Restating MS-CAIPIRINHA as an In-plane Acceleration Problem: An Efficient Method for Integrating High Coverage Cardiac Perfusion MRI into Clinical Workflow

Target Audience: Clinicians interested in cardiac perfusion and MR physicists interested in using MS-CAIPIRINHA.

Purpose: In recent years, the simultaneous multi-slice Parallel Imaging technique MS-CAIPIRINHA (1) has proven its efficiency for extending the anatomic coverage in time-critical 2D multi-slice applications such as myocardial perfusion MRI (2). In this work, we demonstrate how the reformulation of MS-CAIPIRINHA as a pure in-plane acceleration problem facilitates the integration of MS-CAIPIRINHA in a clinical environment with existing inline post-processing options.

Materials and Methods: MS-CAIPIRINHA employs multi-band radio frequency (rf) pulses to excite N_S slices at the same time. By providing the different slices with individual rf phase cycles, the slices are shifted in phase-encoding direction with respect to each other in the FOV, improving the separation of the slices using parallel imaging techniques. A very simple separation of such simultaneously excited slices can be achieved by N_S-fold oversampling the FOV in phase-encoding direction (3). In this case, of course, the measurement is non-accelerated with respect to a sequential measurement of the slices. This non-accelerated formulation, however, allows for a very flexible and lean integration of MS-CAIPIRINHA into existing clinical applications. Starting from the N_S-fold oversampled FOV, standard in-plane GRAPPA and SENSE acceleration methods can be utilized to speed up the measurement. Thus, accelerated MS-CAIPIRINHA acquisitions can be performed without severe modifications to the sequence or the image reconstruction chain. As shown in Fig. 1, apart from protocol and user interface adjustments, only the rf excitation has to be replaced by the desired multi-band excitation. In addition, the reconstruction chain has to be extended by a simple FOV-splitting method required to fully separate the images.

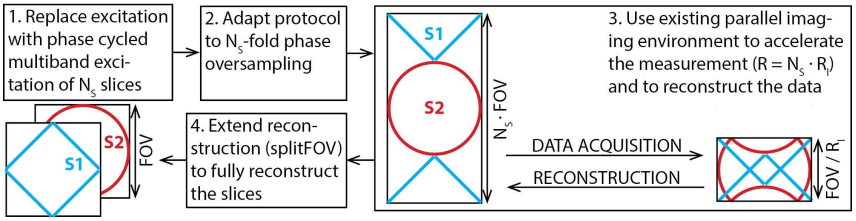

Fig.1: *Basic concept: The simultaneous multi-slice excitation (1.) is applied to a protocol with N_S-fold phase oversampling (2.), converting the multi-slice problem to a standard in-plane acceleration problem. Standard inbuilt parallel imaging functionality thus can be used (3.). To complete the slice separation, the reconstruction chain is extended by a FOV-splitting functionality (4.). In this example: R=3, N_S =2 and R_I=1.5.*

In order to demonstrate this lean approach, a sequence prototype was built by modifying a 2D sequence with TurboFLASH contrast and TGRAPPA (4) in-plane acceleration for cardiac dynamic imaging to support MS-CAIPIRINHA with slice acceleration factor N_S = 2. The excitation rf phase in S1 was kept unmodulated, in S2 it was toggled between 0° and 180°. For slice planning, the geometrical slices were visualized independent of the slice acceleration. Phase oversampling was set to 100% to double the FOV for N_S = 2. To improve the spatial resolution in addition to the anatomical coverage, TGRAPPA in-plane acceleration was applied. Images were reconstructed using the standard TGRAPPA image reconstruction program with only minor reparametrization and the FOV-splitting functionality added. The presented lean approach requires that the actually measured data (slices shifted by ½ FOV) is identical to the data generated by undersampling the corresponding fully sampled data set with acceleration factor R = $N_S \cdot R_I$. This condition is met for N_S = 2, if R is odd, which in turn means that the in-plane acceleration factor has half integer value (i.e. R_I = 1.5, 2.5, …). Here R = 5 was chosen in the UI, so that R_I = 2.5. The prototype supported the inline correction of respiratory motion, the acquisition of initial proton density (PD)-weighted frames for normalization of image intensities (5) as well as the calculation of up-slope maps (all inbuilt).

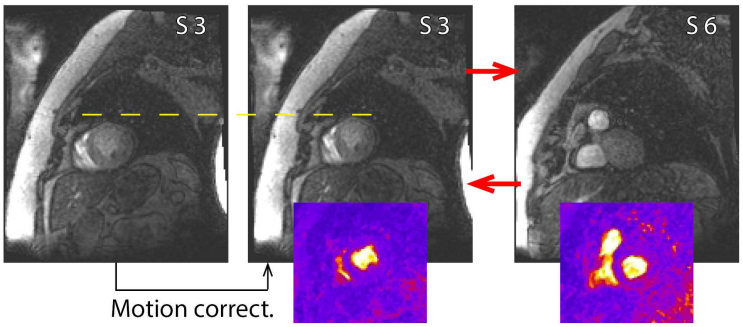

Fig.2: *Exemplary slice pair (Slice 3 and 6) with R = 5 acquired 363ms after trigger. The MS-CAIPIRINHA implementation facilitates attaching post-processing functionality like motion correction (visualized on the left for slice 3) and up-slope map calculation (bottom for both slices). Note that the wrap artefacts from one slice appear at the edges of the other slice (red arrows).*

Results: The lean integration of MS-CAIPIRINHA was successfully tested on 2 volunteers (MAGNETOM Skyra, Siemens AG Healthcare, Erlangen, Germany, 6 slices, thickness: 5mm, R=5, TI=100, TE=1.1ms, TR=2.4ms, T_{Acq}=209ms, flip=10deg, 2.5x2.5x5mm^3). Fig. 2 shows exemplary images from a simultaneously acquired slice pair post-processed using the inbuilt motion correction and up-slope map calculation. Performing the motion correction allows obtaining smooth signal intensity time curves (data not shown), which in turn is required for the map calculation. Note that wrap artefacts from one slice appear at the edges of the other slice (red arrows).

Discussion and Conclusion: The described lean implementation of MS-CAIPIRINHA facilitates myocardial perfusion imaging with extended anatomic coverage within a clinical environment. MS-CAIPIRINHA was introduced without changing the operator workflow. Employing half-integer in-plane acceleration factors allows using the inbuilt parallel imaging functionality, which in turn provides the flexibility to attach available post-processing functionality, like, e.g., motion correction. In addition, for half-integer acceleration factors the image centers are free of artifacts that otherwise can be introduced there by discontinuities in the calibration data (6-7). Future developments could support in a similar fashion external PAT reference scans and more advanced iterative reconstruction schemes and extended applications like quantitative perfusion.

References: [1] Breuer FA, Magn Reson Med 53: 684-691 (2005), [2] Stäb D, J Magn Reson Imag 39: 1575–1587 (2014), [3] Glover GH, J Magn Reson Imag 1: 457-461 (1991), [4] Breuer FA, Magn Reson Med 53: 981-985 (2005), [5] Xue H, Med Image Comput Assist Interv 12:741-749 (2009), [6] Blaimer M, Magn Reson Imag 24:444-450 (2006), [7] Setsompop, Magn Reson Med 67:1210–1224 (2012).