RECENT ADVANCES IN PARALLEL IMAGING FOR MRI: WAVE-CAIPI TECHNIQUE

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KEYWORDS*:* Parallel Imaging, Caipirinha, Wave-CAIPI, GRAPPA, SAMPLING, BUNCH PHASE ENCODING, Aliasing, Sinusoidal Gradients,

ABSTRACT

The aim of this work is to illustrate the principles and advantages of the modern technique of Parallel Imaging (PI), Wave-CAIPI. Wave-CAIPI applies two sinusoidal gradients, Gy and Gz, during frequency encoding, with a phase shift of one quarter of a full cycle. In combination with the 2D-CAPIRINHA effect, the result is the origin of sinusoidal waves, staggered between them, that incur in "corkscrew" trajectories inside the k-space, that cross the layers, "slices per slice". The result is reduced acquisition times (Tacq), with an "aliasing" well distributed over all three dimensions of space, and an adequate signal/noise ratio (SNR). In the literature, scientific studies have shown a greater efficiency of the Wave-CAIPI than the 2D-CAIPI and GRAPPA methods. In fact, compared to a 2D-CAIPI with equal acceleration factor (R) and Tacq, the SNR is greater, thanks to geometric factor values (g) almost perfect. Similarly, compared to the GRAPPA technique, with the same number of coils channels and R, lower Tacq are described. Among the techniques of PI, the Wave-CAIPI is a technique that allows an effective acceleration of Tacq maintaining an adequate SNR, a fundamental prerequisite for clinical applications and research, in particular in the field of Neuro-MRI.

INTRODUCTION

In the field of MRI, reducing scanning times has always been one of the biggest challenges in recent years. In particular, among the technological developments, the Parallel Imaging (PI) techniques have allowed the achievement of high spatial resolution images, avoiding long signal encoding times and long acquisition times. The subject of our study is the Wave-CAIPI technique, recently proposed among the PI techniques to allow a greater acceleration of high resolution volumetric imaging, leading to an effective acceleration of acquisition times, maintaining also an adequate Signal/Noise ratio (SNR), a fundamental prerequisite for both clinical and research applications.

TECHNIQUE E METHODOLOGY

Parallel Imaging techniques in MRI (pMRI)

The development of pMRI techniques has allowed a significant reduction in acquisition times in various clinical applications while maintaining high spatial resolution and appropriate imaging contrast. In particular, they exploit spatial informations provided by each multichannel coil receivers to correct aliasing due to sub-sampling data. The aliasing phenomenon occurs when the Nyquist-Shannon criterion of data sampling is not met. This theorem states that, in order to correctly sample (without loss of information) a limited band signal, it is sufficient to use a sampling frequency equal to at least twice the maximum frequency of the spectral component of the signal, and which is called precisely Nyquist Frequency. However, the performance of PI methods is limited by the capacity of the acceleration factor R and the spatial encoding of the coil sensitivity and the coil geometry itself (g-Factor). In detail, the signal/noise ratio (SNR) with the application of pMRI techniques (SNR_{PI}) depends proportionally on the SNR in the absence of pMRI (SNR_{full}) and inversely proportionally on the g-Factor and the acceleration factor R, according to the following relation:

$$SNR_{PI} = SNR_{full} / g\sqrt{R}$$

The various pMRI techniques are classified, based on the algorithm applied to correct the aliasing due to the subsampling of k-space data, in techniques that act on the image domain, such as ASSET (GE), SENSE (Philips), SPEEDER (Toshiba/Canon), RAPID (Hitachi), and those working on the frequency domain such as GRAPPA (Siemens), ARC (GE), SMASH, AUTO-SMASH and VD-AUTO-SMASH. In particular, techniques that act on the domain of the image, first reconstruct and then correct, while those that act on the domain of frequencies, first correct and then reconstruct. In order to better understand the Wave-CAIPI technique, it is advisable to know and analyze the precursor methods that are the basis of the study technique.

pMRI techniques operating on the Space Frequency Domain of K-space: the GRAPPA method

The GRAPPA method is classified, as previously mentioned, as pMRI k-space based technique, which acts on the domain of space frequencies. In fact, the GRAPPA algorithm is based on the principle that some k-space information in a given Mkx Mky point is also contained in the nearby points of k-space, so any missing data can be retrieved by combining appropriately data originating from nearby points (Fig.1).

In the data acquisition phase, each single coil channel captures phase encoding lines of each k-space respecting the acceleration factor R, but as multiple

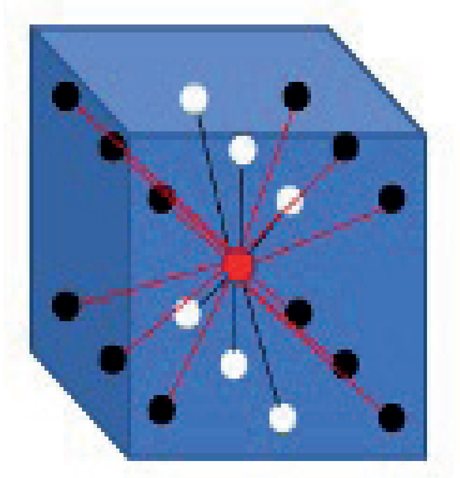

Fig.1 - *Schematic representation of the GRAPPA algorithm (Generalized Autocalibrating Partial Parallel Acquisition)*

phase encoding passes are skipped, a subsampling will result. However, the central lines (essential data) that make up the ACS (Autocalibration Signal) are sampled. Known ACS data are used to calculate the weighting factors for each coil. The weighting factor is the factor that will allow us to map "source" data on the basis of "target" data. Missing data are estimated iteratively using these global weighting factors combined with known local data for each small region (kernel block). To be able to map the Target Points it is necessary to calculate the required combination for each of the points acquired, each with the ACS, and so it will be possible to extrapolate the GRAPPA kernel or a small portion of the k-space, which describes the number and position of Source Points and Target Points (Fig.2).

Throughout the convolution of Kernel block and ACS, and on the basis of the mathematical relations, the missing data are obtained. This last step allows to obtain artificial or synthetic harmonics useful to obtain a k-space with the totality of the information. The application of this method leads to a g-factor noise that resides in the synthetic harmonics and not on those acquired. However, when high R acceleration values are applied due to variability of geometries and sensitivity of coils, severe aliasing artifacts and relative loss of SNR may occur.

2D-CAIPIRINHA Technique (Controlled Aliasing in Parallel Imaging Results in Higher Acceleration)

A further improvement in the quality of the image reconstruction was made possible by applying the CAIPIRINHA technique, which compared to GRAPPA applies a more efficient strategy, with acceleration along the Ky and Kz directions, and application of an additional phase offset (slice-shift) along Kz. This results in unique frequency patterns and therefore a simpler aliasing to solve. Figure 3 shows graphically, in a simplified way, the 2D-CAIPIRINHA technique, with evidence of the "slice shift" along Kz, and the corresponding aliasing generated by data subsampling.

Wave-CAIPI technique

Previous pMRI techniques are affected by a limited degree of capability to achieve high R acceleration factors without reducing the SNR. Wave-CAIPI is a parallel imaging method that allows to obtain acceleration values R 9 times superior without any degree of penalty of the SNR. This technique, in particular, originates

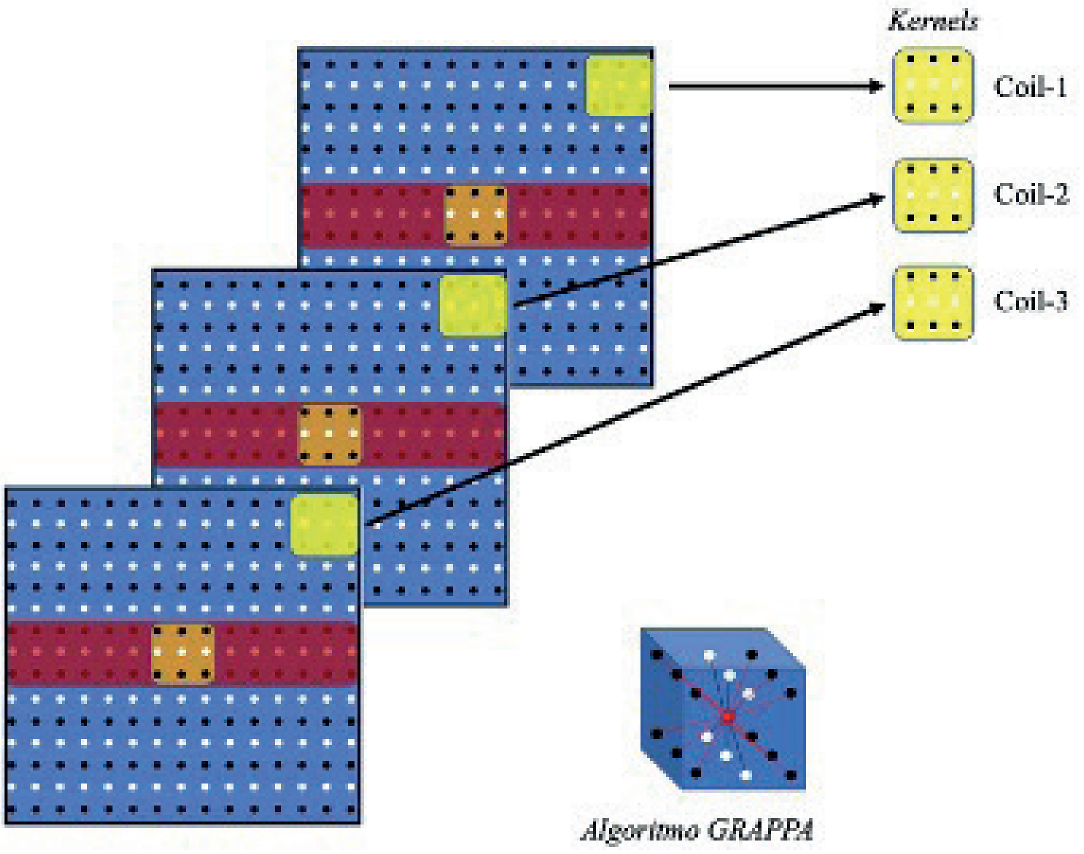

Fig.2 - *Estimating missing data for each coil and using the Kernel data to synthesize them iteratively.*

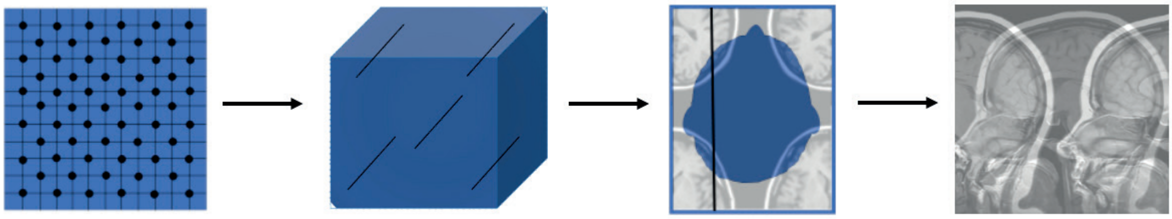

Fig.3 - *2D-CAIPIRINHA sampling method with slice-shift phase along phase Kz encoding and representation in terms of Aliasing.*

from the association, to the 2D-CAIPIRINHA method, of the Bunch Phase Encoding (BPE), that is a "Zig Zag" sampling along Gy and Gz, which determines a controlled aliasing on all three spatial directions. In association with the "slice-shift" effect of the 2D-CAIPIRINHA method, two sinusoidal gradients Gy and Gz are applied during the Gx gradient readout, with a shift of π/2, and this leads to the generation of a wave trajectory, defined more simply "corkscrew trajectory", along the voxels (Figure 4). By combining these two additional sinusoidal gradients with the "slice-shift", a well-distributed aliasing pattern is created on all three spatial dimensions. This allows Wave-CAIPI to fully exploit the information on the sensitivity of the coil, allowing a high R acceleration factor, with negligible noise amplification and reduced artifacts. In the domain of the image the additional phase deposition results in a diffusion along the only readout direction that varies linearly depending on the position along Gy and Gz. To better understand this concept, let's analyze (as shown in Figure 6) what happens with the Gy application alone, not taking into account the gradient Gz applied and the slice-shift 2D-CAIPI. We can consider this Gy as an extra-phase modulation of K-space. In the image domain this results in the introduction of a PSF along the direction of the readout gradient, which also depends on the position along *y*. Thus, at the center of the FOV we will have a very little spread, namely a small PSF, while in the more peripheral areas of the FOV along the y-axis, we have an increasing diffusion. Considering the image domain, to understand what happens to a particular voxel, for each voxel there is a corresponding PSF that spreads with convolution of z. Wave-CAIPI, unlike other very fast acquisitions such as EPI, Radial imaging or Spiral, is not subject to blurring from data gridding or artifacts from distortion from uneven magnetic field B0, thanks to a constant crossing of k-space along the readout direction Kx, resulting in the same chemical displacement effect observed in conventional Cartesian imaging sequences. The Wave-CAIPI acquisitions, as previously mentioned, therefore can be reconstructed efficiently thus avoiding K-space data gridding processes. This is possible because the wave trajectory can be represented as additional phase deposition in Cartesian k-space. Using a PSF the voxel diffusion effect from Wave-CAIPI is modeled through a convolution that varies spatially in the image domain efficiently as a phase modulation in hybrid space (Kx, y, z).

Reconstruction and correction of the image in the Wave-CAIPI technique.

Characterizing with precision the effective trajectory of waves in order to correctly reconstruct and correct the image is crucial. Wave trajectories along phase coding Gy and Gz are estimated through fast scans in the x-y plane to characterize the Py-Wave, in the x-z plane to characterize the Pz-Wave through a double acquisition with and without the Wave gradient. The encodings created by the sinusoidal gradients Gy and Gz are convoluted through a PSF, and the k-space data and the PSF are put in relation. Thanks to the Fourier Inverse Transform, we get information about the additional phase effect imparted along the image domain, along the Gz and Gy phase encoding in the shift along the trajectory of the K-space.

$$Wave\,[x, y, z] = \sum_k e^{i2\pi kx/N} \left(e^{-i2\pi\,(Py\,[k]y\,+\,Pz\,[k]z\,)} \sum m\,[x, y, z]\; e^{i2\pi kx/N}\right.$$

or

$$Wave\,[x, y, z] = F_x^{-1} \cdot Psf\,[x, y, z] \cdot (F_x \cdot m\,[x, y, z])$$

This expression relates the acquired image with wave gradients (x, y, z), to the magnetization Mx, My, Mz,

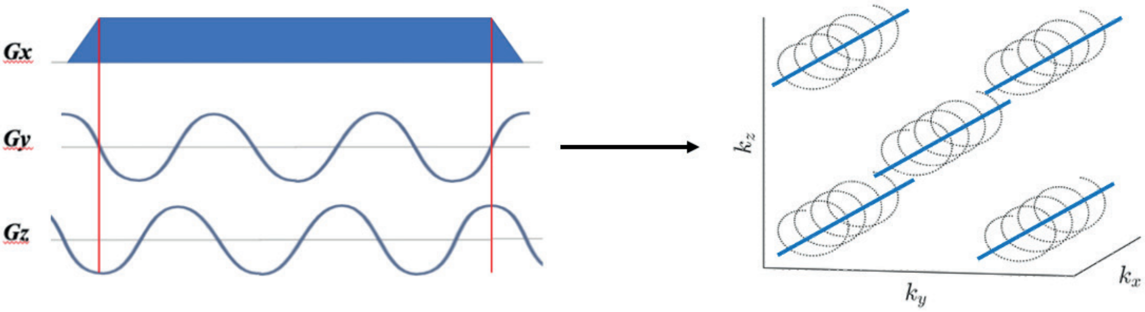

Fig.4 - *Wave-CAIPI sampling system. The sinusoidal gradients Gy and Gz with a offset of π/2 between waveforms run into a corkscrew trajectory in the k-space.. The waves are also offset thanks to the 2D-CAIPI sampling strategy to create the slice shift.*

and suggests a simple explanation for the effect of wave gradients: each readout line is convoluted with the PSF which depends on the spatial position (y, z) to produce the image of the acquired wave. In particular, Fx represents the Discrete Fourier Transform (DFT) along the readout encoding axis and the PSF represents the effect of Wave gradients. Note that the gradients of the Gy and Gz wave do not cause the diffusion of the voxel in y and z directions but the only diffusion effect is along the readout encoding. This effect is explained by the fact that Gy and Gz wave gradients combined with shifts along the volume of partitions create a diffusion in all directions of space. With the Wave-CAIPIRINHA technique, therefore, the Aliasing is spread along the three directions of the space with optimal correction of the sensitivity profiles of the 3D coils, which allows to obtain images with high SNR, with optimal geometric factor values g and higher acceleration factor values R, compared to other parallel imaging methods.

Clinical applications of the Wave-CAIPI technique in MRI

From a review of the scientific literature, some study groups applied the Wave-CAIPI method to the MP-RAGE sequence showing promising results, compared to conventional PI techniques, in terms of signal/noise ratio, acceleration of acquisition times, application of increasing acceleration factors and geometric factor. Longo et al have studied the application of the Wave-CAIPI MP-RAGE, compared to the MP-RAGE with GRAPPA technique, demonstrating the same reliability and lower acquisition times with Wave-CAIPI while using higher R acceleration factors. A further study, conducted by Polak et al, compared the Wave-CAIPI technique with the 2D-CAIPI applied to the MP-RAGE, demonstrating a better SNR, with lower values of g factor, equal acceleration factor R, isotropic resolution and acquisition times. In addition, the same study group then compared the Wave-CAIPI with the GRAPPA method applied to the MP-RAGE sequence, demonstrating that at the same isotropic resolution (1 mm) it is possible to obtain images with similar SNR, while using higher R acceleration factors in the Wave-CAIPI technique. Further evaluations and studies have been carried out to compare the Wave-CAIPI to other conventional parallel imaging techniques, such as GRAPPA and 2D-CAIPI, also in other fundamental 3D sequences in the field of Neuro-MR Imaging, such as T1 SPACE, SWI, SPACE FLAIR.

CONCLUSION

We have analyzed in detail the rapid acquisition technique Wave-CAIPI that allows to obtain images with high space and time resolution. The Wave-CAIPI technique, involving a subsampling of the k-space with 2D-CAIPIRINHA methodology combined with the trajectory of the Wave gradients, allows an optimal use of the intrinsic spatial information of the coils and allows a higher acquisition speed with reduced noise amplification and less artifacts. The Wave-CAIPI technique continues to evolve and expand into multiple volumetric sequences, constituting one of the most stimulating advances in the field of MRI.

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