Dynamic Autocalibrated Parallel Imaging Using Temporal GRAPPA (TGRAPPA)

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Current parallel imaging techniques for accelerated imaging require a fully encoded reference data set to estimate the spatial coil sensitivity information needed for reconstruction. In dynamic parallel imaging a time-interleaved acquisition scheme can be used, which eliminates the need for separately acquiring additional reference data, since the signal from directly adjacent time frames can be merged to build a set of fully encoded full-resolution reference data for coil calibration. In this work, we demonstrate that a time-interleaved sampling scheme, in combination with autocalibrated GRAPPA (referred to as TGRAPPA), allows one to easily update the coil weights for the GRAPPA algorithm dynamically, thereby improving the acquisition efficiency. This method may update coil sensitivity estimates frame by frame, thereby tracking changes in relative coil sensitivities that may occur during the data acquisition. Magn Reson Med 53:981–985, 2005. Published 2005 Wiley-Liss, Inc.†

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Image acquisition time is one of the most important considerations for clinical magnetic resonance imaging. Recently, several partially parallel acquisition (PPA) strategies (1–7) have been described to speed up the acquisition time by decreasing the number of phase encoding steps by a reduction factor R. Normally, this undersampling is performed by increasing the distance between adjacent acquired k-space lines while maintaining the maximum k-values. All PPA reconstruction algorithms require extra coil sensitivity information from an array of multiple radiofrequency receiver coils to remove the aliasing artifacts that result from undersampled k-space. Naturally, this sensitivity information is acquired in an additional reference experiment, thereby degrading the efficiency of the actual PPA experiment. In dynamic parallel imaging, a time-interleaved acquisition scheme similar to UNFOLD (8) and TSENSE (9) may be exploited in order to obtain this sensitivity information directly from the actual accelerated dynamic imaging experiment, thereby realizing the full image acceleration. To this end, directly adjacent time frames can be merged to build a fully encoded, full-resolution reference data set, which can be used as autocalibration signals (ACS) for an improved GRAPPA (7) reconstruction. With every acquired time frame in the series a new set of ACS lines can be generated. This allows one to update the coil coefficients for the GRAPPA algorithm dynamically, thereby automatically tracking changes in relative coil sensitivities over time efficiently. In particular, this method is beneficial whenever coil sensitivity maps, as required for the SENSE algorithm, are difficult to obtain. This is the case in, for example, inhomogeneous regions with low signal-to-noise ratio (SNR) (e.g., the lung). In this work, TGRAPPA reconstructions of accelerated (reduction factor 2 to 4) real-time (nongated), free breathing cardiac studies are presented.

METHODS

All experiments were performed on a Sonata 1.5-T clinical whole body scanner (Siemens Medical Solutions, Erlangen, Germany) equipped with eight independent receiver channels. For signal reception, an eight-element receiver coil array (Nova Medical, Wilmington, MA) was used. A trueFISP sequence was chosen for real-time non-breath-held cardiac imaging. The imaging parameters were TE = 1.11 ms, TR = 2.22 ms, FOV = 36.0 × 29.2 cm, matrix = 128 × 60, slice thickness = 8 mm, readout flip angle = 50°. The final image resolution is 2.8 × 4.8 mm. The phase encoding direction was chosen to be in the AP direction in all experiments. Four volunteers were examined and informed consent was obtained before the study. Nongated dynamic cardiac imaging experiments during different breathing scenarios were performed at frame rates accelerated from approximately 7.5 frames per second (fps) (R = 1) to 30 fps (R = 4). The experiments were performed under "normal breathing," "fast breathing," and "deep breathing" conditions. The proposed TGRAPPA scheme derives the autocalibration signals over time directly from the undersampled data itself. The final PPA image reconstructions were performed off-line with the GRAPPA algorithm as described in the original GRAPPA paper (7) using the MATLAB programming environment (The Mathworks, Natick, MA). The GRAPPA parallel imaging reconstruction is performed in k-space by calculating the missing k-space lines in each coil in the array using a weighted sum of adjacent lines from all coils. The weighting coefficients are determined by solving a set of linear equations using the ACS lines acquired according to the proposed TGRAPPA scheme. The Matlab reconstruction times, which were not optimized for real time applications, were approximately 2–3 s per frame. Optimized software-based reconstruction should be feasible at frame rates of 15–30 fps.

Figure 1 shows a schematic depiction of the time-interleaved acquisition scheme for an acceleration factor of R = 4. In this example, at least four adjacent time frames need to be merged to build a complete set of k-space data (also

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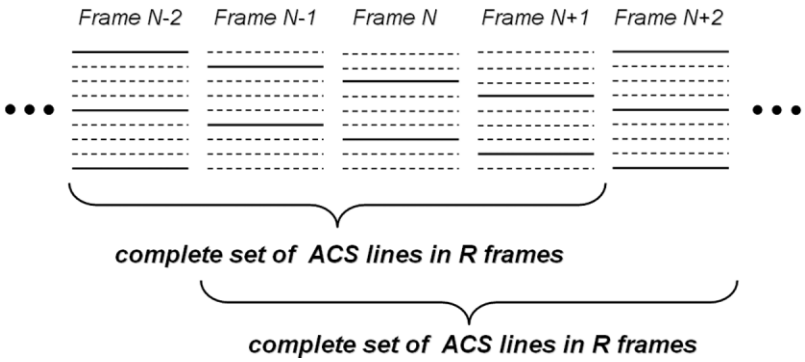

FIG. 1. Schematic description of the time interleaved acquisition scheme for a reduction factor of $R = 4$. At least R adjacent frames must be merged to build a fully encoded full-resolution reference ACS data set for a GRAPPA reconstruction of frame N. With every acquired time frame in the series, a new set of ACS lines can be derived to reconstruct the next frame in the time series.

known as autocalibration signal or ACS lines) for the GRAPPA reconstruction of one time frame. In general, more neighboring frames can be averaged to increase the SNR of the ACS data, resulting in a potentially improved GRAPPA reconstruction. With every acquired time frame in the series, a new set of ACS data may be accomplished to reconstruct the next frame in the time series, thereby tracking changes in relative coil sensitivities over time.

The TGRAPPA reconstruction procedure was set up as follows. For the first 4 ($R = 2$), 5 ($R = 3$), or 7 ($R = 2$) time frames of the series the GRAPPA reconstruction coefficients were derived from the first 6 ($R = 2$), 9 ($R = 3$), or 12 ($R = 4$) time frames. After that a dynamic update was used as depicted in Fig. 1 by merging 6 ($R = 2$), 9 ($R = 3$), or 12 ($R = 4$) time frames. Similarly, the GRAPPA reconstruction coefficients for the last time frames were derived from the last 6 ($R = 2$), 9 ($R = 3$), or 12 ($R = 4$) time frames.

RESULTS

In Fig. 2, representative images for acceleration rates of (a) $R = 1$ (unaccelerated) (7.5 fps), (b) $R = 2$ (15 fps), (c) $R = 3$ (22.5 fps), and (d) $R = 4$ (30 fps) under normal breathing conditions are shown. The coil weighting coefficients for the GRAPPA reconstructions were derived from 6 ($R = 2$), 9 ($R = 3$), or 12 ($R = 4$) neighboring time frames forming a high SNR, fully encoded, full-resolution set of ACS data, corresponding to a temporal window of 0.4 s. This results in a GRAPPA reconstruction with good artifact suppression up to frame rates of 30 fps.

Figure 3 illustrates the influence of inaccurate sensitivity information, which may arise due to significant respiratory motion during deep breathing. As an example, two time frames (Frames 5 and 151) are shown from an accelerated ($R = 4$) nongated, non-breath-held dynamic cardiac imaging experiment with a temporal resolution of approximately 30 fps. The image reconstructions were done using the GRAPPA algorithm with reconstruction weights calculated (a) only once at the beginning of the series (first 12 frames), (b) only once by integrating all the data acquired during the whole series, and (c) dynamically updated during the time series (12 neighboring frames). This example shows that respiratory motion can significantly change the position of the flexible coil array, resulting in residual

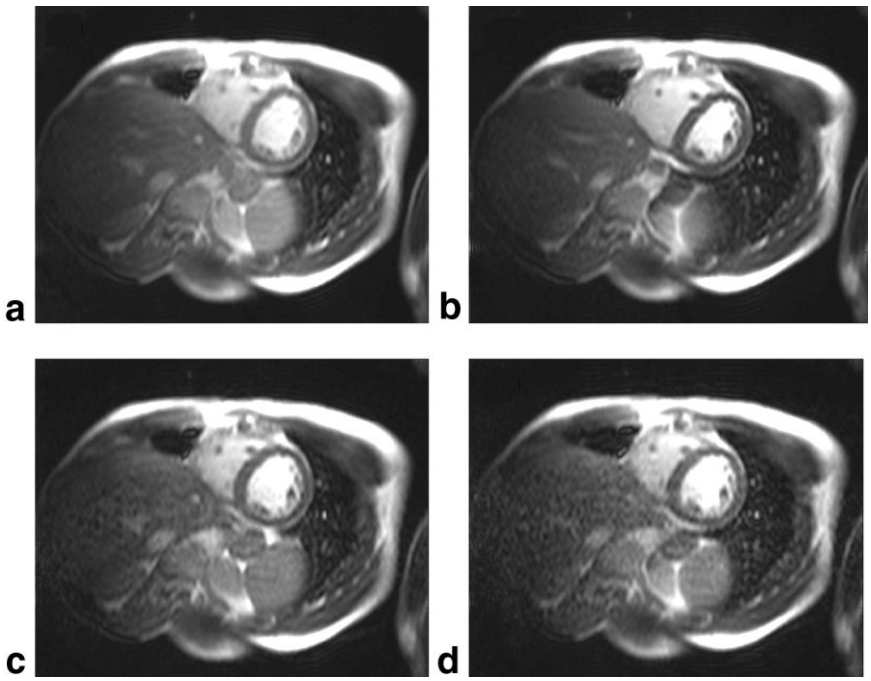

FIG. 2. Example images after GRAPPA reconstruction for acceleration rates of (**a**) $R = 1$ (unaccelerated) (7.5 fps), (**b**) $R = 2$ (15 fps), (**c**) $R = 3$ (22.5 fps), and (**d**) $R = 4$ (30 fps) under normal breathing conditions are shown. The coil weighting coefficients for the GRAPPA reconstructions were derived from 6 ($R = 2$), 9 ($R = 3$), or 12 ($R = 4$) neighboring time frames.

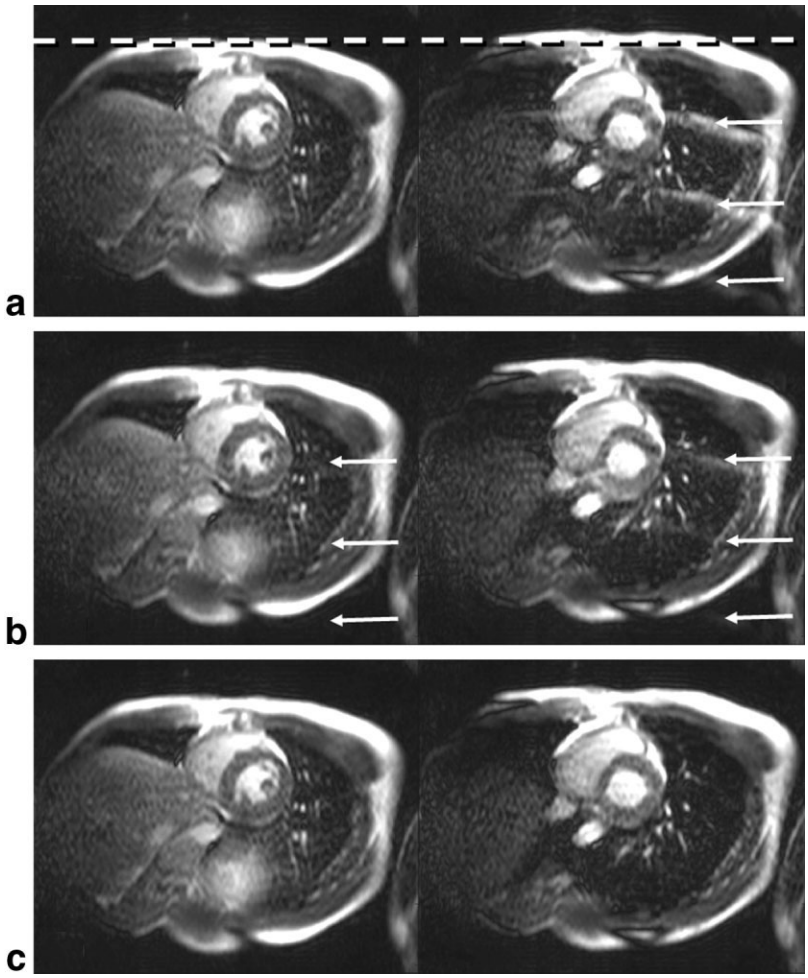

FIG. 3. Illustration of the influence of inaccurate sensitivity information on a successful PPA reconstruction. For demonstration purposes, two time frames (Frames 5 and 151) are shown from an accelerated ($R = 4$) real-time TrueFISP non-breath-held dynamic cardiac imaging experiment with a temporal resolution of 30 fps. The image reconstructions were done using the GRAPPA algorithm with reconstruction weights calculated (**a**) only once at the beginning of the series, (**b**) only once by integrating all the data acquired during the whole series, and (**c**) dynamically updated during the series.

artifacts in time frames where the reference data for coil calibration does not match the actual coil position. These artifacts disappear if the reconstruction parameters are updated dynamically for each time frame.

The benefit of having full resolution reference data for the normal GRAPPA reconstruction is demonstrated in Fig. 4. Rate 4 undersampled images after a standard GRAPPA reconstruction using different number of ACS lines for coil calibration are shown. The image quality suffers significantly with decreased number of ACS lines. In this case a block of at least 32 ACS lines is necessary to provide acceptable image quality. Since normal autocalibrated GRAPPA requires additional ACS lines to be acquired for each frame during an exam where the reconstruction weights must be dynamically updated, the effective acceleration rate for this example would be reduced from rate $R = 4$ to approximately $R = 1.6$. In contrast, the TGRAPPA approach does not require additional reference data, thereby providing full image acceleration.

DISCUSSION

TGRAPPA is easy to implement and has been presented as an efficient method for improving reconstruction quality in dynamic parallel imaging. TGRAPPA was successfully applied to real-time, nongated, free-breathing dynamic cardiac imaging. We have shown that TGRAPPA reconstructions result in excellent image quality without any residual artifacts up to frame rates of 30 fps, even when the coil positions change significantly during the acquisition.

PPA reconstruction with GRAPPA is particularly beneficial in applications where accurate coil sensitivity maps may be difficult to obtain (10). For example, a precise estimation of spatial coil sensitivities may be difficult in inhomogeneous regions with low spin density such as the lung and the abdomen. TGRAPPA provides a means of eliminating the overhead required for acquiring additional ACS lines. In this example with 60 phase encode lines and rate 4 undersampling, if 32 ACS lines were required, the effective acceleration rate would be reduced from rate $R = 4$ to approximately rate $R = 1.6$. Furthermore, the TGRAPPA approach benefits from having the coil sensitivity maps with full spatial resolution, which provides improved artifact suppression.

The time-interleaved sampling scheme could by itself also be used to generate full resolution images using a simple sliding window approach. The output frame rate of this view-sharing technique is essentially the same as the actual frame rate. However, the resulting effective temporal resolution is reduced due to temporal blurring caused by the sliding window strategy. Additionally, a simple

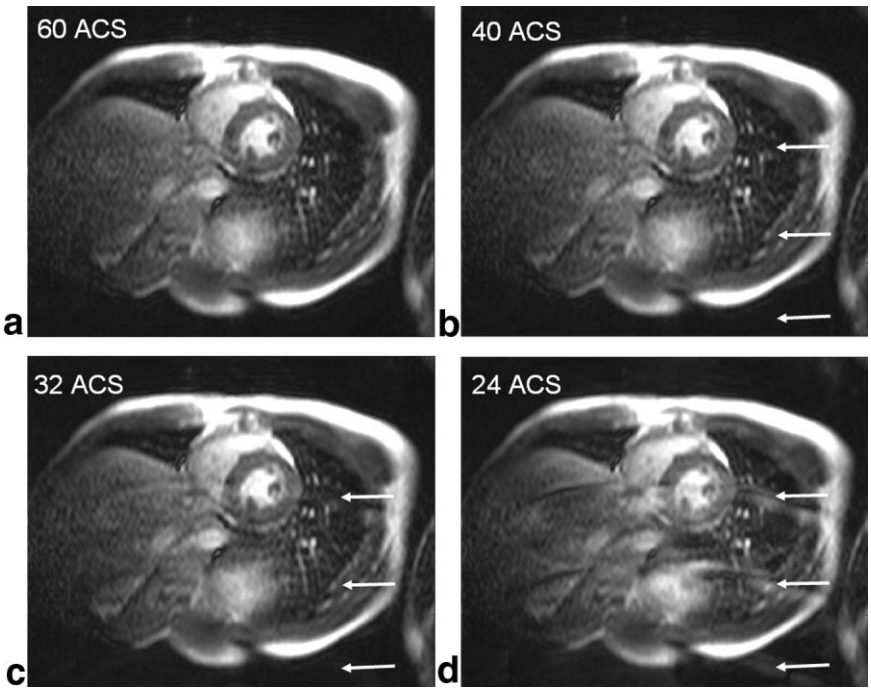

FIG. 4. Rate 4 undersampled example images after GRAPPA reconstruction using (**a**) 60 ACS lines (full spatial resolution), (**b**) 40 ACS lines, (**c**) 32 ACS lines, and (**d**) 24 ACS lines as reference data. The image quality improves significantly with increased number of ACS lines. Residual aliasing artifacts are visible even with 40 ACS lines as reference data.

view shared reconstruction may have ghosting artifacts due to motion. In the TGRAPPA approach, the ACS data, which are used for the TGRAPPA reconstruction, are also generated by using this sliding window strategy; therefore, the ACS data have reduced temporal resolution. However, since the coil sensitivities are relatively static (with respect to the imaging rate) in most applications, the lower temporal resolution of the ACS data, used only for coil calibration purpose, does not reduce the output temporal resolution of the TGRAPPA images. For this reason, in contrast to view sharing, TGRAPPA provides full temporal resolution even when the ACS data are of reduced temporal resolution.

A frame-to-frame update of the reconstruction coefficients can require a long total reconstruction time. However, the high frame rate may allow one to update the reconstruction coefficients much less frequently, since coil motion caused by respiratory motion occurs more slowly than the actual frame rate of 30 fps. Once the reconstruction coefficients are calculated for one frame, they could be used to reconstruct multiple subsequent frames in the series in a short time. During this time, new coil coefficients can be calculated to reconstruct later frames in the series. This adapted concept results in a significantly improved overall reconstruction time, without visible degradation of image quality (11). This concept in combination with a highly optimized GRAPPA algorithm would be a promising technique for true real-time on-the-fly image reconstructions.

CONCLUSION

In this work an efficient method for dynamic parallel imaging by combining a time-interleaved acquisition scheme with autocalibrated GRAPPA was presented. No additional reference data need to be acquired, since the signal from directly adjacent time frames can be merged to form a set of fully encoded full-resolution reference data for coil calibration, thereby realizing full image acceleration. We also demonstrated that the coil coefficients for the GRAPPA algorithm can be easily updated dynamically, thereby tracking changes in relative coil sensitivities during the data acquisition, which may occur due to respiratory motion. TGRAPPA reconstructions of accelerated ($R = 2$ to 4) real-time (nongated), free breathing cardiac studies were presented with excellent image quality and without any visually apparent residual artifacts up to frame rates of 30 fps. This method compensates efficiently for significant changes in coil position due to respiratory motion.

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