Extended coverage first pass perfusion imaging using slice interleaved TSENSE

Peter Kellman, J. Andrew Derbyshire, Kwabena O. Agyeman, Elliot R. McVeigh, and Andrew E. Arai
Laboratory of Cardiac Energetics, National Heart Lung and Blood Institute, NIH, DHHS, Bethesda Maryland 20892 USA

INTRODUCTION

Parallel imaging is applied to first pass contrast enhanced cardiac MR to yield greater spatial coverage for a fixed temporal resolution. The method combines rate R=2 acceleration using TSENSE with shot-to-shot interleaving of R=2 slices. The √R SNR loss is largely compensated by the increased flip angle that is used with slice interleaving. In this manner, increased spatial coverage is achieved while maintaining approximately the same signal quality. Single heart beat temporal resolution was accomplished with spatial coverage of 8 slices at heart rates up to 71bpm, 6 slices up to 95bpm, and 4 slices up to 143bpm.

Coverage of the entire heart during a first pass contrast enhanced MRI with single heartbeat temporal resolution is desirable for quantifying perfusion abnormalities. Current imaging protocols limit the ability to image the entire heart with single heartbeat temporal resolution, particularly at high heart rates. Multi-slice coverage may be achieved using FGRE with echo-train readout and saturation recovery with a relatively short preparation time (TI) [1]. Imaging quality may be improved at the expense of coverage [2] by increasing TI and readout flip angle. Alternatively, a notch pulse scheme [3] may be used to increase the effective TI by imaging a slice while the following slice is being prepared. However, this method may result in artifacts resulting from the flow of saturated blood. SSFP (FISP) imaging may also be used with saturation recovery to produce high quality images without resorting to echo-train readout. A full comparison between FISP and FGRE methods remains to be done. The proposed accelerated imaging method herein uses slice interleaving as a method for increased coverage without loss in image quality.

METHODS

Imaging time may be reduced by under-sampled acquisition with full-FOV reconstruction using either UNFOLD [4] or parallel imaging methods such as SENSE [5]. The TSENSE [6] method may be used with interleaved phase encode acquisition order to adaptively derive or update B1-map estimates as well as for additional alias artifact suppression. The proposed method combines rate R=2 acceleration using TSENSE with shot-to-shot interleaving of R=2 slices. Slice interleaving shares a single saturation pulse for the 2 interleaved slices thereby reducing the net preparation time (as shown in Figure 1). Furthermore, the effective TR is increased by R=2 permitting use of an increased readout flip angle. The √R SNR loss is largely compensated by this increased flip angle. A larger prep time (TI) may be used for further improved image contrast and point spread function. Slice interleaving combined with accelerated imaging maintains the same overall image acquisition window.

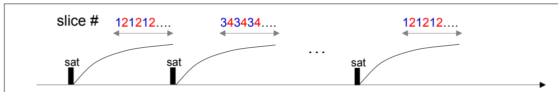

Figure 1. Timing for shot-to-shot slice interleaved acquisition.

Imaging was performed on a GE 1.5T CV/*i* scanner, using a multi-shot EPI FGRE sequence with the following parameters: echo-train length 4, TR=6.9ms, ±125k BW, and 10% trigger window. The acquisition matrix was 128x80 with typically 40x25 cm2 FOV producing a nominal resolution of 3.1x3.1 mm^2 and 8 mm slice thickness. Three methods were compared with the following parameters: {prep flip angle, readout flip angle, TI, acceleration factor (R)}: (a) method 1 {70º/10º/80ms/R=1} per reference [1], (b) method 2 {90º/20º/120ms/R=1} modified for improved image quality, and (c) method 3 {90º/30º/120ms/R=2} with slice interleaving and R=2 TSENSE acceleration. TI is defined at the center of k-space acquisition rather than to the 1st readout as in [1,2]. The effective TR for method 3 with slice interleaving was 13.8ms permitting an increased flip angle. Variable parameters are listed in Table 1.

Table 1. Variable parameters for 3 methods.

	Method 1	Method 2	Method 3
Prep Flip Angle	70°	90°	90°
Readout Flip Angle	10°	20°	30°
Prep time*, TI (ms)	80	120	120
Effective TR (ms)	6.9	6.9	13.8
Acceleration factor	1	1	2

* defined as time to center of *k*-space

The number of slices (SAX) acquired per heartbeat was a function of heart rate. The initial image for each slice was used as a reference for B1-map estimation and did not have any saturation preparation. A fixed 10º readout flip angle was used for the initial reference image of all methods which also served to normalize surface coil intensity variation. A standard GE 4-element cardiac surface coil array was used. All individuals in this study (n=6) were normal, healthy volunteers giving informed consent in accordance with an NIH approved protocol. Data was acquired using all 3 methods for each volunteer. Care was taken to use the same coil positioning and slice orientation for the 3 exams conducted on different days. Reconstructions were performed using both TSENSE and UNFOLD methods. UNFOLD temporal filtering used 80% of the available bandwidth (1 dB). The SNR and CNR measurements were made in 6 equiangular segments of the SAX. Variations in surface coil intensity due to coil positioning were normalized using the reference image without saturation preparation.

RESULTS

Image reconstruction for the accelerated imaging case (method 3) was performed using SENSE with and without UNFOLD temporal filtering, as well as UNFOLD alone, for comparison of artifact suppression performance. The combined TSENSE with UNFOLD filtering provided the greatest artifact suppression and was most robust. Figure 2 shows example SAX images for a single slice acquired using method 3 and reconstructed with UNFOLD alone (top row), SENSE alone (middle row), and combined SENSE and UNFOLD (bottom row). The 3 cases (columns) illustrate various artifact mechanisms. The case shown in the left column illustrates the time of peak RV contrast enhancement. The reconstruction using UNFOLD alone has a FOV/2 artifact of the RV due to the rapid change in contrast. The case shown in the center column illustrates an artifact in the UNFOLD alone reconstruction due to breathing motion toward end of acquisition. The case shown in the right column illustrates a time with residual alias artifact for the SENSE alone reconstruction. This is caused by EPI distortion which leads to errors in the sensitivity map estimated in-vivo using the TSENSE method.

Figure 3 shows example SAX images for a single slice acquired using the 3 methods. All images are scaled for equal noise standard deviation and are displayed using the same window-level. The parameters of method 2 have improved quality as compared to method 1 at the expense of spatial coverage. The image quality for method 3 has comparable quality to method 2 with 2x spatial coverage. The contrast enhancement (CE) (signal difference between pre- and post- contrast) is graphed in Fig. 3(a) (mean ± std, N= 72 segments/method) for the 3 methods, normalized to method 1. For the normalized CNR shown in Fig. 3(b), the CE for method 3 is scaled by the factor g√R which is approx. 1.5 using the UNFOLD noise equiv. BW of 0.8 and SENSE g-factor ≈ 1.2 using the 4-coil array, thus yielding comparable CNR for methods 2 and 3.

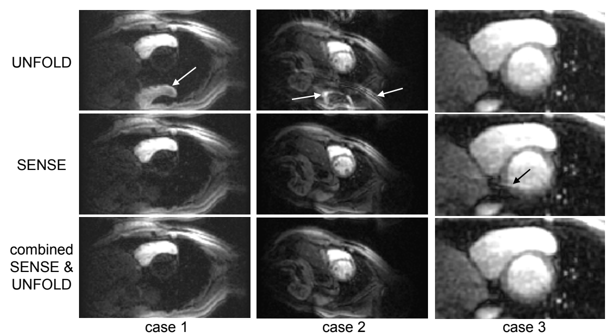

Figure 2. Illustration of artifacts for 3 cases using various reconstruction methods. Case 1 illustrates UNFOLD artifact due to dynamic contrast enhancement. Case 2 illustrates UNFOLD artifact due to breathing motion. Case 3 illustrates residual SENSE artifact due to EPI distortion related errors in in-vivo sensitivity map estimates.

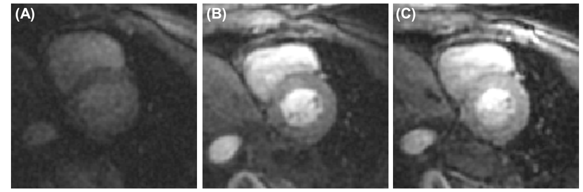

Figure 2. Example 1st pass contrast enhanced images post-contrast for (a) method 1, (b) method 2, and (c) method 3, reconstructed using TSENSE with UNFOLD temporal filtering.

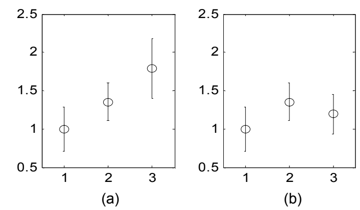

Figure 3. (a) Normalized contrast enhancement, and (b) normalized CNR for 3 methods (mean ± std).

DISCUSSION

Various mechanisms may contribute to residual undersampling artifacts for the different reconstruction methods:

- UNFOLD method
  - dynamic contrast enhancement may cause artifacts
  - breathing motion causes artifacts
- SENSE method
  - artifact suppression limited by errors in-vivo sensitivity map estimates (caused by EPI distortion in TSENSE auto-calibrating reference image)
  - residual artifacts may appear for severe breathing motion
- Combined SENSE & UNFOLD
  - generally good artifact suppression

CONCLUSIONS

It has been demonstrated that slice interleaving with TSENSE achieves 2x spatial coverage without reduction in image quality. Higher accelerations factors may be practical using a greater number of coils, although the SENSE g-factor may increase. Using 8-coils systems the R=2 SENSE g-factor is expected to be on the order of 1.1 or less.

REFERENCES

1. Ding S, et al., *MRM.* 1998 Apr; 39(4):514-9.
2. Bertschinger KM, et al., *JMRI.* 2001 Nov; 14(5):556-62.
3. Slavin GS, et al., Radiology. 2001 Apr; 219(1):258-63.
4. Madore B, et al., *MRM.* 1999 Nov; 42(5):813-828.
5. Pruessmann KP, et al., *MRM.* 1999 Nov; 42(5):952–962.
6. Kellman P, et al., *MRM.* 2001 May; 45(5):846-52.