Autocalibrating CAIPIRINHA: Reformulating CAIPIRINHA as a 3D Problem

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Introduction: In CAIPIRINHA, multiple slices are excited simultaneously and a unique phase cycle is applied to each slice, resulting in reduced aliasing in the final image [1]. The superimposed slices are reconstructed either using a SENSE type reconstruction [1] or using a GRAPPA type reconstruction by converting the slice dimension to the phase encoding dimension [2]. Although autocalibrated CAIPIRINHA acquisition is possible [2], a separate reference scan is usually needed to reconstruct the aliased slices [1, 2]. In this work, the reconstruction problem in CAIPIRINHA is reformulated as the reconstruction problem of an undersampled 3D Cartesian dataset. The need of a separate reference scan is eliminated by acquiring autocalibrating signal (ACS) in the 3D dataset.

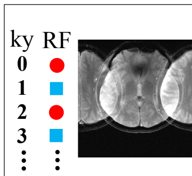


Fig.1. *CAIPIRINHA for 2 slices. 2 RF pulses are applied alternately (Dot: RF_0, Square: RF_1, as defined in the text). 2 slices are shifted by 0, FOVy/2 along the phase encoding direction.*

Methods: Suppose N_s slices are excited simultaneously and the *l*-th ($l=0...N_s-1$) slice is shifted by $l\bullet FOVy/R$ (integer $R \geq N_s$) in the phase encoding direction. The RF pulse applied for the *n*-th($n=0...Ny-1$) phase encoding step is $RF_n(t)=\Sigma_l [rf_l(t)e^{-i2\pi nl/R}]$, where $rf_l(t)$ is the RF pulse which excites the *l*-th slice with zero phase and is independent of *n*. Because of the periodicity $RF_{n+R}(t)=RF_n(t)$, only *R* distinct RF pulses, $RF_0 ... RF_{R-1}$, are needed. An example case where 2 slices are excited simultaneously is shown in Fig.1. If RF_j ($j=0...R-1$) is applied for all the phase encoding steps, the received baseband signal is

$$S_j(k_x,k_y)=\int_x\int_y \left[\sum_{l=0}^{N_s-1} m(x,y,l)e^{-i2\pi jl/R}\right]e^{-i2\pi(k_x x+k_y y)}dxdy \qquad \text{(Eq. 1)}$$

Where $m(x,y,l)$ is the image of the *l*-th slice. Eq.1 depicts that $RF_0...RF_{R-1}$ are able to conduct DFT encoding along the slice select direction. Alternating the multiband pulses in CAIPIRINHA is therefore equivalent to undersampling in the ky-kz plane of the k-space of the N_s simultaneously excited slices, as shown in Fig.2 (a). Reconstructing the individual slices is therefore equivalent to reconstructing the 3D undersampled Cartesian k-space data. Furthermore, extra data acquired at central ky could serve as the ACS data (Fig.2 (a)), thus eliminating the need of a separate reference scan. The ACS data could be included in the final reconstruction to further improve the image quality. Eq.1 also shows that when $R=N_s$, N_s slices are distributed equidistantly on the CAIPIRINHA image and the multiband pulses perform DFT encoding on the excited N_s slices. While when $R>N_s$, the DFT encoding is performed on the excited N_s slices concatenated by $R-N_s$ zero images. In addition, the proposed method could be adapted to reconstruct the aliased slices when additional undersampling is applied in ky.

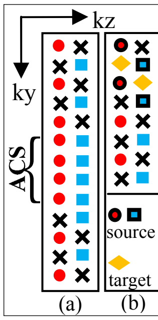


Fig.2. *Proposed autocalibrating CAIPIRINHA for 2 slices. Coil and kx dimensions are omitted. (a) Alternating the multiband pulses is equivalent to undersampling in the ky-kz plane. Fully sampled central ky can serve as ACS data. Dot: data acquired using RF_0, Square: data acquired using RF_1, Cross: unacquired data; (b) Reconstruction kernel used in this work.*

Experiments: Multiband pulses were constructed by modulating a windowed sinc pulse and were implemented as the excitation pulse for a GRE sequence. Brain images of a healthy volunteer were acquired with an 8 channel head coil on a 1.5T GE scanner (TR/TE/α/thick/matrix = 500ms/30ms/20°/8mm/256×256). Fully sampled 3D k-space data was acquired by applying RF_0 or RF_1 alone through all phase encoding steps, and was retrospectively undersampled to mimic the k-space data acquired in a CAIPIRINHA experiment. Reconstruction of the aliased slices was conducted in Matlab using both the proposed autocalibrating method and the conventional GRAPPA type method. For the proposed method, the ACS data was directly taken from the fully sampled 3D dataset and a kernel of size 3×2×2 (kx×ky×kz, Fig.2 (b)) was used to interpolate the missing data using 2D-GRAPPA [3]. For the conventional method, the ACS data was synthesized from the fully sampled 3D dataset and a kernel of size 3×4 (kx×ky) was used to reconstruct the aliased slices using 1D GRAPPA (reduction factor 3) [2, 4, 5]. The ACS data and the kernel sizes were chosen in such a way that both methods use the same number of acquired k-space points to interpolate a missing point, and that both methods use the same amount of ACS data to calibrate the interpolation coefficients. The ACS data was not included in the final image in either method. The relative root mean squared (RRMS) errors between the fully sampled and the accelerated images were calculated as a quantification of the net reconstruction error, as used in previous studies [6]. In addition, a CAIPIRINHA experiment with ky undersampled by 2 was also mimicked.

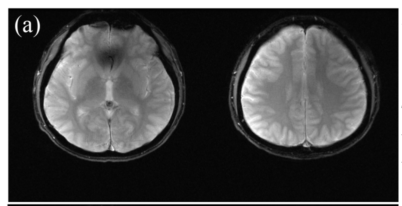
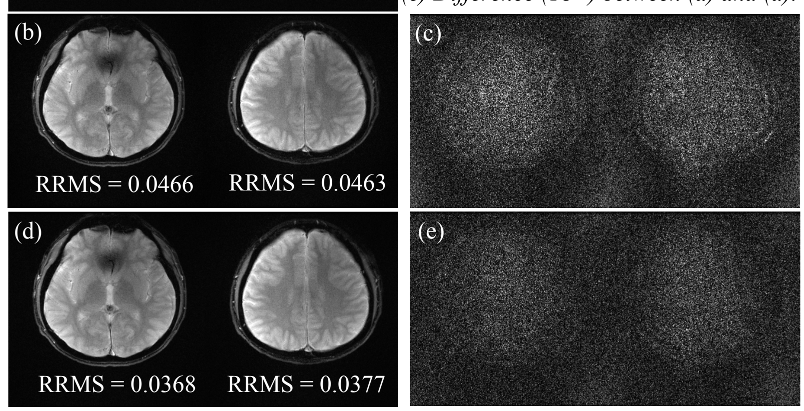


Fig.3. *(a). Fully sampled multiband images (gap 3cm). CAIPIRINHA aliased image is shown in Fig.1; (b) Reconstructed by the conventional scheme; (c) Difference (18×) between (a) and (b); (d) Reconstructed by the proposed scheme; (e) Difference (18×) between (a) and (d).*



Results: No visible artifacts arose in the reconstructed images in either method, as shown in Fig.3(b),(d). When comparable kernel size as well as comparable quantity and quality of ACS data were used, the proposed method introduced less noise than the conventional method. This can be seen both from the difference images shown in Fig.3(c),(e) and from the RRMS error values shown in Fig.3(b),(d). Fig.4 demonstrates that the proposed method is also applicable when additional inslice undersampling is conducted.

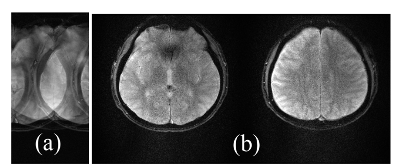


Fig.4. *(a) Aliased image acquired by 8 channel coil when ky is undersampled by 2. (b) Reconstructed using the proposed method.*

Discussion: By reformulating the reconstruction problem in CAIPIRINHA as the reconstruction problem of a 3D undersampled Cartesian dataset, the DFT encoding nature of the multiband RF pulses used in CAIPIRINHA is better utilized and superior reconstruction results are generated compared to conventional GRAPPA type reconstruction. In addition, the calibration data could be directly formed by part of the desired k-space data. There is no need to acquire a separate reference scan for sensitivity map estimation or calibration data calculation.

References:
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