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● *Original Contribution*

T2-WEIGHTED MR IMAGING OF THE LIVER: OPTIMIZATION OF HYBRID-RARE SEQUENCES

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The objectives of this study were to optimize T2-weighted hybrid-RARE pulse sequences for clinical MR imaging of the liver, and to compare them to the conventional spin-echo (CSE) sequence. Specifically, the ranges of the echo train length (ETL) and the effective echo time (TE_{eff}) were investigated to optimize image quality and liver-spleen contrast, in healthy volunteers. A total of thirteen volunteers were scanned at 1.5 Tesla with an extensive array of hybrid-RARE scans. The images were analyzed quantitatively with respect to CNR (contrast-to-noise ratio of spleen vs. liver), SNR (signal to noise ratio of the spleen), SIR (signal intensity ratio of liver and spleen) and CDR (contrast difference ratio between the spleen and liver). The images were also analyzed qualitatively with respect to image sharpness, vascular artifacts, ghosting, chemical shift, and truncations. Results of quantitative analysis indicated that CDR and SIR of hybrid-RARE at higher ETL (>13) were consistently better than both the reference CSE and the lower ETL sequences ($p < 0.05$) at all TE_{eff}. SNR was slightly inferior for all hybrid-RARE sequences than for the CSE sequence. Image quality for hybrid-RARE sequences with ETL > 13 proved to be consistently better than that for the CSE (TE = 90 ms) with respect to imaging sharpness, vascular artifacts and ghosting artifacts ($p < 0.05$). In conclusion, the optimized hybrid-RARE sequences with ETL greater than or equal to 13 are capable of producing sharp and relatively artifact free images with the advantage of a much greater acquisition time efficiency. © 1997 Elsevier Science Inc.

Keywords: **Hybrid-RARE; Optimization of MR pulse sequence; Liver; Image quality; Image contrast.**

INTRODUCTION

Diagnosis of patients with focal hepatic lesions[1–3] can be achieved by conventional spin-echo (CSE) technique as well as various new hybrid imaging techniques. A hybrid imaging technique distinguishes from the conventional CSE by the fact that more than one k-space acquisition is performed after a single excitation. Hybrid imaging techniques, suitable for the study of focal hepatic lesions, include a number of variants on the hybrid-RARE (rapid acquisition with relaxation enhancement) pulse sequence,[4–6] the ultrafast Turbo Spin-Echo technique,[7] and the Echo Planar imaging (EPI)[8] technique. Among them, only the first two techniques can be implemented under the existing clinical setting because they require no special imaging hardware modifications.

Although CSE is still regarded as the gold standard for liver imaging, its diagnostic powder is often limited by its comparatively long scan times, typically lasting 10 min for a multi-slice acquisition covering the entire liver with a matrix size of 128 × 256 and 2 excitations. With the hybrid-RARE technique, however, scans of comparable contrast and anatomical coverage can be achieved in less than 4 min. These hybrid-RARE images have the same spatial resolution with considerably less motion-induced ghosting artifacts. MR imaging of the upper abdomen with hybrid-RARE has been the subject of a number of studies,[9–14] yet the optimum protocol has not been identified.

To carry out our study, it is clearly impractical to evaluate a large number of possible hybrid-RARE protocols with similar contrast or sharpness on real patients. Therefore, an extensive array of hybrid-RARE sequences with a fixed k-space raster (linear profile order) were compared with the standard CSE technique, all performed on healthy volunteers. The primary objective of this work is to determine the ranges of the key hybrid-RARE parameters (Fig. 1), namely,

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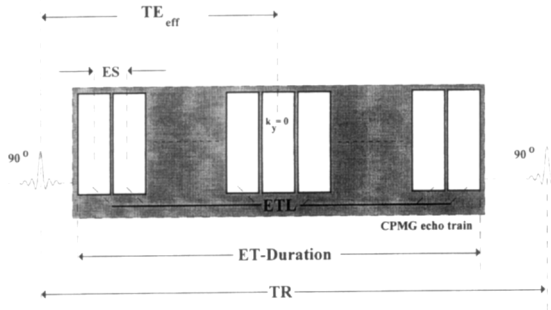

Fig. 1. Key scan variables of the hybrid-RARE MR imaging pulse sequence. With the "linear profile order" raster, the condition TE_{eff} = ET-Center, is always satisfied.

1) the effective echo time (TE_{eff}), 2) the echo train length (ETL), and 3) the echo spacing (E-Space), which produce maximum contrast between liver and spleen. The last parameter must also include qualitative grading scales in terms of the vulnerability to a wide range of artifacts including 1) blurring, 2) vascular artifacts, 3) ghosting artifacts, 4) chemical shift artifact, 5) truncation, and 6) overall image quality.

The observed T2 difference between healthy spleen (T2 $\approx$ 62 ms) and liver (T2 $\approx$ 43 ms) has been observed to approximate that between liver parenchyma and many pathologic lesions. Therefore, the liver and spleen relative MR signal behavior has been proposed as an approximate model for contrast of focal hepatic lesions.[3] Studies of the liver and spleen relative MR signal behavior is particularly useful for in vivo optimization of contrast with T2-weighted sequences because it also provides information regarding the vulnerability of the pulse sequences to motion. The specific influence of the key hybrid-RARE scan parameters will be discussed with the purpose that the results can be extrapolated to applications on other hardware platforms.

MATERIALS AND METHODS

Subjects

A total of thirteen healthy volunteers (10 males and 3 females) were examined with a research protocol which was approved by the Institutional Review Board of our institution. Ages of the volunteers ranged from 25 to 56 years (mean, 44). No liver or spleen lesion was detected in any of them. Informed consent was obtained from all the participants.

Imaging Protocol

The images were acquired in the axial plane with full spatial coverage of the liver on a 1.5 Tesla, 10 mTesla/m MR imager (Gyroscan ACS II, software release 3, Philips Medical Systems, Shelton CT). Each participate was scanned first with a dual spin-echo CSE sequence: TR = 3000 ms, TE = 20/90 ms, number of excitations (NEX) = 4, half scan factor (HF) = 0.6, 13 slices, 320 mm field of view, 128 × 256 matrix (75% rectangular), slice thickness = 10 mm, and no fat suppression. To reduce the artifact due to abdominal motion, the technique of PEAR (phase encoding artifact reduction) was implemented. Total image time for each CSE sequence was 12 min. This was followed by an array of hybrid-RARE scans with the same spatial coverage, section thickness, and number of excitations as the reference CSE images. The key hybrid-RARE scan parameters are summarized in Table 1. Each volunteer was imaged with a total of 18 pulses sequences varying only in the values of TE_{eff}, ETL, and E-Space. The reason of using matrix size of 128 × 256 instead of 256 × 256 was mainly to reduce image time. With 18 hybrid-RARE pulse sequences and one CSE sequence, all at 128 × 256 , each participant had to be remained in the magnet for at least 75 min. Very little uncontrolled motion was detected by the authors during the lengthy imaging time.

A second objective of this study was to further establish the potential of the contrast-optimized hybrid-RARE sequences for the narrower range of scan parameters determined from the 18 pulse sequences in clinical application. This was now done at twice the spatial resolution (matrix 256 × 256) while keeping field of view and section thickness unchanged. Five volunteers were imaged with six hybrid-RARE sequences (Table 2). Only the higher value region of

Table 1. Hybrid-RARE scan variables used in images of matrix sizes 128 × 256

Scan #	ETL	TE_{eff} & E-Space (ms)			Scan time (min : s)
1, 2, 3	5	60 & 20	90 & 30	120 & 40	3:54
4, 5, 6	7	60 & 15	90 & 22.5	120 & 30	2:54
7, 8, 9	9	70 & 14	90 & 18	120 & 24	2:16
10, 11, 12	11	75 & 12.5	90 & 15	120 & 20	3:36
13, 14, 15	13	85 & 12.1	100 & 14.3	120 & 17.1	3:00
16	15			120 & 15	2:36
17	17			120 & 13.3	2:24
18	19			120 & 12.0	2:12

Table 2. Hybrid-RARE scan variables used in images of matrix sizes 256 × 256

Scan #	ETL	TE_{eff} & E-Space (ms)	Scan time (min : s)
1	13	120 & 17.1	4:36
2	15	120 & 15.0	4:00
3	17	120 & 13.3	3:24
4	19	126 & 12.6	3:12
5	17	120 & 13.3 (RT)	4:16
6	17	120 & 13.3 (RT & FS)	6:21

ETL (from 13 to 19) were investigated. The relative benefits of fat suppression and respiratory triggering were investigated at ETL = 17. Because of the long scan times required, CSE scans were not performed at this higher spatial resolution.

Quantitative Analysis

A uniform criterion for selecting the anatomical regions for signal intensity measurements was applied to all images. Average signal intensities (SI) were measured in the liver and spleen by tracing the contour of the entire organs. Noise was measured anterior to the abdominal wall, as the standard deviation (SD) of spurious signal in a broad region of interest. Images were compared quantitatively with respect to contrast-to-noise ratio of spleen vs liver (CNR = [SI(spleen)–SI(liver)]/SD(noise)), signal-to-noise ratio of the spleen (SNR = SI(spleen)/SD(noise)), signal intensity ratio (SIR = SI(spleen)/SI(liver)), and contrast difference ratio (CDR = [SI(spleen)–SI(liver)]/SI(liver)] of spleen vs liver. The parameters SIR and CDR were measured in addition to SNR and CNR because they are influenced much less by noise, and consequently are more robust indicators of contrast changes.

All measured values are expressed as mean ± SD. To compare the image variables between CSE and each of the hybrid-RARE sequences, over the same group of subjects, statistical analysis was performed on a PC using Student's paired *t*-test.

Qualitative Analysis

Image quality of the hybrid-RARE images was compared to the corresponding CSE (ET = 90 ms) images by two radiologist who graded all images independently, with images of hybrid-RARE sequences evaluated in a randomized, blinded fashion. A score from zero to three was assigned to each of the five criteria of the 18 pulse sequences: 1) image sharpness, 2) vascular artifacts, 3) ghosting artifacts, 4) chemical shift artifacts, and 5) truncations. The scoring scale was defined as follows: 0 = considerably worse; 1 = slightly worse; 2 = comparable; 3 = considerably better. An overall imaging quality (QUA) score was given to each pulse sequence by summation of all of the individual scores. These scores were then normalized to an arbitrary value of 10 which was assigned to the reference CSE image. For high resolution hybrid-RARE images an absolute scoring scale for overall image quality was used according to: 1 = poor; 2 = fair; 3 = good; 4 = very good; and 5 = excellent.

Statistical significance of the data from the qualitative analysis was tested with the paired-sample sign test.

RESULTS

Quantitative Analysis

The findings of the measured image variables, SIR, CDR, CNR, and SNR, are summarized in Table 3 which shows the general tendencies exhibited by the data for four groups of scans: CSE, hybrid-RARE (ETL = 5–11, all TE_{eff}), hybrid-RARE (ETL = 13–19, all TE_{eff}) and hybrid-RARE (ETL = 13–19, TE_{eff} = 120 ms). Of the four variables measured, SIR, and CDR, which are less dependent on the measurement of noise, achieved statistical significance in differentiating these four groups of scans. On average, hybrid-RARE scans with ETL above and equal to 13 exhibited higher liver-spleen contrast ($p < 0.05$) than the corresponding CSE (TE = 90 ms). Representative images are displayed in Fig. 3. Furthermore, the data in this ETL range show statistically significant improvement

Table 3. Statistical analysis for measured variables: CCR, SIR, CNR, and SNR. All values expressed as Mean ± one SD. Student's Paired-t Test was used for the analysis. Comparisons were taken between CSE and each hybrid-RARE scan, over the same group of subjects

Measured variable	CSE mean over volunteers (TE = 90 ms)	Hybrid-RARE mean over volunteers, and over ETL: 5–11, All TE_{eff}	Hybrid-RARE mean over volunteers, and over ETL: 13–19, All TE_{eff}	Hybrid-RARE mean over volunteers, and over ETL: 13–19, TE_{eff} = 120 ms
CDR	48.8 ± 8.9	47.4 ± 8.1	50.9 ± 8.1	53.9 ± 6.4
SIR	2.0 ± 0.3	2.0 ± 0.3	2.1 ± 0.3	2.3 ± 0.4
CNR	16.6 ± 8.7	18.5 ± 7.6	19.2 ± 6.6	19.6 ± 6.7
SNR	33.8 ± 12.8	27.4 ± 12.6	25.7 ± 9.3	26.2 ± 6.7

in liver-spleen contrast relative to the ones acquired with fewer echoes ($p < 0.05$).

Data plotted as function of individual ETL/TE_{eff} pairs over all subjects are displayed in Fig. 2 for QUA, CDR, and SIR. The results further support the general tendencies inferred from Table 3. Liver-spleen contrast (CDR and SIR) fluctuates around the CSE contrast level. For every value of ETL, better contrast is achieved at longer TE_{eff} values, as expected for T2-weighted images. At the longest TE_{eff} value (120 ms) used in the experiments, the contrast improves systematically as function of increasing ETL, or equivalently as function of decreasing echo spacing allowable by system hardware. This contrast is consistently superior to the one exhibited by the reference CSE scan ($p < 0.01$). SNR was slightly inferior for all hybrid-RARE sequences than for the CSE reference sequence. Analysis of the data in terms of CNR and SNR proved to be of limited value due to the large variance exhibited by the measurements (see Table 3).

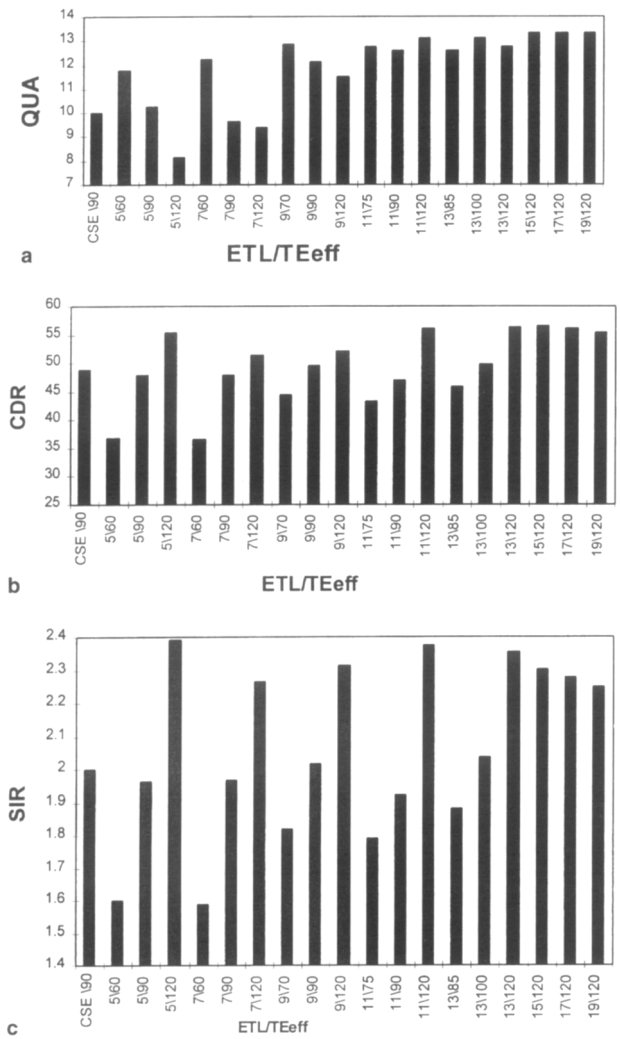

Fig. 2. Results of the measured variables, averaged over all subjects, as function of ETL/TE_{eff} pairs. a) QUA, b) CDR, and c) SIR.

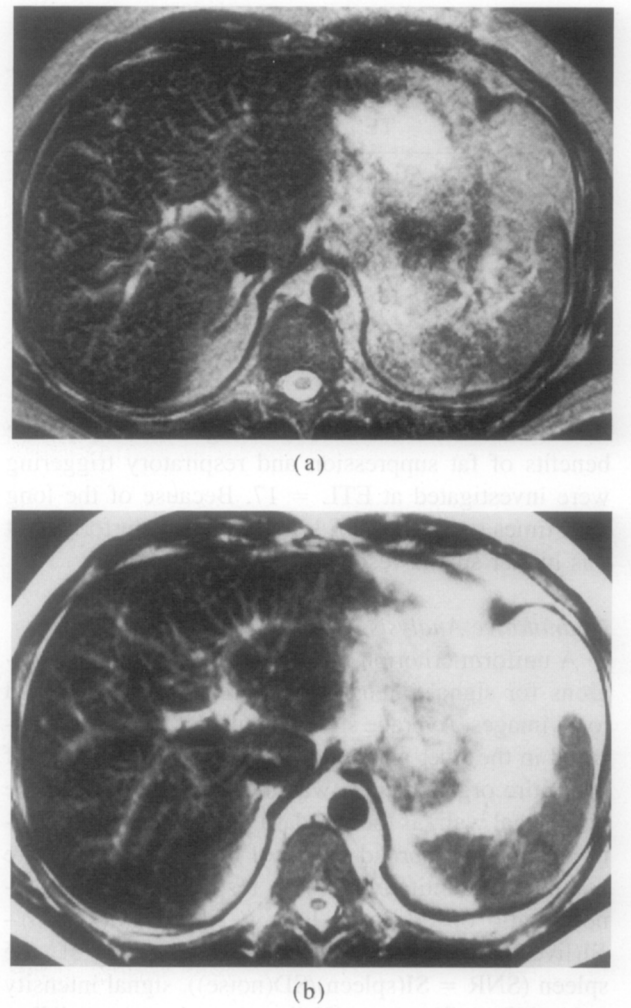

Fig. 3. Representative images: CSE and hybrid-RARE, no special image options, such as respiratory triggering (RT) or fat suppression (FS). a) CSE (128 matrix, 75% rectangular, TE = 90 ms, NEX = 4, HF = 0.6), b) Hybrid-RARE (128 matrix, 75% rectangular, TE_{eff} = 120 ms, NEX = 4, HF = 0.6, ETL = 17).

Qualitative Analysis

Table 4 contains the qualitative assessment of hybrid-RARE as compared to CSE over various key parameter ranges. In imaging sharpness, the hybrid-RARE sequences, with ETL 13 and higher, showed less image blurring (73% for all TE_{eff} and 81% for TE_{eff} = 120 ms, $p < 0.05$). The hybrid-RARE also demonstrated less vascular artifact (87% for all TE_{eff} and 76% for TE_{eff} = 120 ms) and less ghosting artifacts (70% for all TE_{eff} and 76% for TE_{eff} = 120 ms) than CSE sequence ($p < 0.05$). In chemical shift and truncation artifact, the hybrid-RARE and the CSE sequences are compatible to each other. The overall im-

Table 4. Qualitative comparison of hybrid-RARE and CSE pulse sequences. All values are percentages. Statistical significance was determined by using pair-sample sign test at cutoff value of 0.05

	Better image sharpness			Less vascular artifact			Less ghosting artifact			Less chemical shift artifact			Less truncation artifact			Overall image quality		
	RARE	CSE	Equal	RARE	CSE	Equal	RARE	CSE	Equal	RARE	CSE	Equal	RARE	CSE	Equal	RARE	CSE	Equal
ETL = 5–11																		
All TE_{eff}	59	25	16	*67	12	21	*59	23	18	33	18	49	6	16	*78	*70	23	7
ETL = 13–19																		
All TE_{eff}	*73	3	24	*87	0	13	*70	8	22	35	0	65	11	5	*84	*81	0	19
ETL = 13–19																		
TE_{eff} = 120 ms	*81	0	19	*76	0	24	*76	0	24	24	0	*76	0	0	*100	*76	0	24

RARE is the abbreviation of Hybrid-RARE. All values are presented as percentages.
* $p < 0.05$.

age quality was consistently superior than the CSE sequence for all hybrid-RARE scans ($p < 0.05$).

The results of the implementation of hybrid-RARE sequences at a higher spatial resolution, and with ETL/TE_{eff} pairs in the optimum range (ETL/TE_{eff} = 13–19/120) determined from the 18 sequences, are shown in Fig. 4. The values of SIR and QUA were plotted after being multiplied by a factor of 10 for the purpose of comparison. Because of the small number of volunteers, the variation in values of either CDR and SIR did not reach the level of statistical significance. The overall image quality, however, resulted in approximately a twofold improvement in overall image quality with fat suppression and respiratory triggering. Representative images at higher resolution are displayed in Fig. 5. The images demonstrate the image quality possible with higher resolution at higher ETL, or echo-packed hybrid-RARE sequences. They also illustrate the benefits of respiratory triggering and fat suppression.

DISCUSSION

Because of the time constrains introduced by the large number of sequences studied, the bulk of this study was performed at a lower spatial resolution than is normally used in actual imaging protocols. The CSE parameters were chosen to parallel as close as possible the hybrid-RARE protocols. Common parameters included voxel dimensions ($2.5 \times 2.5 \times 10\ mm^3$), matrix size, spatial coverage, number of excitations, TR, and did not include imaging options such as respiratory triggering or fat suppression. Although the measured mean SNR of CSE exceeds that for high-ETL hybrid-RARE scans (see Table 3), a fair comparison should taken into account the large reduction in total scan time achievable with hybrid-RARE sequences, from 12 min to less than 2.5 min (Table 1). Should the scan time of hybrid-RARE be increased to 12 min by incrementing the number of excitations, the theoretical

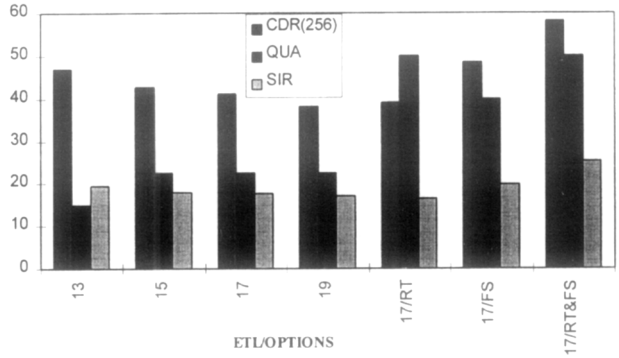

Fig. 4. Results of QUA, CDR and SIR as function of ETL at higher image resolution. SIR values were plotted after multiplying by a factor of 10 for the purpose of comparison.

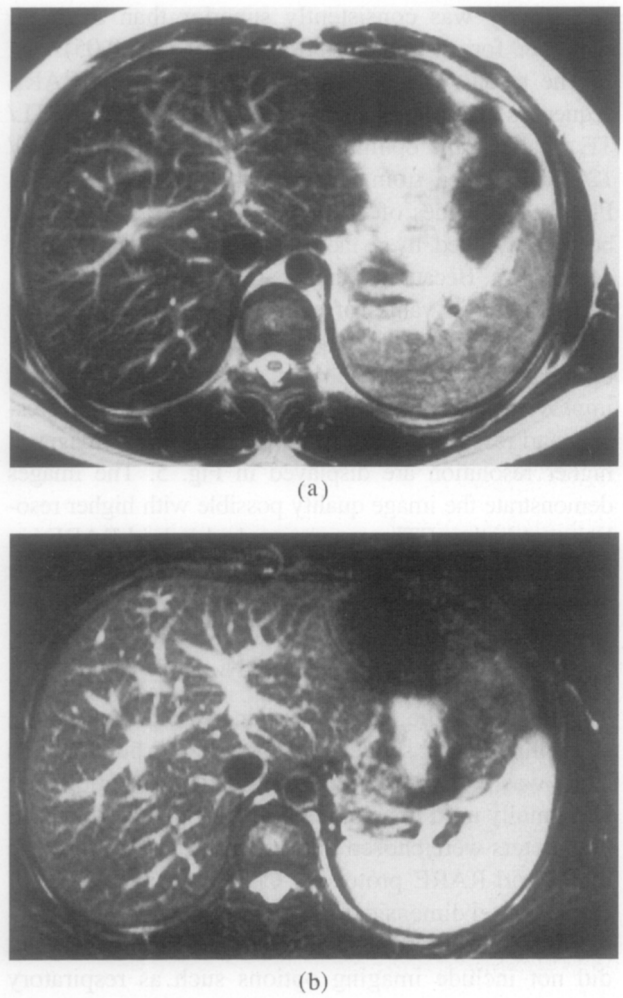

Fig. 5. High resolution images a) Hybrid-RARE (256 matrix, 75% rectangular, ETL = 17, RT), b) Hybrid-RARE (256 matrix, 75% rectangular, ETL = 17, RT, FS).

SNR would be on the order of 50, leading to a factor of $\approx$1.5 advantage in intrinsic SNR for hybrid-RARE (ETL = 17, E-Space = 13 ms) over CSE. This relative advantage in intrinsic SNR is likely to increase with improvements in MR imaging technology, specifically by reducing the minimum E-Space with the implementation of stronger gradient systems.

Standardization and optimization of multi-line, segmented k-space acquisitions such as hybrid-RARE is difficult because, in these schemes, contrast and geometry (image sharpness) are interrelated and influenced by a common set of scan parameters. The parameters such as ETL, TE_{eff}, E-Space, the echo train duration, the echo train unit module, the time from the excitation to the center echo train (ET-Center), and the inter relationship between them are shown in Fig. 1. An additional difficulty stems from the specific relations between the scan parameters which can be manufacturer-specific, depending on the trajectory in k-space (raster) followed during the acquisition of the raw data. For example, as illustrated in Fig. 6, with the scrollable profile raster first discussed by Melki,[5] it is possible to increase TE_{eff} keeping both ETL and E-Space fixed. This is not the case with non-scrollable rasters, such as the linear profile order used in this study, in which an increment in TE_{eff} at fixed ETL necessarily results in a longer E-Space. Caution should be exercised when translating hybrid-RARE protocols across platform, particularly with respect to the meaning of TE_{eff} which coincides with the midpoint of the echo train in the linear profile order, but can be scrolled within the echo train in Melki's raster. Undoubtedly, a better understanding of the effects of k-space raster in image sharpness, image contrast, and conspicuity of small short-T2 lesions, would be useful in the fine tuning and standardizing hybrid-RARE pulse sequences, as well as in the optimization of other multi-line segmented k-space acquisitions, such as EPI, ultrafast Turbo Spin-Echo, and GRACE (Gradient-And-Spin-Echo).[15]

CONCLUSION

The effects of varying two of the key hybrid-RARE scan variables (ETL and TE_{eff}) for a specific k-space raster (linear order profile) on image quality and contrast have been investigated in this work. A consistent trend of image quality improvement for hybrid-RARE

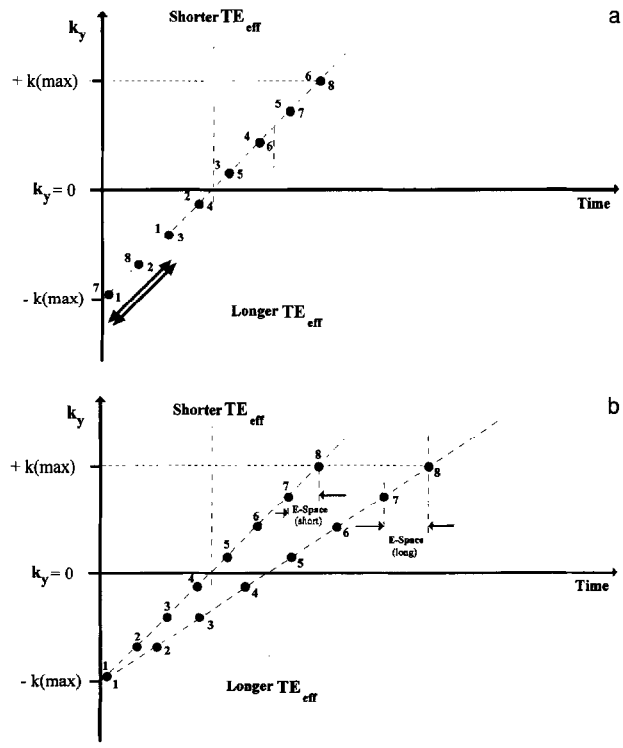

Fig. 6. K-space rasters a) Scrollable-Melki raster, b) Non-scrollable "linear profile order" raster.

scans with closely packed echo trains (ETLT > T13, TE_{eff}) was found. Undoubtedly, the diagnostic power of multi-line, segmented k-space MR imaging pulse sequences can be benefited significantly from technological advances leading to even shorter echo spacings. Since E-Space is ultimately limited by the duration of the echo train unit module, the use of stronger imaging gradients and faster receivers, could result in significant diagnostic advantages of hybrid-RARE sequences, relative to CSE.

In summary, the optimized hybrid-RARE sequences defined in this study are capable of producing sharp and relatively artifact free images of the upper abdomen. Their efficacy to delineate small short-T2 hepatic lesions needs further evaluation in systematic clinical trials. Also, experimentation with properly designed phantoms simulating such structures, would be useful in determining the effects of ETL, TE_{eff}, E-Space, and k-space raster, on lesion conspicuity in the absence of motion.

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REFERENCES

1. Ferrucci, J.T. Liver tumor imaging: Current concepts. Am. J. Roentgen. 155:473–484; 1990.
2. Mitchell, D.G. Focal hepatic lesions: The continuing search for the optimal MR imaging pulse sequences. Radiology 193:17–18; 1994.
3. Stark, D.D.; Wittenberg, J.; Edelman, R.R. et al. Detection of hepatic metastases: analysis of pulse sequence performance in MR imaging. Radiology 159:365–370; 1986.
4. Hennig, J.; Friedburg, H. Clinical applications and methodological developments of the RARE technique. Magn. Reson. Imaging 6:391–395; 1988.
5. Melki, P.S.; Mulkern, R.V.; Panych, M.S.; Jolesz, F.A. Comparing the Faise method with conventional dual-echo sequences. J. Magn. Reson. Imaging 1:319–326; 1991.
6. Listerud, J.; Einstein, S.; Outwater, E.; Kressel, H.Y. First principles of fast spin-echo. Magn. Reson. Q. 8:199–244; 1992.
7. Elevelt, A.J.; van Vaals, J.J.; van Yperen, G.H. Single-breath hold respiratory-triggered imaging of the complete liver using ultrafast Turbo Spin Echo. Thirteenth Annual Meeting of the Society of Magnetic Resonance in Medicine, Vol. 1 , San Francisco, CA:SMRM; 1994: p. 301.
8. Goldberg, M.A.; Hahn, P.F.; Saini, S.; Cohen, M.S.; Reimer, P.; Brady, T.J.; Muelle, P.R. Value of T1 and T2 relaxation times from echoplanar MRimaging in the characterization of focal hepatic lesions. AJR 160:1011–1017; 1993.
9. Catasca, J.V.; Mirowitz, S.A. T2-Weighted MR imaging of the abdomen: Fast spin-echo versus conventional spin-echo sequences. AJR 162:61–67; 1994.
10. Semelka, R.C.; Shoenut, J.P.; Kroeker, R.M. T2-Weighted MR imaging of focal hepatic lesions: Comparison of various RARE and fat-suppressed spin-echo sequences. JMRI 3:323–327; 1993.
11. Siewert, B.; Muller, M.F.; Foley, M.; Wielopolski, P.A.; Finn, J.P. Fast MR imaging of the liver: Quantitative comparison of techniques. Radiology 193:37–42; 1994.
12. Kreft, B.; Layer, G.; Steudel, A.; et al. Evaluation of Turbo spin-echo sequences for MRI of focal liver lesions at 0.5 T. Eur. J. Radiol. 4:106–113; 1994.
13. Low, R.N.; Hinks, R.S.; Alzate, G.D.; Shimakawa, A. Fast spin-echo MR imaging of the abdomen: Contrast optimization and artifact reduction. JMRI 4:637–645; 1994.
13. Outwater, E.K.; Mitchell, D.G.; Vinitski, S. Evaluation of a fast-spin echo sequence for abdominal imaging. Radiology 190:425–429; 1994.
14. Feinberg, D.A.; Oshio, K. GRASE (Gradient-And-Spin-Echo) MR Imaging: A new fast clinical imaging technique. Radiology 181:597–604; 1991.