Wave-CAIPIRHINA: a method for reducing g-factors in highly accelerated 3D acquisitions

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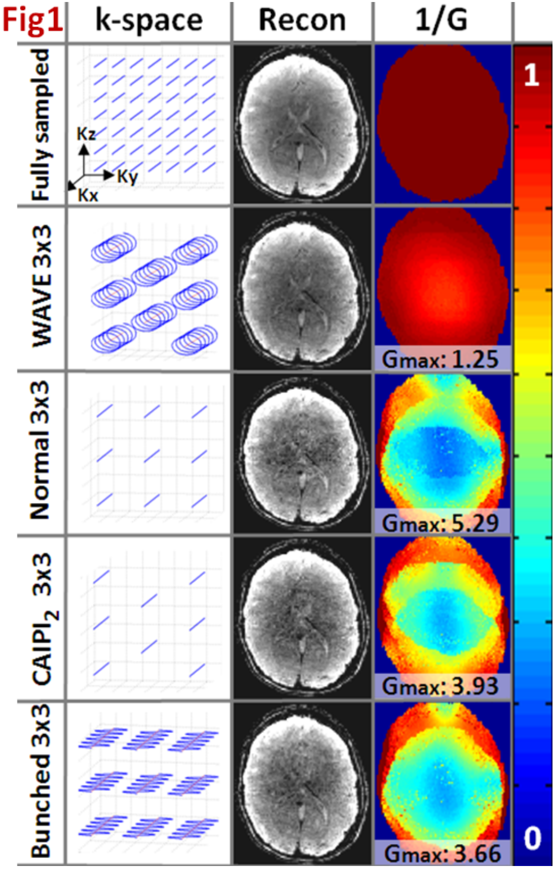
Introduction: Recent modifications to standard rectilinear 3D k-space sampling trajectories have provided more robust parallel imaging reconstructions of highly undersampled datasets. In 2D CAIPIRINHA (1), the phase encoding sampling strategy is modified to shift the spatial aliasing pattern to reduce aliasing and better exploit the coil sensitivity variation. In Bunched Phase Encoding (BPE) (2), a G_y gradient is applied during the readout of each PE line to create a zigzag trajectory which can be reconstructed using Papoulis's generalized sampling theory to give an alias-free image. BPE has also been combined with parallel imaging (3-4) whereby the zigzag trajectory allows utilization of the coil sensitivity variation in the readout direction to improve reconstruction.

Fig1

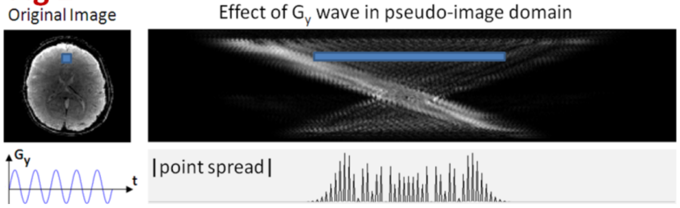


Here, we introduce a wave-CAIPIRINHA acquisition combining 2D CAIPIRINHA with a BPE strategy in both PE directions to create a highly efficient k-space sampling scheme which spreads the aliases relatively evenly in all spatial directions and thus takes full advantage of the 3D coil sensitivity distribution. For the reconstruction, we demonstrate an efficient algorithm based on generalized SENSE but perform in a pseudo-image domain (without gridding). This reconstruction technique can be thought of as a way to sparsify the encoding matrix of the generalized SENSE formulation of wave-CAIPIRINHA and dividing it into small, decoupled matrices which are computationally easy to invert and amenable to parallel processing.

Theory: K-space sampling: Figure 1 shows 3D k-space trajectories compared for R=3x3. The proposed wave-CAIPIRINHA method (2nd row) utilizes a modified phase encoding strategy of 2D CAIPIRINHA (4th row) as well as sinusoidal gradient waveforms similar to BPE (5th row). The G_y and G_z sinusoids are applied simultaneously with a ¼ of a cycle relative phase shift during the G_x readout, resulting in a "cork-screw" trajectory.

Reconstruction: Generalized-SENSE formulation (5) can be expressed by: $\underline{k} = [E]\underline{i}$, where $\underline{k}$ is the vector of acquired k-space data, $[E]$ is the encoding matrix and $\underline{i}$ is the image vector sought, usually via conjugate gradient. Here, we sparsify $[E]$ of wave-CAIPIRINHA so that it can be decoupled into many small, simple to invert independent matrices by pre-multiplying $[E]$ with a uniform iDFT matrix (ie. the matrix that provides transformation from k-space to image domain if sinusoidal gradients were not applied). With this pre-multiplication, Eq.1 becomes $\underline{\tilde{k}} = [\tilde{E}]\underline{i}$, where $\underline{k}$ has been transformed into a "pseudo-image" $\underline{\tilde{k}}$ and $[\tilde{E}]$ is now sparse. To understand why $[\tilde{E}]$ is sparse, first consider a fully sampled dataset with BPE applied along y and with readout acquisition oversampled to enlarge the image $\mathrm{FOV}_{\mathrm{read}}$. Applying uniform iDFT to this data results in a pseudo-image shown in Fig 2, where the G_y BPE gradient acts to blur the voxel along the readout direction; with the amount of blurring being linearly dependent on y. An example voxel case (in blue) is shown along with its corresponding point spread function (PSF). Applying a R=2 PE_y undersampling results in half FOV_y in the pseudo-image. The combined effect of BPE and R=2 undersampling is therefore a pair-wise aliasing of two *rows* of voxels ($\mathrm{FOV}_y/2$ apart) in the pseudo-image space; ie. a sparse $[\tilde{E}]$ matrix that can be decoupled into small matrices each corresponding to a system of equations for two rows of image data. In actual implementation, the small matrices can be formed from knowing the PSF; it's not necessary to calculate $[\tilde{E}]$. Extending this method to G_z extends the blurring in the readout (now with z-dependence). Lastly, with the use of 2D CAIPIRINHA shifts of the cork-screw trajectories, the sets of aliased rows are modified but the encoding matrix can still be sparsified in the same manner.

Fig 2



Analyzing the pseudo-image shows that wave-CAIPIRINHA increases the *average* distance between the aliasing voxels (via blurring) and takes full advantage of the 3D coil variation to improve the g-factor. The pseudo-image also provides intuition on the value of acquisition oversampling in x, without which the blurred voxels wrap in the read direction and cause increased aliasing.

Methods: We tested our wave-CAIPIRINHA acquisition on a volunteer using 3T Siemens TIM Trio scanner with a 32-ch array coil using an R=3x3 3D FLASH acquisition with FOV=192x192x120 mm; resol = 2mm iso; TR/TE= 35/25ms, BW= 300, Flip =12°. The applied G_y and G_z sinusoidal waveforms contained 5 cycles per readout line (max slew of 130 T/m/s.) A 6x data oversampling was used to increase $\mathrm{FOV}_{\mathrm{read}}$. For comparative purposes, data from fully sampled and other R=3x3 strategies were also collected. For the BPE acquisition, the same G_y that was used in wave-CAPIRINHA was applied together with the same data oversampling rate.

Results: Figure 1 shows the reconstructions of the various k-space trajectories and corresponding 1/g-factor maps for the imaging slice with the highest g-factor for wave-CAIPIRINHA. Wave-CAIPIRINHA with R=3x3 closely matches the fully sampled data with a g-factor penalty close to unity in most locations. The resulting ~uniform 3-fold SNR reduction ($\sqrt{9}$) is prominent in the center of the image where the intrinsic SNR of the coil array is lowest. With normal undersampling (3rd row), significant image degradation is observed (G_{max}=5.29). The 2D CAIPIRINHA and BPE methods provide a better reconstruction (G_{max}=3.93 and 3.66) but significantly higher G-factors than the wave-CAIPIRIHINA method (G_{max}=1.25).

Conclusion: We introduced the wave-CAIPIRIHINA acquisition and reconstruction method, and demonstrated its associated g-factor improvement for highly accelerated 3D acquisition.

Support: NIBIB K99EB012107, NIBIB R01EB006847 and NCRR P41RR14075 **References: 1.** Breuer FA. et al, MRM 2006:55:549. **2**. Moriguchi H. et al, MRM 2006:55:633. **3.** Moriguchi H. et al, ISMRM 2005 p.287. **4.** Breuer FA. Et al, MRM 2008:60:474 **5.** Pruessmann KP. Et al, MRM 1999 42:952