resulting in acquisition windows of 77 msec and 87 msec, respectively. Temporal view-sharing (15), as implemented on the Siemens Sonata scanner where the four most central views are sampled for each cardiac phase and the three outermost views are shared between phases, resulted in effective temporal resolutions of 45 msec and 50 msec. All studies were performed with a 350 mm field-of-view (FOV), a slice thickness of 6 mm, and an acquisition matrix of 256 × 128. Studies were completed in a 19–cardiac cycle breath-hold and compared to those acquired with a conventional non-breath-hold nonsegmented TE14 sequence having the following parameters: 350 mm FOV, 6 mm slice thickness, acquisition matrix 256 × 128, TE = 14 msec, TR = 22 msec, temporal resolution 50 msec, and acquisition duration 128 cardiac cycles. Initial acquisitions (using the above parameters) were performed in a constant flow phan-

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**Table 1**

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Axis</th>
<th>Moment 0 cycles/m</th>
<th>Moment 1 cycles/(m/s)</th>
<th>Moment 2 cycles/(m/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TE14</td>
<td>Slice-select</td>
<td>0</td>
<td>0</td>
<td>0.009</td>
</tr>
<tr>
<td>Velocity sensitized</td>
<td>Slice-select</td>
<td>0</td>
<td>-0.99</td>
<td>-0.002</td>
</tr>
<tr>
<td>Acceleration sensitized</td>
<td>Slice-select</td>
<td>0</td>
<td>0</td>
<td>0.004</td>
</tr>
<tr>
<td>TE14</td>
<td>Frequency encoding</td>
<td>0</td>
<td>0</td>
<td>0.003</td>
</tr>
<tr>
<td>Velocity sensitized</td>
<td>Frequency encoding</td>
<td>0</td>
<td>-1.08</td>
<td>-0.004</td>
</tr>
<tr>
<td>Acceleration sensitized</td>
<td>Frequency encoding</td>
<td>0</td>
<td>0</td>
<td>0.004</td>
</tr>
</tbody>
</table>
tom that consisted of a straight 20-mm diameter tube with an abrupt 50% narrowing formed from a 5-mm thick annular insert. The flow velocity through the unstenosed sections of the tube was approximately 1 m/sec.

Prospectively ECG gated conventional TE14, breath-hold velocity-sensitized, and breath-hold acceleration-sensitized acquisitions were performed in four healthy volunteers (mean age 28 years, range 25–31 years) and in eight patients (mean age 55 years, range 45–67 years) with flow disturbances due to either valvular heart disease (N = 5) or to coarctation (N = 3). The imaging parameters for each sequence were as in the previous paragraph. Informed consent was obtained from all patients and healthy subjects. Following standard clinical protocols, the image plane was selected for each patient so as to best demonstrate the flow disturbance. In four of the patients, acquisitions with all three sequences were carried out in two image planes, resulting in a total of 12 studies available for comparison in the patient group. In the healthy volunteer group, acquisitions with all three sequences were performed in three image planes—the four-chamber view to demonstrate flow through the mitral and tricuspid valves and the left and right ventricular outflow tract (LVOT and RVOT) views to demonstrate flow through the aortic and pulmonary valves, respectively—resulting in a total of 12 studies being available for comparison. For each dataset in each patient, the cinematic (cine) frame showing the maximum signal loss was selected and the area of signal loss was manually delineated by an experienced observer on two separate occasions. Intraobserver variability was calculated as the single determination standard deviation (SDSD) of the absolute differences between the two measurements. Analysis of variance was then performed to test the null hypothesis that there were no significant differences in the extent of signal loss obtained with all three sequences. The image quality of each cine data acquisition was scored by two independent observers according to the presence of respiratory and blood-flow artifacts: with 0 = no or minimal artifacts, 1 = minor artifacts, 2 = moderate artifacts, and 3 = severe artifacts. In cases of disagreement, a consensus opinion was reached. Friedman’s analysis of variance was used to determine if there were any significant differences in the image quality obtained with the conventional, the breath-hold velocity-sensitized, and the breath-hold acceleration-sensitized sequences. If so, matched pair Wilcoxon analysis with Bonferroni correction for multiple testing (16) was performed to determine where the differences lay.

RESULTS
Phantom images acquired with the conventional TE14 sequence and with the empirically-adjusted velocity- and acceleration-sensitized sequences of Figure 1b and c are shown in Figure 2a, b, and c, respectively, and show comparable signal loss.

For all subjects studied, the conventional TE14, the breath-hold velocity-sensitized, and the breath-hold acceleration-sensitized sequences produced similar patterns of signal loss. In one of the eight patients, severe respiratory artifacts obscured the area of signal loss when using the conventional TE14 sequence and delineation of its extent was not possible. In the remaining patients, analysis of variance showed no significant differences in the extent of signal loss as determined by the three sequences, with the mean maximal areas of signal loss being 1782 mm², 1862 mm², and 1831 mm² for the conventional TE14, the breath-hold velocity-sensitized, and the breath-hold acceleration-sensitized sequences, respectively (P = ns). The intraobserver variability for determining the extent of signal loss was 46 mm².

Figure 3 shows the results of using the sequences in a subject with mitral stenosis and regurgitation, with the acquisitions being performed in the horizontal long axis plane. Systolic frames, showing a regurgitant jet extending into the left atrium, are shown in Figure 3a–c, and diastolic frames, showing signal loss within the left ventricle, are shown in Figure 3d–f. Figure 3a and d show systolic and diastolic frames from the conventional TE14 sequence acquired over approximately two minutes. In this example, the image quality is good and respiratory motion has not noticeably degraded the image quality obtained. The corresponding cine frames from the velocity-sensitized sequence of Figure 1b are
shown in Figure 3b and e and show a similar extent of signal loss to the conventional sequence, although this is more apparent when both datasets are viewed as cines. However, although the images are free from respiratory motion artifacts, they are considerably degraded by artifacts from beat-to-beat variations in blood-flow velocity, which smear out in the phase encode direction and obscure the area of signal loss. In contrast, Figure 3c and f, which show the corresponding cine frames acquired with the acceleration-sensitized sequence of Figure 1c, where constant velocity material is rephased at the center of the echo readout, are of high quality and devoid of both respiratory motion and blood-flow artifacts.

Figure 4 shows the results of using these sequences in a patient with aortic stenosis, with cine acquisitions having been made in both oblique coronal (Fig. 4a–c) and LVOT (Fig. 4d–f) planes. All of the images shown are systolic frames and show complex flow extending into the aorta. However, it is clear that in this case, the images acquired with the conventional TE14 sequence are considerably degraded by respiratory motion artifacts. Those acquired with the breath-hold velocity-sensitive sequence (Fig. 4b and e) are devoid of respiratory motion artifacts but artifacts from constant-velocity blood are present, although not to as great an extent as that in the patient shown in Figure 3. The image quality obtained when using the acceleration-sensitized sequence (Fig. 4c and f) is again superior.

The appearances observed in Figures 3 and 4 were similar for all subjects studied, with the comparable patterns of signal loss being even more apparent when viewing the data as a cine. Table 2 shows the mean image quality scores for the three sequences used in patient and healthy volunteer groups, both separately and combined. The quality of the free-breathing TE14 acquisitions was frequently poor, with severe respiratory motion artifacts often being present. Although the image quality achieved with the breath-hold velocity-sensitized sequence (Fig. 1b) was significantly better (mean image score 1.92 vs. 2.75, \( P < 0.01 \)), it was generally degraded by blood-flow ghosting artifacts. In contrast, the image quality obtained using the acceleration-sensitized sequence (Fig. 1c) was consistently excellent and significantly better than that from both the breath-hold velocity-sensitized and the conventional sequences (mean image quality score 0.33 vs. 1.92 and 2.75, respectively; both \( P < 0.01 \)).

**DISCUSSION**

Signal void is indicative of complex flow, which is associated with valvular dysfunction when using longer TE conventional gradient echo pulse sequences. However,
the acquisition duration of such sequences is long and respiratory motion artifacts are a frequent problem, often resulting in poor quality images as shown in Fig. 4a and b. We have addressed the problem of maintaining the signal void in sequences which allow more rapid acquisition. Two segmented sequences have been developed with empirically-adjusted phase sensitivity to velocity (Fig. 1b) and to acceleration (Fig. 1c), which generate extents of signal loss in complex flow similar to a conventional gradient echo sequence (both \( P = ns \)). By comparison, the acquisition durations are considerably reduced (from 128 to 19 cardiac cycles) and breath-hold imaging is feasible, removing respiratory motion artifacts.

The most obvious approach to generating signal loss is to add velocity-sensitivity to a previously compensated sequence, as in Fig. 1b. However, although respiratory motion artifacts are removed and image quality for the group as a whole is significantly improved when compared to the conventional TE14 sequence \( (P < 0.01) \), we have shown that with this approach the images are often degraded by blood-flow artifacts, which may sometimes be severe (Fig. 3b and d). These are thought to originate from variations in the blood-flow velocity from beat-to-beat and during the relatively long segment acquisition (17–19). Instead, signal loss is best generated by using the acceleration-sensitized sequence shown in Fig. 1c, where both stationary and constant velocity blood signal are rephased at the center of the echo readout (Fig. 3c and f). Using this sequence, it is thought that high acceleration, and other high orders of motion only present in the region of highly complex flow, generate a wide range of intravoxel phase shifts that tend to result in signal cancellation. The image quality obtained when using this sequence is

![Figure 4](image-url)

**Figure 4.** Systolic frames from oblique coronal and LVOT cine datasets acquired using: a conventional TE14 sequence (a,d); the breath-hold velocity-sensitized sequence (b,e); and the breath-hold acceleration-sensitized sequence (c,f) in a patient with aortic stenosis.

### Table 2
Average Image Quality Scores for Cine Acquisitions Using the Conventional TE14 Sequence, the Breath-Hold Velocity Sensitized Sequence (Fig. 1b) and the breath-hold acceleration sensitized sequence (Fig. 1c)

<table>
<thead>
<tr>
<th></th>
<th>Conventional TE14 sequence</th>
<th>Breath-hold velocity sensitized sequence</th>
<th>Breath-hold acceleration sensitized sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patients (12 studies)</td>
<td>2.67</td>
<td>1.83</td>
<td>0.42</td>
</tr>
<tr>
<td>Healthy volunteers</td>
<td>2.83</td>
<td>2.0</td>
<td>0.25</td>
</tr>
<tr>
<td>Combined (24 studies)</td>
<td>2.75</td>
<td>1.92</td>
<td>0.33</td>
</tr>
</tbody>
</table>

\( 0 = \text{no or minimal artifact, } 1 = \text{minor artifact, } 2 = \text{moderate artifact, } 3 = \text{severe artifact.} \)
consistently and significantly better than that obtained with both the breath-hold velocity-sensitized and the conventional TE14 sequences.

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REFERENCES