Multi-Slice Two- and Four-Fold Acceleration with Single- and Eight-Channel Coils, Respectively

A. Jesmanowicz[1], **S-J. Li**[1], **and J. S. Hyde**[1]
[1]Biophysics, Medical College of Wisconsin, Milwaukee, WI, United States

INTRODUCTION: The purpose of this work was to reduce the time needed for whole brain resting-state functional connectivity imaging (R-fMRI) using an EPI sequence with sufficiently thin slices that signal dropout from intravoxel dephasing no longer occurs. Functional connectivity across the whole brain requires acquisition of each whole-brain dataset within a TR value that is approximately the same as the hemodynamic response—about 2s. Use of thin slices is an effective way to reduce signal drop-out. Using conventional methods now in practice, it can take more than 10 s to acquire whole-volume thin-slice images. Multi-slice excitation was introduced more than 20 years ago (1), and although there have been some publications in the intervening years, the method is not in common use. This may be because problems in slice reconstruction have not been effectively solved. In contrast, the SENSE technique and its derivatives are extensively used on commercial scanners for within-slice acceleration of data collection. It is noted that the efficacy of the SENSE method in reducing the TR value is lessened because time required for fat suppression, slice selection, and crusher pulses remains the same, in contrast to the across-slice method of acceleration introduced here.

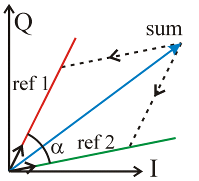

Fig.1. *Back projection.*

OVERVIEW OF THE METHOD: Tailored pulses are formed from the inverse FT of the required slice profiles including not only positions but also relative phases (2). Each complex-valued composite RF pulse is formed from a single transmit frequency. In this way, reference slices needed for multi-slice separation can be acquired with exactly the same phase as the combined image by masking the unneeded part of the composite profile. For two slices, 90-degree phase difference between slices is an obvious choice. In the ideal case of uniform phase profile in each slice and absolute phase aligned with the I acquisition channel, the first slice would be in the I channel and the second in the Q. This is the basis of two-fold acceleration with a single RF coil. In practice, phases vary across each slice and orthogonality is not achievable in all pixels. Figure 1 shows the situation in a single pixel where reference slice phases are not orthogonal, as indicated in red and green. The blue vector, representing acquired signal from both slices, is back projected onto the unit vector pairs (1, 2) in the process of slice separation, which is equivalent to solving two linear equations in the complex domain—namely, finding two real values x_i as solutions of the form $\mathbf{A} \cdot \boldsymbol{x} = \boldsymbol{b}$, where $\boldsymbol{b}$ contains I and Q components of a multiple slice. In few pixels, the phases can happen to be parallel and solution is impossible because the determinant of the matrix A is zero. With use of a Singular Value Decomposition (SVD) technique to solve these equations, singularities are reported and values of these pixels in both slices are set to zero, as can be seen in Fig. 4 (bottom). For more channels, a different approach was found to be necessary. As seen in Fig. 2, vectors were formed from whole slice reference images, and projections similar to those of Fig. 1 were made. The resulting images had all values of one, as required, except for outside noise areas. As such, they can be used for fMRI analysis, as shown in Fig. 3, where the BOLD effect signal change is shown in the first slice as a Δ1 deviation. For visualization, separated slices were later multiplied by the square root of the sum of squares of the reference images. Mathematically, this is equivalent to back projection, as shown in Fig. 1.

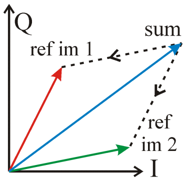

Fig.2. *Proj. on image.*

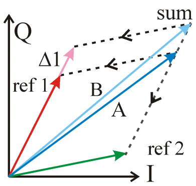

Fig.3. *BOLD effect.*

EXPRIMENTAL METHODS: The study was performed on a GE Signa EXCITE 3 T MR scanner. A gradient EPI sequence of our own design (3) was used and acquisition was done off-line using a computer equipped with three Mercury ECDR-GC316 cards (4) running Linux OS. Acquisition parameters were: TR = 1 sec, BW = 208 kHz, FOV =24 cm, slice 3 mm. At 1 NEX and 64 × 64 resolution, TE = 26 ms, at 96 × 96, TE = 40ms. Tailored transmit pulses lasted 6.4 ms and were loaded with 4 μs update steps. Ten image time-courses were acquired as reference slices and time-courses of 135 images for fMRI data. The GE Quad Transmit/Receive Head Coil was used as a single channel coil, and an eight-channel receive only high-resolution brain array coil was used for multi-channel acquisition.

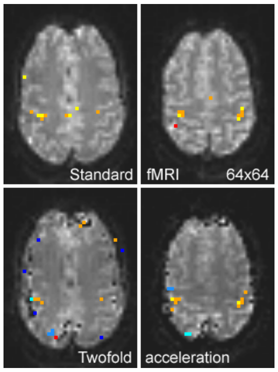

Fig.4. *Two slice fMRI overlay.*

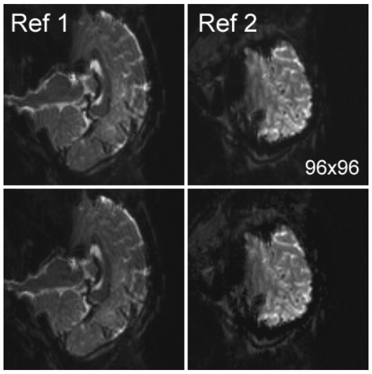

Fig.5. *8-channel, two-fold acceleration.*

RESULTS and DISCUSSION: For a single channel, the two complex equations were used to derive two real values x_i as a solution. Figure 4 (bottom) shows two-fold accelerated images with fMRI overlays using a single RF coil. Upper images were acquired in a conventional manner in a separate pass using complex finger-tapping as a paradigm. For multi-channel coil acquisition, the solutions x_i were in the complex form. The SVD method of least-squares was used because the number of equations exceeded the number of solutions. The number of equations doubled and a minimum of two channels was required for a two-fold acceleration. Figure 5 (bottom) shows two separated slices acquired with an eight-channel coil. Sagittal rather than axial images were acquired because the coil configuration is nearly uniform in the z-direction. Figure 6 shows images obtained with four-fold acceleration. Black pixels on the lower images represent areas where equations were unsolvable. Images obtained with the eight-channel head coil with four-fold acceleration are decent, but also illustrate the limits of acceleration when using this coil. Other limitations have been identified including (a) ghost slices of lower amplitude for spectral separations larger than 50 kHz. This is attributed to the RF pulse D/A minimum sampling rate used of 4 μs. To improve the quality of the tailored pulse, the duration was increased to 6.4 ms, which is long. And, (b) the maximum available excitation power. The average excitation power, for example, is four times higher for four slices than for one and is about the same as a 180-degree pulse. Simulations of the tailored pulse show that the peak power increases 16-fold and can exceed the limit of the transmit amplifier. Nevertheless, because the tailored pulse is narrower, the SAR remains acceptable.

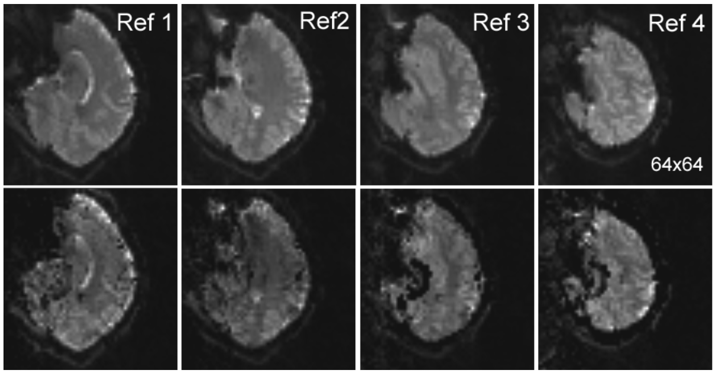

Fig.6. *8-channel, four-fold acceleration.*

CONCLUSION: The tailored multi-slice excitation pulse can be viewed as a composite pulse that is a phase-controlled linear combination of pulses required to excite each member of the slice array, which is a significant aid in slice reconstruction and is believed to be innovative. Preliminary data using tailored pulse excitation and reconstruction of thin slices have been obtained. Analysis indicated that a faster RF pulse D/A clock and a coil with more channels will improve slice quality.

REFERENCES:

1) Müller S. *Magn. Reson. Med.* **6**:364-371, 1988.
2) Jesmanowicz A, Hyde JS. *Proceedings of ISMRM,* Toronto, p. 156, 2003.
3) Jesmanowicz A, Bandettini PA, Hyde JS. *Magn. Reson. Med,.* **40**:754-762, 1998.
4) Jesmanowicz A, Hyde JS. *Proceedings of ISMRM*, Seattle, p. 2027, 2006.