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Simultaneous multiple volume (SMV) acquisition algorithm for real-time navigator gating

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Abstract

Navigator gating techniques can effectively reduce motion effects in MRI by accepting data only when the object is in a small range of positions at the cost of significantly prolonging scan time. A simultaneous multiple volume (SMV) algorithm is reported here that can substantially increase the scan efficiency while maintaining the effectiveness of motion suppression. This is achieved by acquiring different image volumes at different motion states. Initial experiments demonstrate that SMV can significantly increase the scan efficiency of navigator MRI.

Keywords: Navigator; Simultaneous multiple volume; SMV; Motion suppression; Magnetic resonance imaging

1. Introduction

Magnetic resonance imaging is the method of choice for noninvasive diagnosis of soft tissue disease, and has wide applications in cardiovascular diseases. Fast gradient technology has made high-resolution 3D imaging possible, including MRA of coronary and pulmonary arteries. However, the acquisition time for such data are on the order of minutes. Artifacts from physiological motion occurring during data acquisition, such as respiration and cardiac motion, are the major challenge to cardiovascular MRI.

One robust and effective approach to suppressing motion artifacts is the real-time navigator method, which monitors respiration and controls data acquisition accordingly in real-time [1–11]. Most current navigator techniques are based on gating—they reconstruct images only using data acquired when motion is in a specified range. The motion tolerance range or gating window can be selected to contain the most likely position using the diminishing variance algorithm (DVA) [4]. The image artifacts from residual motion within the tolerance range can be further reduced using the phase ordering with automatic window selection (PAWS) [8]. The final image reconstructions for all these navigator techniques use only data acquired when the position is within one single gating window. Effective motion suppression requires a narrow gating window that leads to a long scan time. Therefore, all these navigator techniques are fundamentally inefficient. Here we present an algorithm that utilizes multiple gating windows simultaneously, thereby addressing this efficiency issue.

1.1. Algorithms

A typical navigator gating implementation acquires a single image volume at a window near the most likely position, as indicated by the peak of the motion histogram. The gating window can be selected automatically [4,8] and the residual motion can be smoothly distributed in k-space through view ordering to further reduce motion artifacts [8]. However, scan time is wasted when position is outside the gating window. Our idea for overcoming the inefficiency issue in navigator gating is to acquire different volumes at different positions while maintaining the same motion tolerance for all volumes. We refer to this method as simultaneous multiple volume (SMV) acquisition.

Illustrated in Fig. 1a is an example of 2- volume SMV. The motion range is divided into two portions. Navigator efficiency (the percentage of data points used for the final image reconstruction) is increased because a second volume is acquired simultaneously at another portion of the histo-

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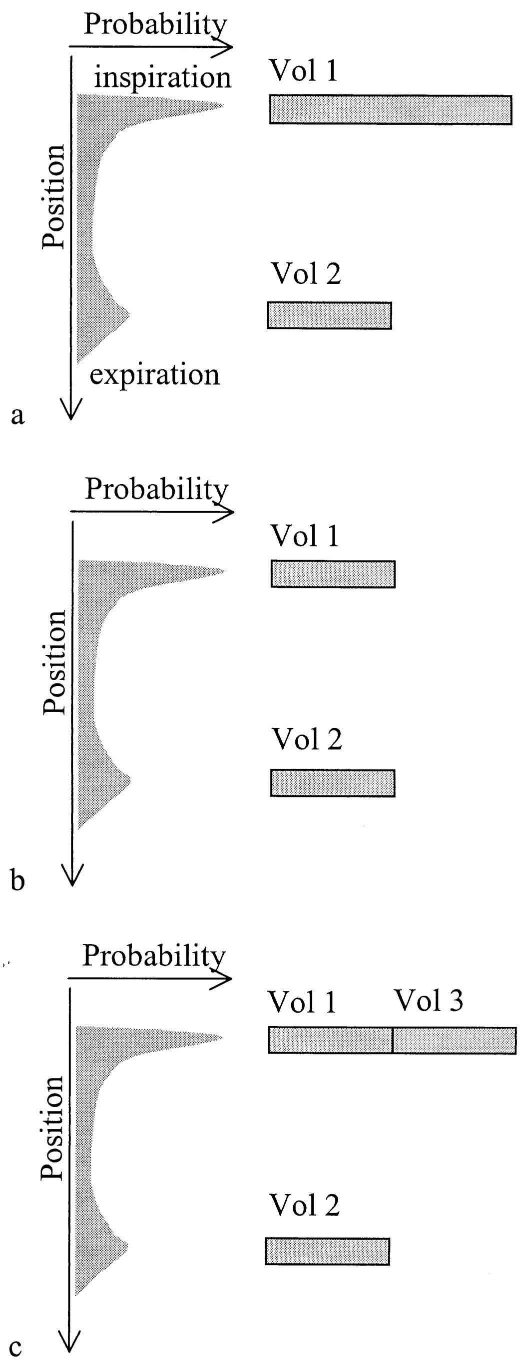

Fig. 1. SMV algorithm simultaneously using 2 gating windows at the two peaks of histogram of motion (respiration as a specific example here) to acquire (a) 2 volumes with their sizes proportional their corresponding histogram peak heights, (b) 2 volumes of equal size, and (c) three volumes of equal size.

gram. In our implementation, the histogram was estimated in an initialization phase (25 navigator echoes acquired in 25 heartbeats in our experiments), during which all position bins (digitized position, 1.5 mm bin width in this study) were used to acquire the first volume. The histogram of respiration may have two peaks, corresponding to expiration and inspiration, which can be identified by fitting the estimated histogram with a pair of Gaussian distributions [4]. The size for each volume can be selected to be proportional to the height of the histogram peak, and the two volumes are completed at approximately the same time.

In the preliminary implementation of SMV presented in this paper, the volume size could not be varied, and multiple volumes of the same size had to be used (Fig. 1b). This implementation provided a feasibility test, but the inflexibility in volume size could substantially reduce the scan efficiency. Considering that in a respiration histogram the peak near expiration may be much larger than the one corresponding to inspiration, a third volume was acquired after the completion of the first volume at the larger peak (Fig. 1c) to increase navigator efficiency. When the two-Gaussian fitting algorithm failed (no two peaks in the histogram), the PAWS algorithm ran sequentially three times to complete all three volumes.

2. Experiments

Experiments were performed on 6 healthy subjects to image the right lung, the heart and the left lung simultaneously on a 1.5T scanner equipped with real-time scan modification capability (CVi Signa, General Electrical Medical System, Milwaukee). The pulse sequence was an ECG-triggered fat-suppressed segmented 3D fast gradient echo sequence. One 2D pencil beam navigator echo positioned at the anterior right diaphragm dome was acquired immediately before the fat suppression pulse at the beginning of data acquisition in each heartbeat to monitor respiration at the diaphragm [6]. The diaphragm position was detected in less than 1 msec using an algorithm consisting of 1) first locating the maximal spatial derivative of the navigator intensity profile for a quick rough estimate of the edge position of the diaphragm and 2) then refining the estimation by searching around the first estimate using the least squares algorithm. The imaging parameters for the 3D acquisition were 30 cm FOV, 256 × 160 × 32 matrix, 0.8 phase FOV, 32kHz receiver bandwidth, TR/TE = 4.5/1.1, 20^0 flip angle, body coil for RF transmission, and 4-element phased array coil (cardiac coil) for RF reception.

The Phase Ordering with Automatic Window Selection (PAWS) algorithm [8], which automatically selects the gating window and is robust against changes in the histogram, was used over the allocated portion of the histogram to acquire each volume. A detailed description of the PAWS algorithm can be found in Ref.8. Our implementation of the PAWS algorithm is concisely summarized by way of example in Fig. 2. The horizontal axis is a dimension of k-space extended by the view index k_y (a complete set of slice encoding values set is acquired for each navigator echo). The object position was digitized with bins of 1.5 mm width (7 bins illustrated in Fig. 2). Whenever the navigator indicated position was in bin 1, the most negative view among the unacquired views was sampled (right-

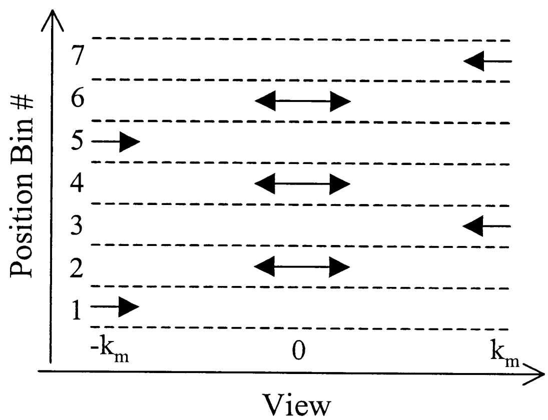

Fig. 2. k-space sampling for modified PAWS algorithm. The arrows indicate the sampling directions in k-space. The k-space center is sampled at every other position bin to ensure smooth motion distribution in k-space for the final reconstructed data.

headed arrow in bin 1). Whenever the position was in bin 2, if there were more unacquired negative views than unacquired positive views, the view of the least magnitude among the unacquired negative views was sampled; otherwise, the view of the least magnitude among the unacquired positive views was sampled (double-headed arrow in bin 2). Whenever the position was in bin 3, the view of the most positive value among the unacquired views was acquired. Data acquisition terminated when a complete set of views were acquired over three contiguous bins (arrows met).

3. Results

Results from the 3-volume SMV experiments are summarized in Table 1. The increase in navigator efficiency of the SMV algorithm ranged from 0 to 50% (average 22.5%)

Table 1
Navigator efficiency (percentage of data used for the final image reconstruction) of SMV versus PAWS for 2-volume and 3-volume acquisitions observed in 6 subjects. The second last row lists the average and range of efficiency increase by SMV compared to PAWS. The last row lists the significance of the efficiency increase as measured by the p-value from the one-tail paired two-sample t-test

	Observed Efficiency			
	2-volume		3-volume	
Subject	PAWS	SMV	PAWS	SMV
a	25.6	28.0	25.7	37.4
b	23.3	31.7	23.6	27.4
c	32.8	32.8	30.3	30.3
d	19.7	23.3	19.7	29.5
e	27.7	30.4	28.0	34.6
f	54.3	54.3	55.5	55.5
Average	30.6	33.4	30.5	35.8
Eff. Incr: ave (range)		12.3% (0–36.3%)		22.5% (0–50%)
P-value (t-test)		.04		.02

over the PAWS algorithm. The efficiency for the PAWS algorithm was computed as follows: the sequential acquisitions of the same three volumes were simulated using PAWS running on the same navigator waveform. This increase in navigator efficiency is significant using a one-tail paired two-sample t test ($p = 0.02$)

Table 1 also demonstrates the efficiency increase for 2-volume SMV. The data were a subset of the above 3-volume SMV acquisition that represents the completion of the first two volumes. The efficiency for the PAWS algorithm was simulated in the same manner. The increase in efficiency ranged from 0 to 36.3% (average 12.3%), which is significant using a one-tail paired two-sample t test ($p = 0.04$). Note that the average increase in efficiency for the 2-volume case is less than that for the 3-volume case.

The histograms sampled during data acquisition are illustrated in Fig. 3. In general, there was a peak near expiration, but the individual histogram profile varied substantially from subject to subject. In one subject, there was one broad peak (Fig. 3e); in two subjects c&f (Figs. 3c&f), the largest peak was more than three times that of the second peaks.

The record of acquired data for each volume at possible position bins is shown in Fig. 4 for the case of subject c (Fig. 3c). Each volume is acquired using PAWS as illustrated in Fig. 2. At the preparation phase (first 25 navigator samples), all position bins were used to acquire volume 1. Then volumes 1 & 3 were assigned to the top half (by area) of the instantaneous histogram, and volume 2 was assigned to the bottom half of the histogram. After completion of volumes 1&3, all bins were used to acquire volume 2. Because the temporal drift of the instantaneous histogram, 1 copy of data for volume 1 and 3 copies for volume 2 were close to completion but had to be thrown away. Approximately a total of 6 volumes of data were wasted in this acquisition, leading to an efficiency of ~30%.

A case is illustrated in Fig. 5 (subject a in Table 1 with histogram in Fig. 3a). The scan time for the 3-volume SMV was 1058 heartbeats, within the same duration only 2.06 volumes could be completed by PAWS. This corresponds to a navigator efficiency increase of 45.6% while image quality remained the same.

4. Discussion

Our preliminary results demonstrate that the navigator efficiency can be increased significantly using the simultaneous multiple volume (SMV) algorithm by simultaneously acquiring multiple volumes at various positions, and that the average increase in efficiency improves as more volumes are acquired. This SMV algorithm increases the navigator efficiency while maintaining the same gating window or the same effectiveness of motion suppression.

Obviously, to our disappointment, the observed increase in scan efficiency was severely limited by our incapability

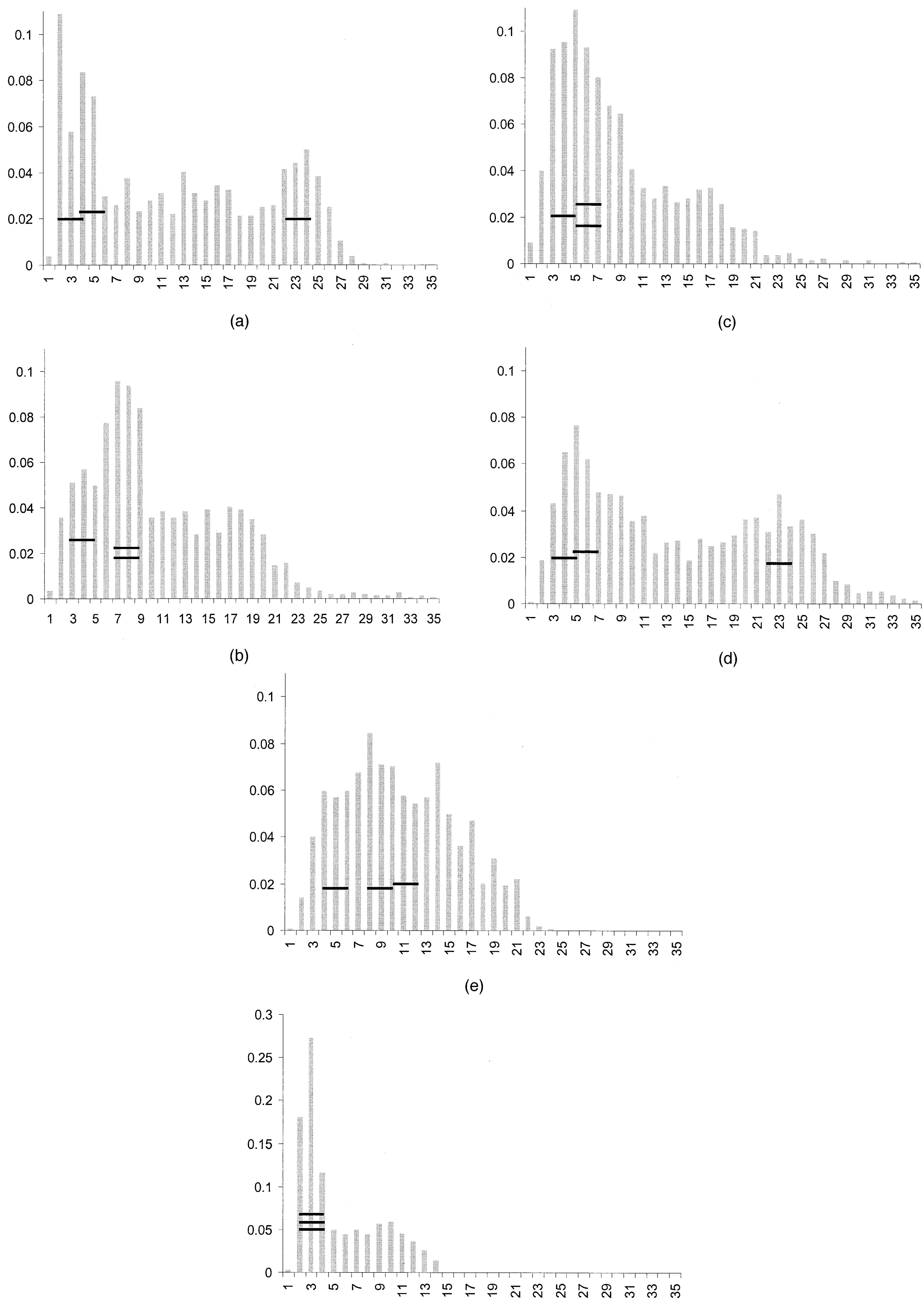
(a)
(c)
(b)
(d)
(e)
(f)

Fig. 3. Respiratory histograms measured in six subjects during 3-vol SMV data acquisition. The horizontal axis is position bin # (1.5 mm per bin), and the vertical axis is the probabilities. In (c) & (f), all three volumes were completed in one peak, providing no efficiency improvement; in (a), (b), (d) & (e), two peaks were used to acquire final image data, providing efficiency improvement.

to change volume size in this preliminary implementation, because the navigator efficiency increases only when volumes acquired at different positions are completed at approximately the same time. When the dominant peak in the histogram is more than 3 times larger than the secondary peak, as in the case of subject f in Table 1 (Fig. 3f), the smaller secondary peak does not have chance to make an observable contribution by completing a volume before the dominant peak completes 3 volumes. In this case, the SMV algorithm can improve the navigator efficiency only if a smaller volume is assigned to the secondary peak or more volumes are assigned to the dominant peak.

The observed increase in the navigator efficiency by the SMV algorithm is also affected by drifts in histogram. For example in the subject c in Table 1 (Fig. 3c), there were substantial changes in the instantaneous histogram derived from every 25 navigator samples. The instantaneous histogram changed from one peak to two peaks and back to one peak with the peak drifting in the board range of the final histogram of Fig. 3c, which is derived from all navigator samples. Much data were acquired for volumes 1 & 2 but was not used for the final data reconstruction, and consequently there was no observed increase in navigator efficiency by the SMV algorithm. In this case, if a greater number of smaller volumes were acquired, a volume might be completed prior to a substantial histogram change, leading to greater usage of the acquired data and a corresponding increase in scan efficiency.

The experiments reported here are our first attempts to test the feasibility of the SMV approach. These experiments were limited in the choice of volume sizes and the number of volumes. The current 3-volume SMV implementation allows a maximum increase in scan efficiency by 50% (which was observed in subject a in Table 1). We are working on overcoming such limitations in our next stage of implementation. It is worth noting that the navigator efficiency can be very high with many volumes and variable volume sizes. For example, with a stable motion histogram and varying the volume sizes according to the histogram heights such that the acquisitions for all volumes are completed in parallel, navigator efficiency can approach 100%.

It is possible to generalize SMV to allow the volumes to overlap for later registration using techniques developed in computer graphics [12]. This would provide a natural way of efficiently acquiring a large volume with minimal motion artifacts. However, registration is not necessary for many clinical applications, for example, slices acquired from different breath-holds are not registered at all in routine clinical chest and abdominal examinations. One possible concern with this approach lies in the fact that smaller volumes have lower signal to noise ratio (SNR). However, for reasonable scan times the major limiting artifacts seem to come from motion and signal averaging may be employed to boost SNR. Another concern is the spin equilibrium state when the data acquisition for a region is interrupted. For the ECG-triggered data acquisition during a short interval in the cardiac cycle, as the case for coronary MRA, the spins are almost fresh at the start of data acquisition in each cardiac

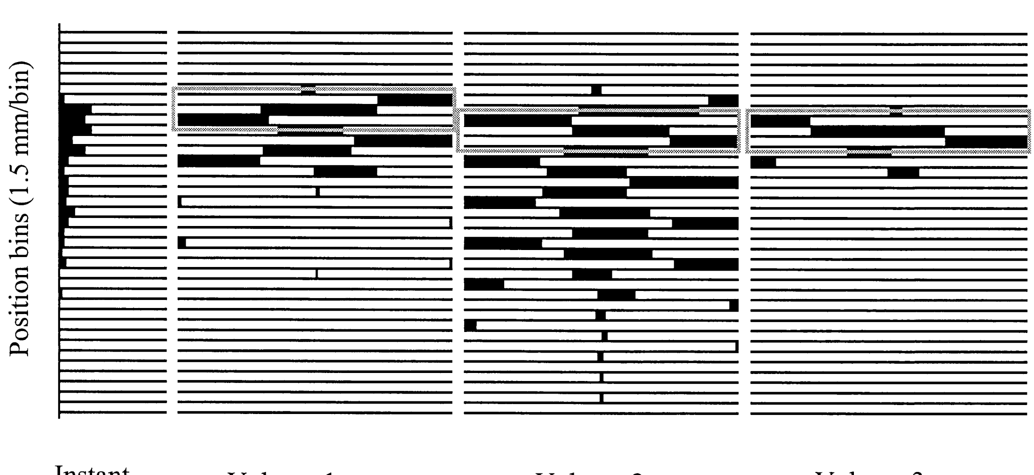

Fig. 4. Snapshot of the instantaneous histogram (derived from the last 25 navigator samples), data acquired for each volume at scan completion for subject c in Table 1 (Fig. 3c). The position bins used for the final image reconstruction for a volume are marked by a gray bar on the left side of the sampling diaphragm of that volume.

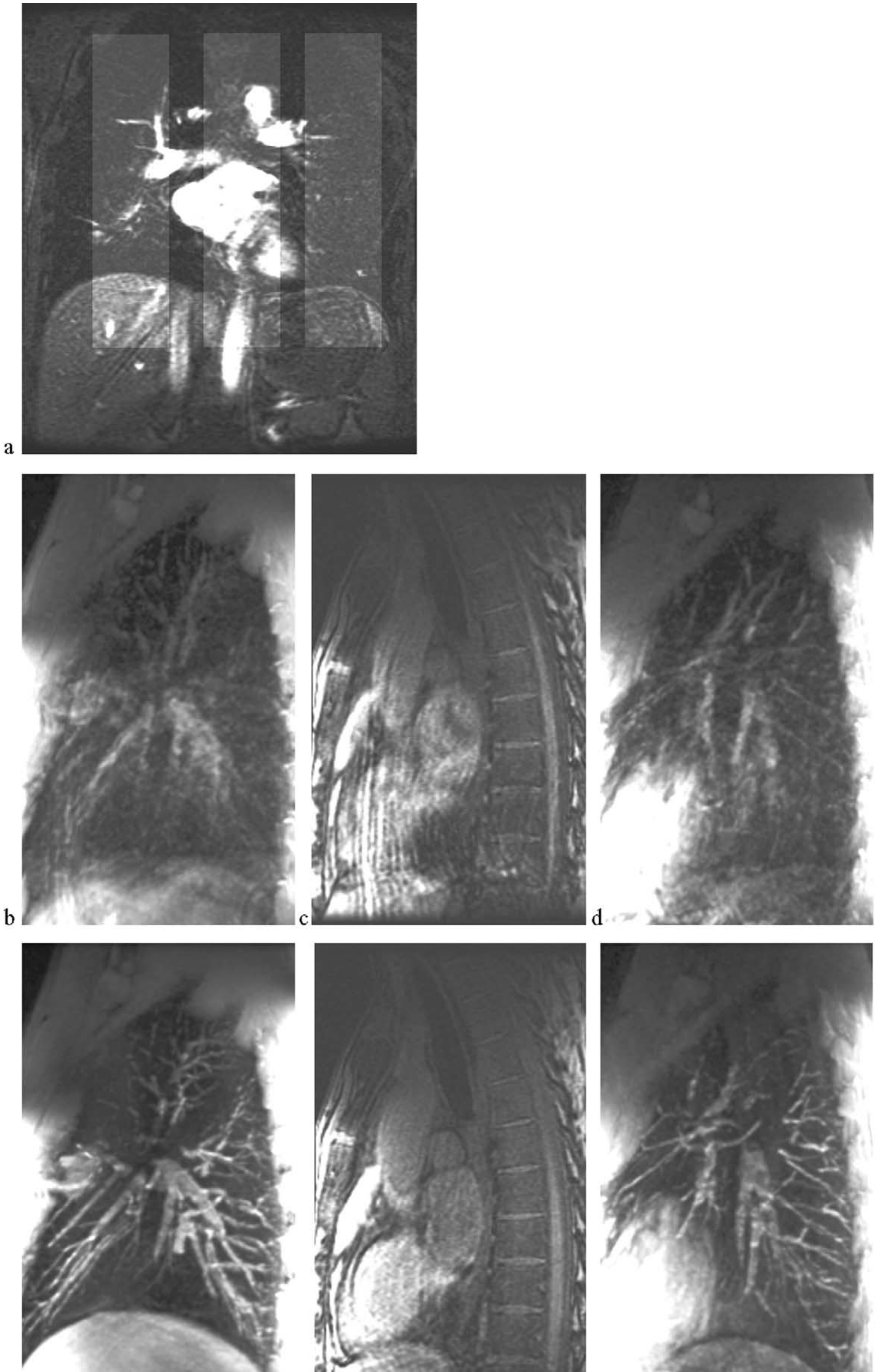

Fig. 5. (a) 3 sagittal volumes (highlighted) for imaging the right lung, heart and left lung. SMV acquisition for the right lung (e, MIP), heart (f, section), left lung (g, MIP). Corresponding acquisition without navigator is illustrated in (b,c,d).

cycle, and correspondingly spin equilibrium is not a concern. However, spin equilibrium has to be addressed for other types of data acquisition.

In conclusion, the simultaneous multiple volume (SMV) approach can significantly increase the scan efficiency of the navigator gated acquisition.

Acknowledgments

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