A 3D-PLUS-TIME RADIAL-CARTESIAN HYBRID SAMPLING OF K-SPACE WITH HIGH TEMPORAL RESOLUTION AND MAINTAINED IMAGE QUALITY FOR MRI AND FMRI

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INTRODUCTION: The novel method PRESTO-CAN [4], [5] for 3D-plus-time resolved MRI includes a radial-Cartesian hybrid sampling, see Fig. 1, right. Golden ratio angular sampling [2] and hourglass filtering provides high temporal resolution, see Fig. 2. When the method is used for fMRI–acquisition, long echo times are used, TE≈37-40 ms, and this result in both field inhomogeneities and phase variations in the reconstructed images. Therefore, PRESTO-CAN also includes an internal calibration and correction procedure. Reconstruction is performed using gridding [1]. Without hourglass filtering, the image quality is almost identical to what can be obtained with conventional Cartesian sampling. With hourglass filtering, data points are first removed and later restored by angular interpolation. This procedure affects the image quality to some extent, we present here a method for circumventing this.

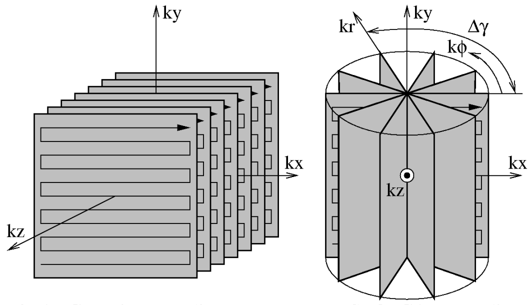

Fig 1. Cartesian sampling PRESTO−CAN sampling

MATERIALS AND METHODS:
K-space sampling: 3D sampling of k-space is normally performed using Cartesian sampling as in Fig. 1, left. PRESTO-CAN, on the other hand, uses a hybrid radial-Cartesian sampling as in Fig. 1 right, i.e. radial sampling in the (kx,kz)-plane and Cartesian sampling in the ky-direction. In Fig. 1, each profile in k-space is sampled using one excitation only, i.e. single-shot. In actual experiments, we used lower EPI-factors. The focus of the following discussion is on the radial data, which is in 2D-space.
Time order sampling: K-space was sampled using N radial profiles at N fixed angle positions. Let the profile numbers be n=0, 1, 2,…, N-1 with the corresponding angles n·360°/N. The smallest angular difference between profiles will then be $\Delta\phi$=360°/(2N). Among all possible angles, the one with profile number n=M and closest to 180° divided by the ***golden ratio*** was chosen. Consequently, the angular increment was chosen to be $\Delta\gamma$=360°·M/N≈180°·2/(√5+1)≈111°. This is different from [2], where the angular increment was exact 180°·2/(√5+1). To guarantee that all profiles were visited before repeating the first profile, N was chosen to be a ***prime number***. The sampling pattern for N=7 profiles is illustrated to the left in Fig. 2 and to the right the profiles were plotted with respect to time. The profile numbers n = 0, 1, 2, 3, 4, 5, 6 agree with the time order t = 0, 1, 2, 3, 4, 5, 6, 0, 1, 2, 3,...

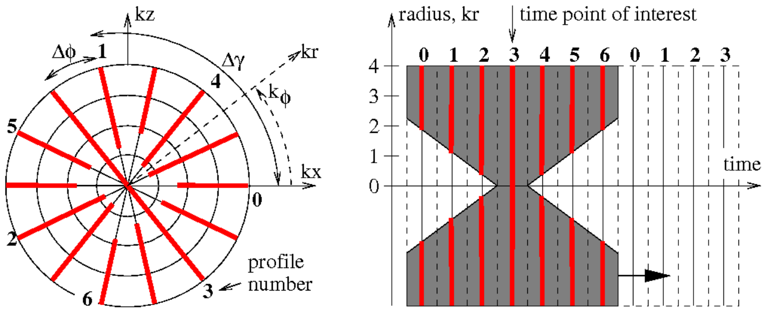

Fig. 2 PRESTO−CAN sampling of k−space and the moving hour−glass filter.

Hourglass filtering: The center of k-space is thus over-sampled and to increase time resolution, 'too old' and 'too new' data may be removed using a non-causal filter. In Fig. 2, the time point of interest was chosen to be profile 3. Then, as much data as possible were removed from the outer profiles (0 and 6). Then data from profile 1 and 5 and finally 2 and 4 were removed. This procedure resulted in the hourglass shaped filter in Fig. 2. The hourglass filter will move forward in time as indicated by the arrow. For each time position a new volume will be reconstructed.
Reconstruction: The ***gridding*** method [1] was used for image reconstruction. The algorithm consists of the following steps: 1) Pre-compensation with the local sampling density, 2) re-sampling with forward mapping using the Kaiser-Bessel interpolation function $C(k_x,k_y)$= $C(k_x)\cdot C(k_y)$, 3) inverse Fourier transform, 4) division with the inverse Fourier transform of $C(k_x,k_y)$. In the case of radial sampling without hour-glass filter, the pre-compensation was trivial and proportional to the radius (except for the samples at the origin). When the hour-glass was applied, it was much more elaborate to determine the pre-compensation. In [5], this was solved by restoring the removed data points by using angular interpolation prior to pre-compensation. However, linear interpolation in k-space introduces small errors. An alternative is to use the method proposed in [3]; an optimal weight function is then iteratively calculated to be used for the pre-compensation. The idea is that sampling of k-space with sample points weighted with the obtained weight function will give ***no aliasing*** in the image domain. In [3], a truncated *jinc*^{2} function $J(k_x,k_y)$ was utilized in the iterative process. (The *jinc*-function is similar to the *sinc*-function and $jinc(r)=J_1(r)/r$ where J_1 is a Bessel function.) The important quality of $J(k_x,k_y)$ is that its inverse Fourier transform $j(x,y)$ has the properties $j(0,0)$=1 and $j(x,y)$=0 for $(x^2+y^2)^{0.5}>F$, where F is the field of view.

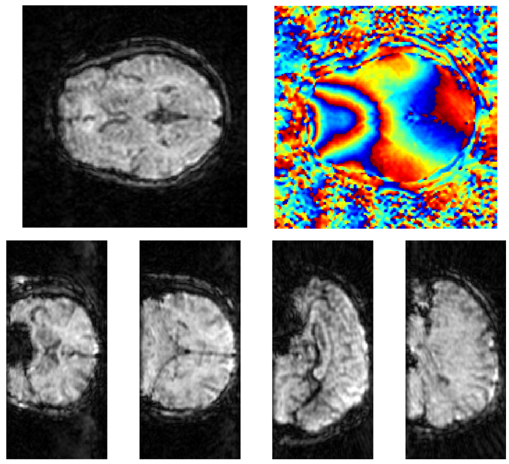

Fig. 3 Reconstructed PRESTO-CAN volume. Upper row: A transversal slice with magnitude (left) and phase (right). Lower row: Two frontal and two saggital slices.

RESULTS: Here we show comparisons of the image quality of the human brain for conventional Cartesian sampling and PRESTO-CAN in Fig 1. As the data acquisition aimed for fMRI-imaging, the echo times were long, TE≈37-40 ms, which resulted in field inhomogeneities and phase variations in the reconstructed images, see the phase image in Fig. 3. A ***novel calibration and correction procedure*** therefore had to be developed for PRESTO-CAN, [5]. It utilizes an initial reference scan and contains 1) conventional forward-and-back correction for EPI, 2) rotation angle position determination and correction, and 3) determination and correction for phase drift in the origin of k-space. The experiments were performed on a Philips 1.5T Achieva scanner. A modified PRESTO pulse sequence was utilized. The repetition time (TR) and echo time (TE) was TR/TE=24/40 and the EPI-factor was 15. The reconstructed volumes were (80,80,41), but in the final step, they were zero-padded once in the Fourier domain. The four experimental types of data can be described as follows: 1) The result from PRESTO-CAN without hour-glass filtering (shown in Fig. 3). 2) The result from conventional Cartesian sampling was almost identical to Fig. 3. 3) The result from PRESTO-CAN with hour-glass filtering and angular interpolation was somewhat degraded compared to Fig. 3. 4) The result from PRESTO-CAN with hour-glass filtering and pre-compensation with the weight function suggested in [3] anticipated to be almost identical to Fig. 3.
CONCLUSION: We aim to use the novel 3D-method PRESTO-CAN for brain fMRI. It has shown to provide excellent temporal resolution and also satisfactory image quality. Hourglass filtration followed by angular interpolation improves the temporal resolution, but affects the image quality slightly. Replacing the angular interpolation with the weight function suggested in [3] is proposed to solve this problem.
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