Two-Dimensional Multiband Diffusion Weighted Imaging

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Target audience: MR physicists with an interest in DWI and multiband methods.

Purpose: The use of 2D RF pulses for reduced FOV (rFOV) diffusion-weighted imaging (DWI) has been shown to provide high-resolution images of targeted regions with minimal distortion [1]. However, the clinical utility of this technique is limited to either organs of limited extent in at least one direction or cases where the location of disease is known *a priori* (e.g. treatment monitoring). We developed a novel DWI technique that builds upon the concepts of rFOV, multiband (MB) and parallel imaging (PI) to extend the high-resolution and anatomical fidelity achievable with small FOV methods over the much larger volumes required by most body applications. Feasibility was demonstrated through phantom experiments and in the breast of a healthy volunteer.

Methods: *Theory:* rFOV methods allow faster k-space traversal with shorter echo train lengths and therefore lower distortion and T2*-induced blurring. A 2D echo-planar RF pulse can excite a limited 2D FOV. The discrete sampling of excitation k-space along the blipped direction translates into periodic replicas of the excitation profile. By blipping along the slice-select direction, the reduced FOV excitation pattern shown in Fig. 1a is produced. While the slice selective refocusing pulse suppresses signal from the excitation side lobes as well as fat, saturation effects limit the max achievable slice coverage per TR. Phase modulating the individual sub-pulses, each band of magnetization can be split into multiple co-planar bands excited at once (Fig. 1b). A MB 180° refocusing pulse can be used to simultaneously refocus a subset of the excited sidebands in the slice direction (e.g. 3 bands in-plane × 3 through-plane), which will contribute signal during imaging [2]. Progressively shifting this excitation pattern along the phase-encode direction, complete coverage can be achieved. If phase encoding is limited to the width of a single band (short ETL, reduced distortion) both in-plane and through-plane fold-over will occur. However, if the distance between the bands is comparable to the distance between the physical receiver elements of a multichannel array coil, signals originating from different bands can be resolved using PI. By exploiting the complementarity of excitation and sensitivity profiles (each band "sees" only a small portion of the object being imaged and the corresponding signal is in turn received by a subset of coil elements in proximity to the excited band) signals originating from simultaneously excited slices can be resolved, while efficiently combining different co-planar strips of magnetization into a composite image with minimal artifacts between adjacent bands. Conversely, the multiple bands augment the coil sensitivity variations in standard MB imaging.

Pulse sequence: Multi-pass, multi-slice 2D single-shot spin-echo EPI with 2D phase-modulated RF excitation and VERSEd [3] MB 180° refocusing pulse. Fat suppression was achieved by design of the 2D RF so that no overlap existed between fat and water for $B_0 \geq 1.5T$ (cfr. Fig. 1).

Image reconstruction: Generalized PI reconstruction with Np x Nc "virtual coils" (Np=number of passes=number of shifts applied to the original excitation pattern; Nc=number of physical receiver coils). A generalized ARC (Autocalibrated Reconstruction for Cartesian imaging [4]) reconstruction with phase-offset multiplanar (POMP) [5] formalism to handle through-plane MB was used. A low resolution, fully sampled EPI acquisition (14s) with the same *in-plane* MB excitation pattern and the same number of passes (Np) used for the actual acquisition was used for PI calibration.

Imaging was performed at 3T (GE MR750, GE Healthcare, Waukesha, WI) using the 20 upper channels of a 32 channel torso array coil for the phantom experiments and a 16-channel breast coil (Sentinelle Medical, Inc, Toronto, ON, Canada) for the in vivo portion of the study. MB factors of 3 both in-plane and trough-plane were used. Four passes were used to cover a 36cm FOV, which gave a total of 20x4 = 80 and 16x4 = 64 "virtual" coils, for the phantom and in vivo experiments respectively, to reconstruct a 4 (in-plane acceleration=FOV reduction factor) x 3 (through-plane acceleration=number of multiplexed slices) undersampled dataset. Reconstructed images were compared to conventional non-MB single-shot EPI with 4x phase acceleration. A higher resolution 2D MB dataset ($0.8x0.8x4mm^3$, 16x4 = 64 "virtual" coils and 8x3 undersampling) was acquired in the breast to show the anatomical fidelity and high-resolution capabilities of the proposed method.

Results and discussion: With a through-plane MB factor of 3, 48 slices (~20cm S/I coverage) and 2 b values were acquired in 5:30. Fig. 2 shows improved in-plane PI performance of 2D MB (a) with respect to the corresponding non-MB acquisition (b) as well as correct separation of the 3 multiplexed slices. Fig. 3 shows 3 multiplexed slices correctly resolved using 2D MB DWI with minimal artifacts at the intersection between co-planar bands (a) and the corresponding slices acquired by conventional full-FOV non-MB DWI with the same in-plane acceleration (i.e. similar distortion). Fig. 4 shows the high-resolution capabilities of the proposed method compared with conventional DWI. The use of in-plane MB allows reduction of the effectively encoded FOV beyond the parallel imaging capabilities of physical array coils at the cost of increased scan time (multiple passes needed to cover the desired FOV). Simultaneously multiplexing multiple slices almost completely recovers the lost efficiency. Additional blips could be used to further improve the through-slice MB performance [6].

Conclusion: We showed feasibility of a novel 2D MB technique for high-resolution DWI, which can be thought of as an extension of a previously reported r-FOV method that can be tailored to the specific imaging requirements and coil geometry. High-resolution with limited distortion was demonstrated in the breast of a healthy volunteer.

References: [1] Saritas E.U. et al. MRM 2008; 60: 468; [2] Banerjee S. et al. ISMRM 2014; p.4437; [3] Hargreaves B.A. et al. MRM 2004; 52: 590; [4] Brau A.C. et al. MRM 2008; 59: 382; [5] Glover G.H. JMRI 1991; 1: 457; [6] Setsompop K. et al. MRM 2012; 67: 1210

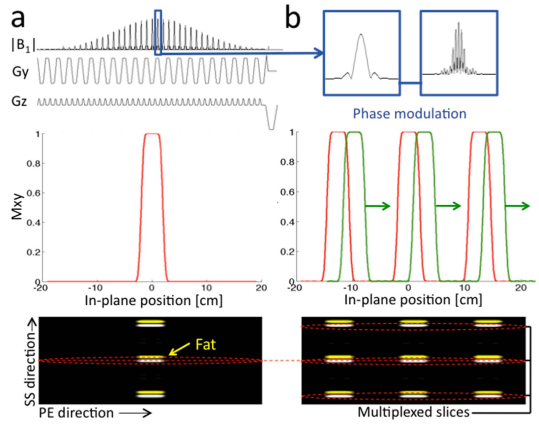

Figure 1: Periodic 2D excitation profile without phase modulation and conventional refocusing pulse (a) and after phase modulation, in combination with the MB refocusing pulse (b). Note that there is no overlap between the 3 slices multiplexed by the MB refocusing pulse and the corresponding excitation profile for fat so that fat is automatically suppressed. By progressively shifting the 2D excitation pattern (b) complete coverage can be achieved.

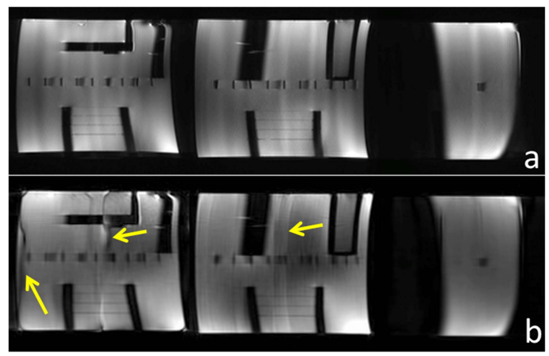

Figure 2: (a) 2D MB multiplexed slices (4x3 PI acc; 3x3 MB factor) and (b) corresponding standard DW-EPI (4x acc. In-plane).

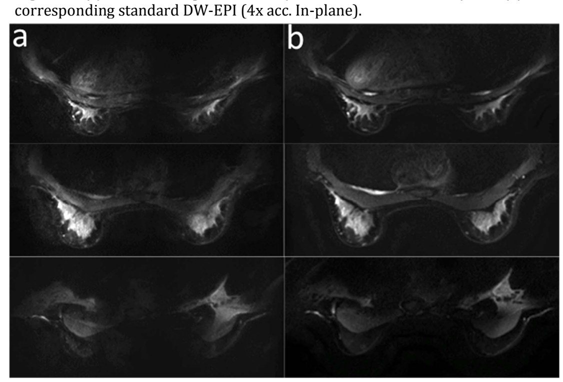

Figure 3: (a) 2D MB multiplexed slices (4x3 PI acc; 3x3 MB factor) and (b) corresponding standard DW-EPI (4x acc. In-plane).

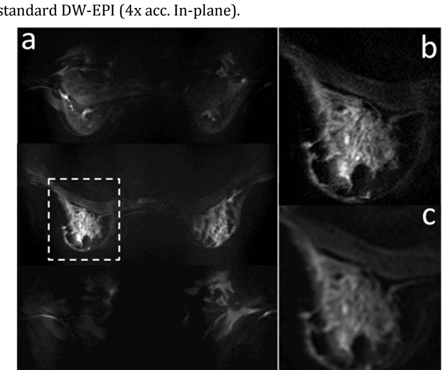

Figure 4: High-resolution 2D MB DWI ($0.8x0.8x4mm^3$, 3x3 MB factor, 8x3 PI acc, $b=600s/mm^2$): (a) multiplexed slices, (b) anatomical detail of right breast and (c) corresponding non-MB DW-EPI ($0.8x0.8x4mm^3$, 4x phase acc).