CAIPIRINHA – Revisited

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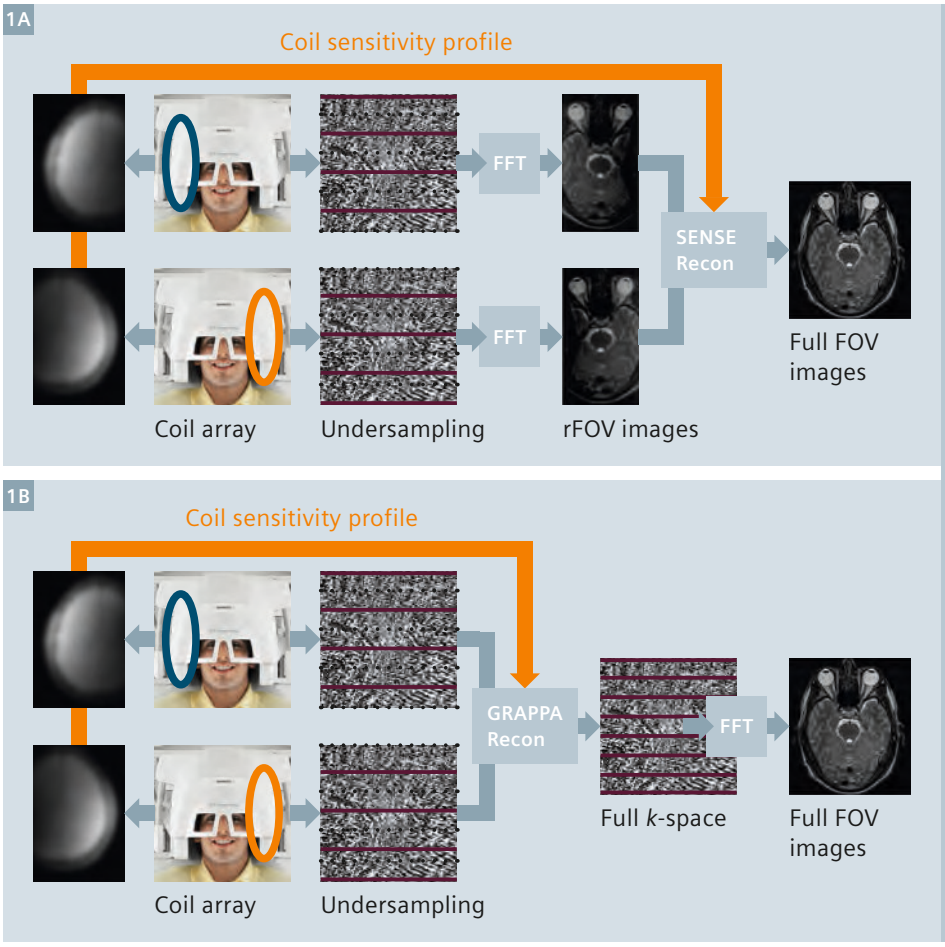
Introduction

Image acquisition time is one of the most important considerations for clinical magnetic resonance imaging (MRI). The development of multi-coil receiver hardware as well as dedicated parallel acquisition techniques (PAT) and respective reconstruction methods allowed for significant decrease of acquisition times in almost all clinical applications. This, for example, enables much shorter breath-holds in abdominal MRI and improves the temporal resolution of dynamic scans but can also be applied to improve image quality while keeping the acquisition time constant. Thus, today, parallel imaging techniques play a substantial role in everyday clinical routine.

Every parallel imaging technique combines (1) a specific acquisition scheme of *k*-space data with a (2) respective reconstruction method.

(1) **Parallel acquisition** operates by reducing the amount of data necessary to form an image. In the Cartesian case, this is usually accomplished by uniformly undersampling the *k*-space (e.g. skipping every other phase-encoding line) resulting in so-called 'aliasing artifacts' in the image domain.

(2) **Parallel reconstruction** methods seek to compensate the lack of spatial encoding by taking into account the spatial sensitivity information, provided by a multi-coil receiver array and can be divided into 2 main groups (Fig. 1): algorithms that combine undersampled images from the individual coil elements in the image domain to a global image, e.g. SENSE [1]. And algorithms that combine the frequency information of each coil



1 Procedure of reconstructing the image information from undersampled datasets with SENSE (**1A**, image based) and GRAPPA (**1B**, *k*-space based). Coil sensitivity profiles and frequency information is received with individual coil elements. With SENSE, reduced FOV images are reconstructed first and unaliased afterwards using the sensitivity information. With GRAPPA the sensitivity information from each coil element is used right at the beginning to calculate missing echos followed by Fourier transformation.

element in the *k*-space domain before Fourier transformation, e.g. GRAPPA [2].

Unfortunately, the PAT concept is intrinsically associated with a signal-to-noise (SNR) loss compared to a fully encoded image. The SNR is reduced

a) by the square root of the acceleration factor, simply due to the fact that less data is acquired, and

b) by the so-called *g*-factor, depending strongly on the encoding capabilities of the underlying receiver array.

Thus, PAT is often limited to applications with sufficiently high base SNR, such as volumetric imaging methods. With the newest generation of MR systems providing up to 128 independent receiver channels, further scan time reductions are potentially achievable. However, in conventional 2D clinical imaging, parallel imaging today is still restricted to relatively moderate scan time reductions (PAT factors of 2-3) due to intrinsic limitations in the coil sensitivity variations along one phase-encoding direction (1D parallel imaging). In 3D and simultaneous multi-slice imaging, parallel encoding can be carried out in two encoding directions (PAT^2 or 2D parallel imaging), thereby employing the sensitivity variations in both phase-encoding directions, as has been demonstrated in, for example, 2D SENSE [3] and MS SENSE [4]. This concept has been shown to significantly improve the reconstruction conditions, allowing for higher accelerations of the acquisition (>3). However, both techniques require sufficient sensitivity variations in two encoding directions for successful image reconstruction and therefore strongly depend on the underlying coil geometry, which is described by the *g*-factor. As mentioned above, spatial encoding with a receiver array is associated with a certain noise amplification known as '*g*-factor noise'. Quantitative *g*-factor estimation methods have been derived for SENSE [1] and GRAPPA reconstructions [5] and serve as a quality metric for PAT reconstructions. One important approach to reduce this *g*-factor noise for a given application is the optimization of the receiver array geometry (e.g. number of coils, coil arrangement) towards the application at hand. However, hardware limitations, the diversity of patient weight and size, the need for flexibility regarding a wider range of applications, as well as sequence or protocol specific considerations, hamper the viability.

The CAIPRINHA concept (Controlled Aliasing In Parallel Imaging Results IN Higher Acceleration) is a specific data acquisition technique that allows to partially overcome these requirements and limitations by modifying the aliasing conditions in a well defined manner. This leads to an improved *g*-factor when compared to standard acquisition with the same acceleration factor. CAIPIRINHA takes effect already during the data acquisition by modifying the RF excitation or gradient encoding scheme in order to use the coil encoding power of the underlying receiver array to full capacity. The concept has been successfully applied so far to 3D imaging where data reduction can be carried out in two phase-encoding directions (2D-CAIPIRINHA) [7] and simultaneous multi-slice imaging (MS-CAIPIRINHA) [6]. In addition, both strategies can be extended to the third remaining direction, namely the read-out direction, by utilizing e.g. zig-zag-shaped read-out trajectories [8] or wave-CAIPI [9, 10]. The following provides a brief overview of 2D-CAIPIRINHA and S-CAIPIRINHA.

Improving parallel imaging performance with CAIPIRINHA

2D-CAIPIRINHA

In contrast to conventional 2D imaging where only one phase-encoding direction is available for scan-time reduction (1D PAT), 3D volumetric imaging with a second phase-encoding direction offers the potential to choose the direction in which undersampling is performed, or even to accelerate in both phase-encoding directions at the same time (2D PAT / PAT^2), where the total PAT factor is the product of the acceleration factors in the individual phase-encoding directions, e.g. 2 x 3 = 6. Given a receiver array geometry providing sensitivity variations in

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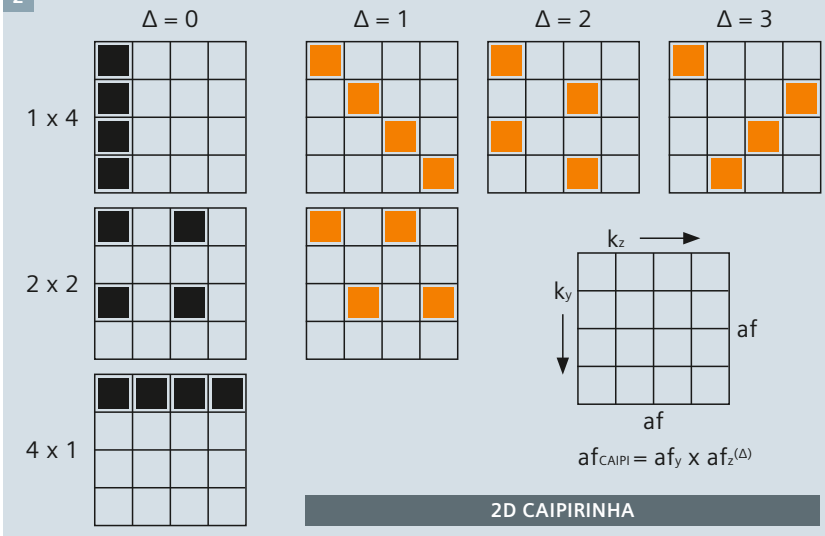
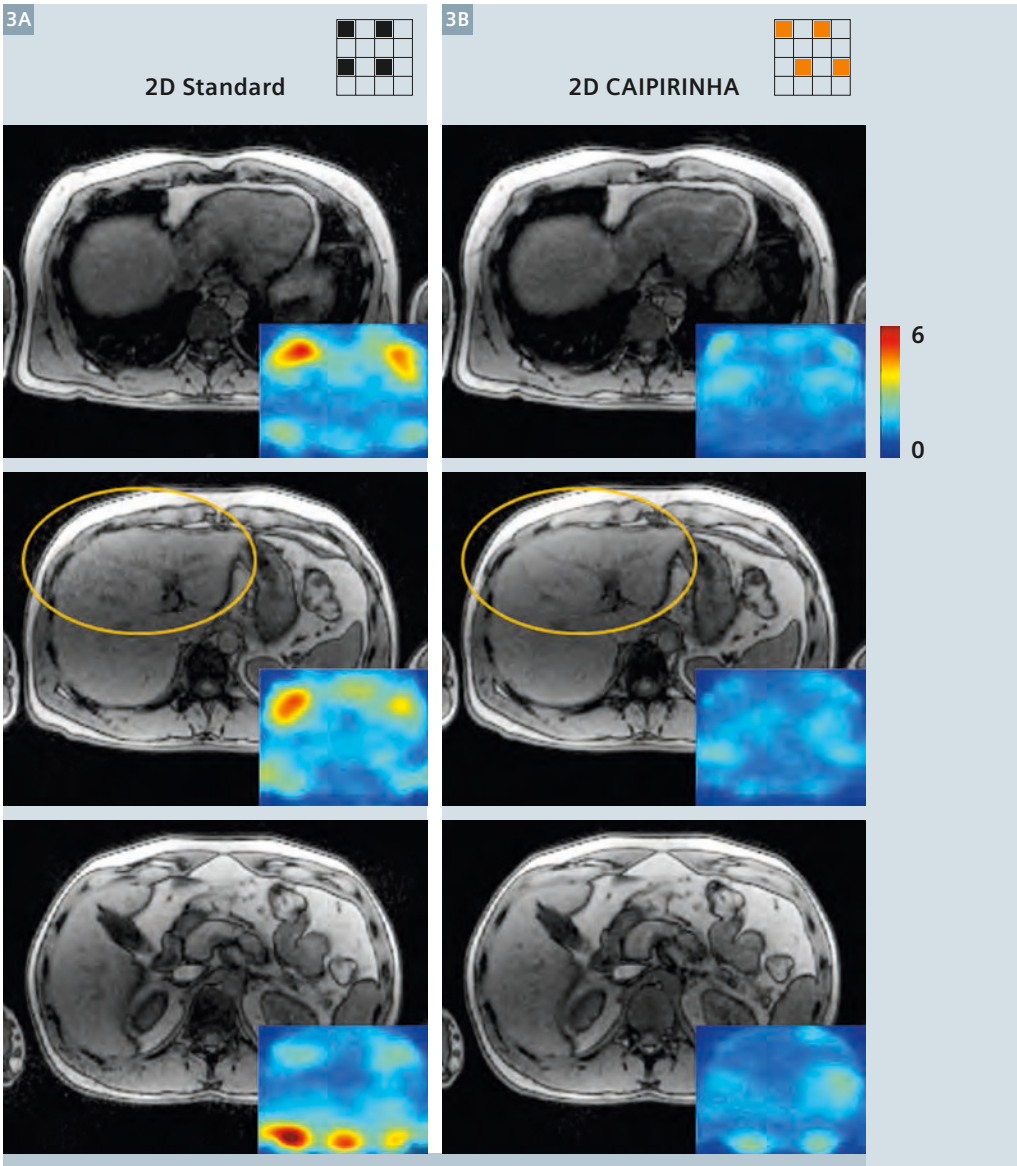


2 Procedure of generating 2D-CAIPIRINHA sampling patterns for a given total acceleration factor, here PAT = 4. All possible sampling schemes can be represented by a PAT x PAT elementary cell with PAT sampling positions to fill. For each undersampling rate in the k_y direction (PAT_y), multiple patterns can be created by shifting sampling positions at row k_y in the k_z direction by a different amount Δ, whereas Δ runs from 0 to PAT_{z-1}, and PAT_z = PAT/PAT_y. Sampling patterns without shift (Δ = 0) are 2D PAT standard acquisitions, while all the other patterns are represented by 2D-CAIPIRINHA-type acquisitions (PAT = PAT_y x PAT_z (Δ)) indicated by the red sampling positions.

both phase-encoding directions, this strategy has shown the potential to allow for higher total image accelerations compared to undersampling schemes restricted to only one direction [4, 5]. However, since the sensitivity variations available for the PAT reconstruction depend not only on the coil geometry but also on the image position and orientation, the FOVs and encoding directions as well as the object position, size and shape, the right choice of the undersampling rate for the individual phase-encoding directions is not easily predictable and remains a challenging task. Thus, in many applications the reconstructed images suffer from severe residual artifacts or strong noise amplifications, depending on the choices made by the operator.

Again, the CAIPIRINHA concept has shown to partially overcome these limitations. It has been realized that, besides the standard rectangular sampling patterns with undersampling using simple integer reductions, many other patterns are conceivable where the sampling positions are shifted from their original positions in the 2D phase-encoding scheme. Here, we restrict ourselves to sampling positions on so-called 'sheared grids' which form periodic lattices [16] resulting in exactly PAT superimposed image pixels at an acceleration factor of PAT as it is the case in all standard rectangular patterns. The procedure of generating the available **2D-CAIPIRINHA** patterns is schematically displayed in Figure 2 for a total image acceleration of PAT = 4. The sampling schemes can be represented by a PAT x PAT elementary cell with PAT sampling positions to fill. For each undersampling rate in the ky direction (PAT_y), multiple patterns can be created by shifting sampling positions at row ky in the kz direction by a different amount d, whereas d runs from 0 to PAT_{z-1}, and PAT_z = PAT /PAT_y. Sampling patterns without shift (d = 0) are 2D standard acquisitions, while all the other patterns are represented by 2D-CAIPIRINHA-type acquisitions. This concept can also be used for prime number accelerations (PAT = 2, 3, 5 ...) where standard accelerations only allow undersampling in one of the phase-encoding directions. The required shifts in *k*-space can simply be realized by applying additional gradient offsets to the phase-encoding gradient tables. These 2D-CAIPIRINHA sampling patterns, analogous to the phase-cycles in simultaneous multi-slice imaging, modify the appearance of aliasing in 2D parallel imaging compared to conventional rectangular reduction schemes and have the potential to relax the requirements of integer reductions to great extent. This is demonstrated in more detail in the original publication [7]. By shifting the sampling positions in a well-directed manner, aliasing can be shifted in such a way that sensitivity variations provided by the underlying receiver array are employed more efficiently. In some cases, the amount



3 *In vivo* liver example; volunteer: Compared are GRAPPA reconstructions (3 example slices) derived from two different reduction schemes **(3A)** Standard 2 x 2 and **(3B)** 2D-CAIPIRINHA 2 x $2^{(1)}$. In addition, the corresponding GRAPPA *g*-factor maps are displayed. In the indicated region the SNR benefit of 2D-CAIPIRINHA can be appreciated.

Imaging details: 1.5T MAGNETOM Avanto, 6-channel body matrix coil combined with 6 channels from the spine matrix coil; VIBE PAT = 4, extra reference scan matrix 32 x 24 x 24. FOV 400 x 312.5 mm^2, matrix 320 x 170 x 50, total acquisition time 9 s breath-hold.

of aliasing can even be reduced. These modified aliasing conditions may then result in a further improvement in parallel imaging reconstruction conditions and therefore in better image quality. Recently, this concept has also been extended to more generalized sampling schemes which are not restricted to sheared grids [17].

In order to demonstrate the benefit of 2D-CAIPIRINHA in vivo, two subsequent accelerated (PAT = 4) abdominal 9 s breath-hold VIBE experiments were carried out on a volunteer. In Figure 3, GRAPPA reconstructions from three out of 50 slices from

a) a standard 2D-PAT 2 x 2 and

b) a 2D-CAIPIRINHA 2 x 2[1]

acquisitions are displayed. In addition, the corresponding *g*-factor maps of the GRAPPA reconstructions are displayed as a quantitative measure of image quality. As indicated by the lower *g*-factor values in the 2D-CAIPIRINHA reconstructions, the improvement of image quality can clearly be observed, even on a visual scale (see region indicated by the orange circle).

Furthermore, the improvements in image quality associated with 2D-CAIPIRINHA are demonstrated taking four different T1-weighted 3D FLASH experiments of a volunteer's brain with different acceleration factors and acquisition schemes (Fig. 4). The acquisitions compared are

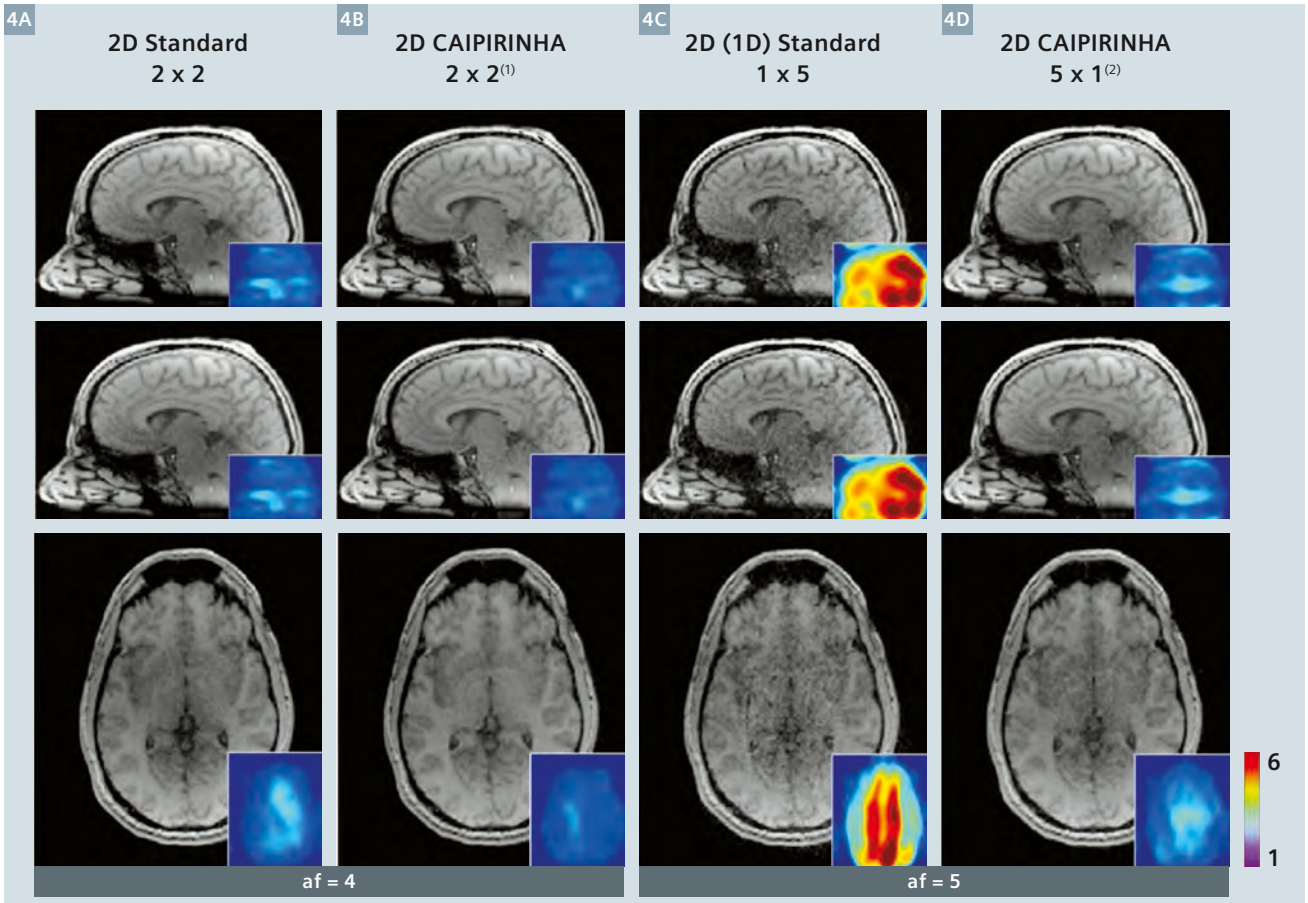
a) a standard 2D-PAT 2 x 2,

b) a 2D-CAIPIRINHA 2 x 2[1],

c) a 2D-CAIPIRINHA 1 x 5[2] and

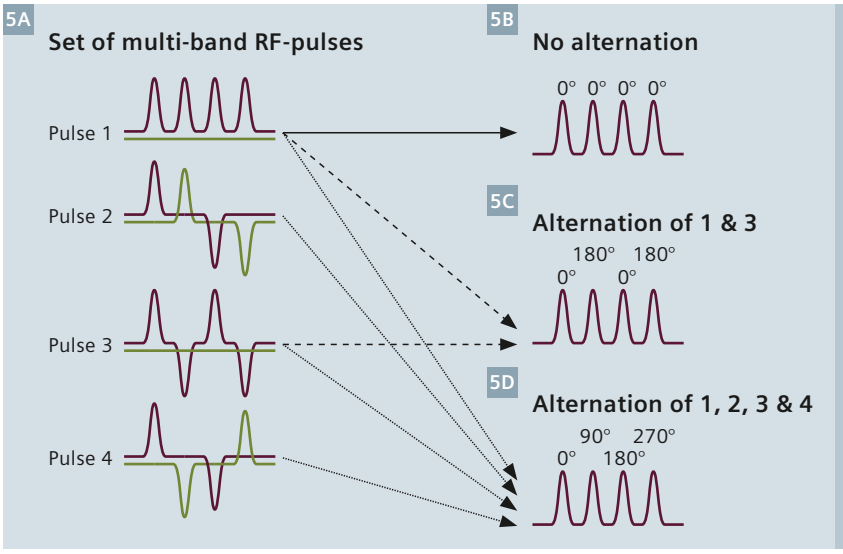
d) a standard 1D-PAT 5 x 1 scheme.

Displayed are the central sections of the reconstructed 3D image data in the sagittal, coronal and axial view in addition to the corresponding quantitative *g*-factor maps. Comparing reconstruction results from PAT = 4 (a) and (b), the improvement of 2D-CAIPIRINHA can clearly be appreciated. Comparing results from PAT = 5 (c) and (d), the gain in SNR is even more obvious. In this case, the parallel imaging performance of 2D-CAIPIRINHA 1 x 5[2] (c) compares pretty well with the standard PAT = 4 (2 x 2) acquisition employed in (a).

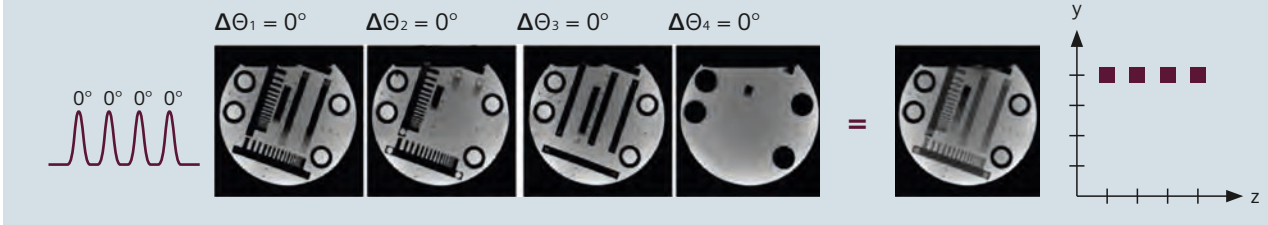


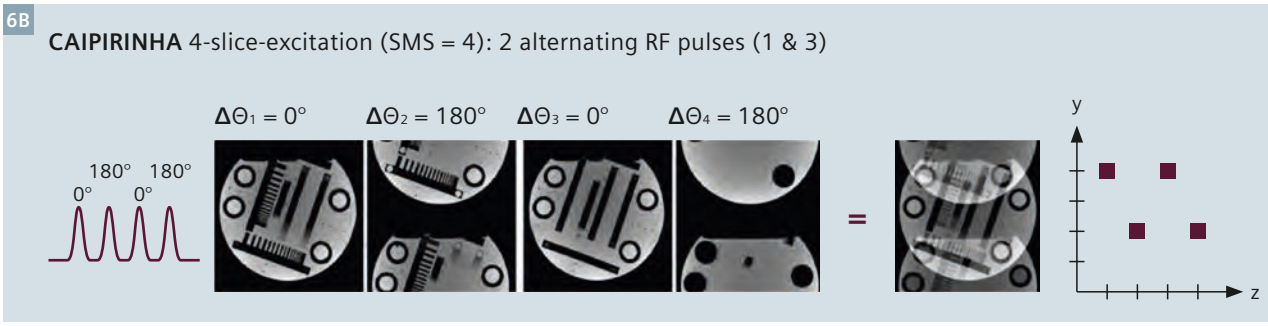
3 *In vivo* 3D FLASH brain imaging using different acceleration schemes: **(4A)** Standard 2D-PAT 2 x 2 **(4B)** 2D-CAIPIRINHA 2 x 2[1] **(4C)** Standard 1D-PAT 5 x 1 **(4D)** 2D-CAIPIRINHA 1 x 5[2]. Displayed are central slices in the sagittal, coronal and axial views. In addition, the corresponding GRAPPA *g*-factor maps are shown.

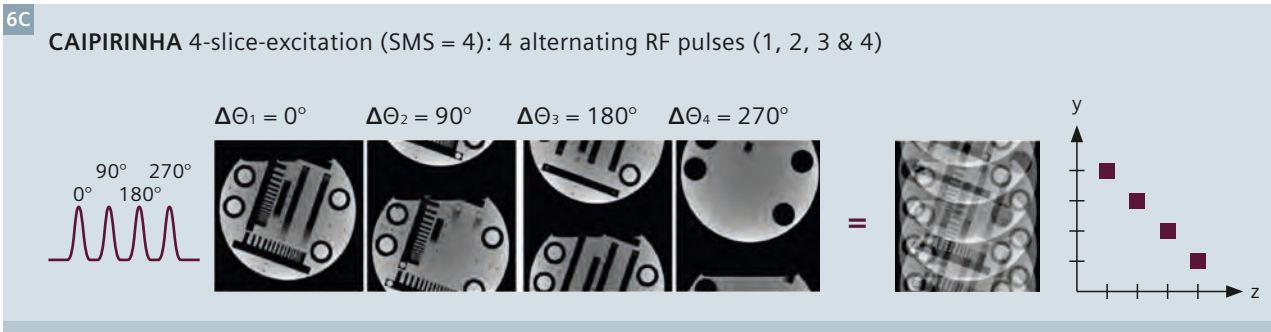
Imaging details: 3T MAGNETOM Skyra, 20-channel head-neck matrix coil, 3D FLASH, GRAPPA with extra reference scan, matrix 32 x 32 x 32, TE / TR 4.3 ms / 16 ms, FA 35°, FOV 256 x 208 x 204 mm³, matrix 256 x 168 x 144; partial Fourier factor 7/8, total scan time 1 min 40 s (PAT = 4) and 1 min 16 s (PAT = 5).



5 Multi-slice excitation with alternating RF pulses taken from **(5A)** a set of 4 RF pulses with different phase modulations (pulse 1 to 4) allows one to provide the individual slices with well defined phase-cycles along the phase-encoding direction. The real part (red) and imaginary part (green) of the pulses are plotted. **(5B)** Using only one pulse (e.g. pulse 1), no phase-cycle is provided (0°, 0°, 0°, 0°). **(5C)** Alternation between pulses 1 and 3 yield no phase-cycle for slice 1 and 3 and an 180° phase cycle for slices 2 and 4 (0, 180°, 0, 180°). **(5D)** Alternation of all 4 pulses allows one to provide all the individual slices with an individual phase-cycle (0, 90°, 180°, 270°).







6 **(6A)** Standard 4-times-accelerated simultaneous 4-slice experiment. The same pulse is applied for subsequent excitations (phase-encoding lines), resulting in all 4 slices projected onto each other. **(6B)** CAIPIRINHA 4-times accelerated simultaneous 4-slice-experiment alternating between e.g. pulses 1 and 3 for subsequent excitations, thereby providing slice 2 and slice 4 with a 180° phase cycle. According to the Fourier Shift Theorem, slices 2 and 4 appear shifted by half of the FOV with respect to slices 1 and 3 in the resulting folded image. **(6C)** CAIPIRINHA 4-times-accelerated simultaneous 4-slice experiment alternating between pulse 1, 2, 3 and 4 for subsequent excitations, thereby providing each slice with a different phase-cycle (0°, 90°,180°, 270°). Each slice appears shifted by FOV/4 with respect to their adjacent slice in the folded image.

While the 2D-CAIPIRINHA patterns in general appear to be more tolerant against user influence and suboptimal patient positioning, the automated extraction of the optimal pattern for the given imaging setup remains a challenging task and has not been sufficiently answered.

MS-CAIPIRINHA

Simultaneous multi-slice (SMS) imaging offers an SNR benefit over standard single-slice imaging which may be either translated into shorter acquisition times or higher spatial resolution. SMS comprises RF excitations with specialized multi-band pulses as displayed in Figure 5. After multi-band excitation, the received signals will accrue from all the slices (bands) and thus are subject to the subsequent gradient-encoding sequence. Simply replacing the standard single-slice excitation pulse with a multi-slice pulse in an MR imaging sequence will therefore result in an image with all the simultaneously excited slices projected onto each other (Figure 6A). As mentioned above, the parallel imaging concept provides an elegant way to separate multiple image signals which are aliased into one image pixel. Thus, sufficient sensitivity variations of the underlying receiver array along the slice direction will then allow for separation of the slices using adapted standard PAT reconstruction algorithms [4, 11]. However, in cases where the sensitivity variations along the slice direction are not sufficient, e.g. as a result of small slice distances or suboptimal coil geometry, the PAT reconstruction will fail and result in large noise amplification. Sensitivity variations, potentially available along the other spatial directions, here the phase-encoding direction, are not employed.

It has been demonstrated that increasing the field-of-view (FOV) by the number of simultaneously excited slices allows the individual slices to be shifted with respect to each other in an extended FOV (along the phase-encoding) [12, 13] such that the slices show no superposition. A similar concept is Hadamard-aided RF encoding [14]. The required shifts mentioned above can be accomplished by employing dedicated alternating multi-band RF pulses providing the individual bands with well-defined phase-cycles along the phase-encoding direction (e.g using the set of RF pulses displayed in Figure 5). Due to the volumetric excitation, this approach offers a benefit in SNR efficiency of square root of the number of simultaneously excited slices compared to single-slice acquisitions, however at the cost of increased pulse energy deposition.

Using this concept in combination with image acceleration (fewer phase-encoding steps), superimposed slices with individual shifts along the phase-encoding direction can be realized by employing alternation of RF pulses taken, e.g. from the set of pulses given in Figure 5. A four-slice excitation at an acceleration of PAT = 4 using only RF pulse 1 yields a superimposition of 4 image pixels originating from all the 4 slices at the same location in the phase-encoding direction (Fig. 6A). Employing an alternation of RF pulses (e.g. pulse 1 and pulse 3, or pulses 1, 2, 3 and 4), the individual slices can be shifted with respect to each other in the FOV (Figs. 6B, C). In this way, as demonstrated in the corresponding *zy*-plots, aliased pixels may now originate from both different slices and different locations in the phase-encoding direction in a well defined manner (MS-CAIPIRINHA), thereby allowing the PAT reconstruction to take advantage of sensitivity variations in the slice and the phase-encoding direction, resulting in lower *g*-factors and consequently a higher SNR.

The benefit of MS-CAIPIRINHA is demonstrated *in vivo* employing a 4-times-accelerated simultaneous 4-slice experiment: Figure 7 shows 4 slices in a volunteer's brain (slice positions are indicated in the sagittal brain image), which are excited simultaneously using specialized multi-band RF pulses taken from the set of pulses given in Figure 5A. In the case of non-alternating RF pulses [4] (MS-Standard), each slice is subject to the same phase cycle along the phase-encoding direction (LR). The slices appear projected directly on top of each other, thereby allowing the PAT reconstruction (here GRAPPA-SENSE hybrid [11]) only to use sensitivity variations available in the slice direction. Due to the relatively small slice distances, the relatively high acceleration factor (PAT = 4) and the limited sensitivity variations provided by the coil array in the slice direction, the reconstruction results in large noise amplifications and thus unacceptable image quality. However, using a MS-CAIPIRINHA acquisition in combination with an adapted GRAPPA reconstruction, the folded image pixels can now be separated almost without any noise amplification. In this example, an MS-CAIPIRINHA scheme as depicted in Figure 6B has been employed. Alternation of pulses 1 and 3 provides slices 2 and 4 with a 180° phase-cycle along the phase-encoding direction, causing these slices to appear shifted by FOV/2 with respect to the slices 1 and 3 which had no phase modulation. Thus, in this case, MS-CAIPIRINHA allowed the acquisition of 4 slices in the same time normally required for a single slice without losing SNR.

In addition, the applicability of MS-CAIPIRINHA to cardiac perfusion imaging is demonstrated in Figure 8. A two-slice CAIPIRINHA saturation recovery TrueFISP sequence has been employed using a total acceleration of PAT = 3. This allows for the acquisition of 12 slices (8 slices in the short-axis view and 4 in the long axis) in only two cardiac cycles. A repetition of the sequence during contrast agent uptake has the potential for cardiac perfusion imaging with significantly increased spatial coverage in high temporal resolution [15].

Conclusion

In all current parallel acquisition techniques, aliasing artifacts resulting from an undersampled acquisition are removed by a specialized PAT image reconstruction algorithm. The CAIPIRINHA concept aims on modifying the appearance of the aliasing artifacts already during the acquisition to improve the following parallel image reconstruction procedure. Specifically, this concept has been successfully applied to 3D imag-

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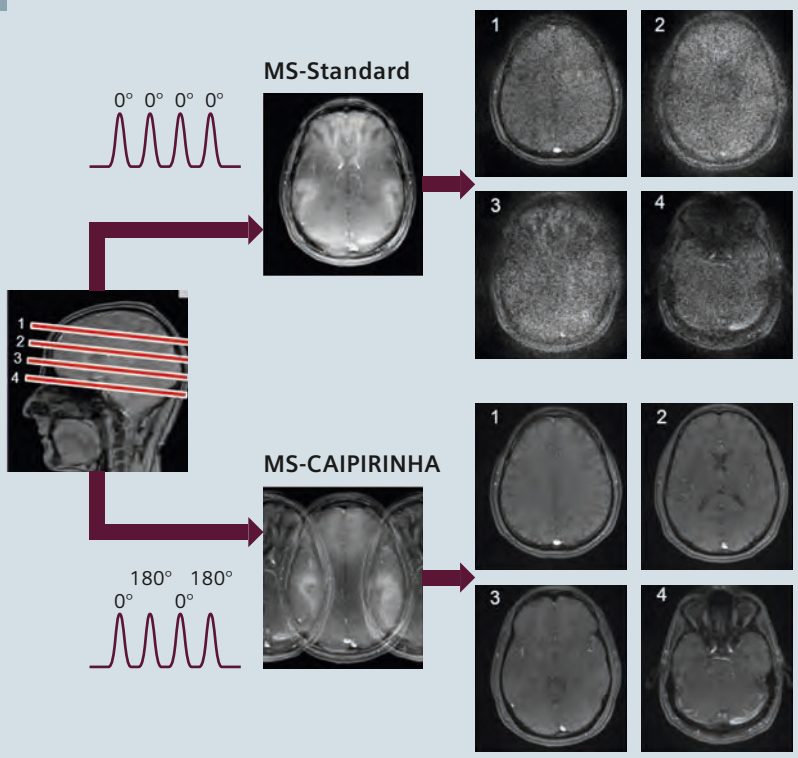

7 *In vivo* brain example:
4 x accelerated simultaneous 4-slice experiment using no phase cycling (MS-Standard) results in superimposition of all the slices directly on top of each other. Due to the lack of sufficient sensitivity variations along the slice direction, strong noise amplifications can be observed after GRAPPA reconstruction. Using MS-CAIPIRINHA, employing 2 alternating multi-band RF pulses, slices 2 and 4 appear shifted with respect to slices 1 and 3 in the folded image. In this way, sensitivity variations in the phase-encoding direction (LR) can be used in addition to the sensitivity variations available in the slice direction. The concept results in significantly improved image quality after GRAPPA reconstruction.

Imaging parameters: 3T MAGNETOM Skyra, TE 3.4 ms, TR 100 ms, FA 50°, FOV 178 x 220 mm², matrix 208 x 320, slice thickness 4 mm, distance factor 300%.

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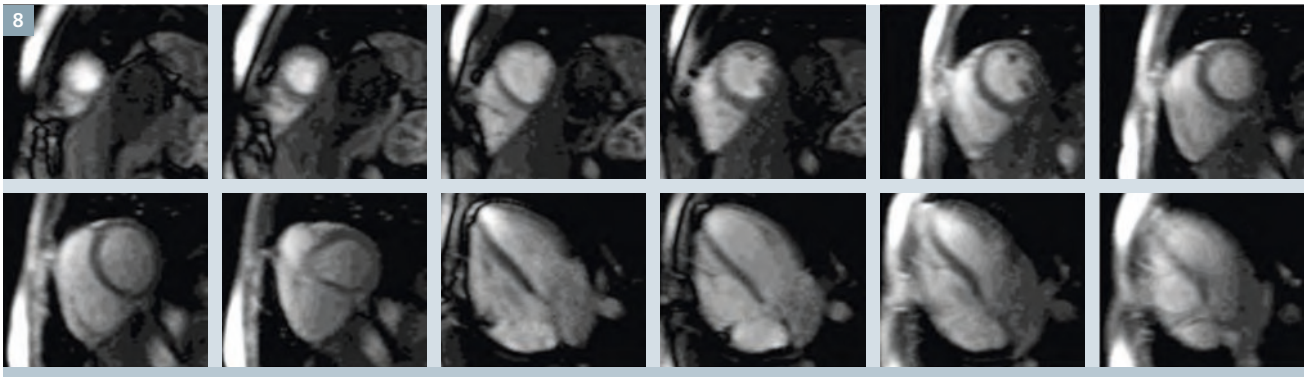

8 *In vivo* cardiac example: The MS-CAIPIRINHA approach enables the acquisition of up to 6 slices per cardiac cycle. Here, 12 slices are acquired within 2 cardiac cycles (8 slices in short-axis view and 4 in the long axis).

Imaging parameters: 1.5 T MAGNETOM Avanto, 32-channel cardiac array (Rapid Biomedical, Würzburg, Germany); Sequence: SR-TrueFISP, CAIPIRINHA phase cycle +90°/-90°; FOV 320 x 260 mm², matrix: 128 x 77, resolution 2.5 x 3.4 mm², slice thickness 10 mm, distance factor (two-slice pulse) of short/long axis: 200%/100%; partial Fourier 6/8, measurements: 20, TR 2.8 ms, TI 120 ms, TE 1.4 ms, FA 50°, reconstruction algorithm GRAPPA (R=3). *Images courtesy of Daniel Stäb.*

ing (2D-CAIPIRINHA) and clinically even to the often more routinely used 2D sequences (TSE; ss-EPI) with simultaneous multi-slice imaging (MS-CAIPIRINHA).

2D-CAIPIRINHA

In conventional PAT-accelerated 3D imaging, data reduction is performed in two spatial dimensions simultaneously by integer-valued undersampling in each phase-encoding direction. Though sensitivity variations can be exploited in two spatial dimensions, this sampling strategy provides suboptimal encoding performance. The 2D-CAIPIRINHA strategy modifies aliasing in a controlled manner already during the data acquisition. This is accomplished by shifting sampling positions in the two-dimensional phase-encoding scheme with respect to each other. In this way, at certain image acceleration values, an optimal sampling pattern can be found which minimizes signal overlap and at the same time allows one to efficiently take advantage of all the sensitivity variations provided by the coil array in the 2D phase-encoding plane. Thus, 2D-CAIPIRINHA provides optimal reconstruction performance given a certain coil configuration and object shape, and therefore results in optimal image reconstruction quality.

MS-CAIPIRINHA

Similar to 2D-CAIPIRINHA, aliasing in simultaneous multi-slice acquisitions can be modified already during the acquisition by employing alternating RF pulses for subsequent phase-encoding lines, thereby allowing the imprint of the individual slices with individual phase-cycles causing the slices to appear shifted with respect to each other thereby improving the reconstruction process minimizing *g*-factor-related noise enhancements. Thus, a CAIPIRINHA-type 4-slice excitation with low *g*-factor values (close to 1) allows the acquisition of 4 slices in the same time usually required for 1 slice without loss of SNR. The initial approach of alternating RF pulses introduced here, however, is not applicable for single-shot sequences such as EPI where only a single RF pulse is used to acquire all lines of *k*-space. Innovative concepts like blipped-CAIPINHA (see also the Article by Kawin Setsompop) where additional gradient magnetic fields are used during the readout to generate the required phase modulations allow to apply SMS to more advanced acquisition schemes such as SSFP [15] EPI [18] and radial [19] simultaneous multi-slice imaging.

However, it is important to note that multi-slice excitations are associated with significantly increased energy deposition, currently limiting the method to a moderate number of simultaneously excited slices, and/or to low flip angles. However, recently, a promising concept for reducing the RF power of multi-band pulses has been introduced [20]. Thus, MS-CAIPIRINHA is expected to become a powerful strategy in the near future allowing for significantly acceleration of many clinical protocols while almost preserving image quality.

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