Optimized canonical sampling patterns in *k-t* space with two and three spatial dimensions for *k-t* BLAST and *k-t* SENSE

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INTRODUCTION Recently, several dynamic imaging techniques have been proposed that sample *k*-space data in a time-varying manner [1-3]. For example, *k-t* BLAST and *k-t* SENSE [3] allow a significant reduction in data acquisition by packing the image signals more tightly in *x-f* space (*x*=spatial position, *f*=temporal frequency) [4]. In these methods, the critical question is how to best sample *k-t* space in order to pack the signals as efficiently as possible [3,5,6]. The most straightforward choice of sampling pattern, which is a linear interleaved order, is unfavorable at higher acceleration factors. The purpose of this work is to present sampling patterns that are generally optimal for typical image series, without specific knowledge about the image series itself. These sampling patterns are important from a practical viewpoint, since they can be determined *a priori*, thus obviating the need to adapt the acquisition on-line to the object being imaged. Moreover, they are likely to stay near-optimal, even in the presence of slight changes in the signal distribution of the object, thereby improving the overall robustness.

THEORY Discrete sampling in *k-t* space leads to a convolution of the true image signals with a point spread function in *x-f* space. Since not all portions of *x-f* space contain the same amount of signals, it is possible to control the amount of overlap judiciously by the choice of the *k-t* sampling pattern. To minimize reconstruction error, the goal is to reduce the amount of signal overlap in *x-f* space, so that there is less aliasing to resolve [3]. In general, the number of possible sampling patterns is astronomical. For example, choosing *M* out of *N* phase-encode lines leads to *N*!/M!(*N-M*)! possibilities. In this work, we focus on Cartesian sampling of *k*-space, so only the locations of the phase-encode lines need to be chosen, while the frequency-encoding axis can be neglected. Also, we focus on sampling patterns with a lattice structure [3,5,6] (i.e. sheared grid), since the corresponding point spread functions are also lattices, which simplify the reconstruction significantly [3]. Without loss of generality, we only consider sampling patterns where all phase-encode steps (as determined by the chosen resolution and field of view) are acquired over time, and the distance between acquired lines are a multiple of the phase-encode step. We refer to these as "canonical sampling patterns", since all other lattice patterns can be derived from them by scaling along the phase-encoding and temporal directions.

Choosing the sampling pattern itself or the corresponding point spread function is equivalent, since the two are related. The present problem simplifies if we consider the latter. The point spread function has a lattice structure, so its main lobes (i.e. positions where the majority of signal aliasing occurs) are uniformly distributed along both the spatial (*x*) and temporal-frequency (*f*) axes [3,5] (Fig. 1). Also, these main lobes are aligned along a straight line that is periodically wrapped (see dashed line in Fig. 1). There are only a very limited number of point spread functions that satisfy these conditions for each acceleration factor, so they can be listed efficiently. To select the most favorable one, one may exploit two characteristics of typical image series: 1. reduced autocorrelation among voxel intensities with increasing distance (i.e. far apart voxels are less similar) [7], and 2. reduced signal magnitude at higher temporal frequencies [8]. As a result, signal overlap is minimized in general by maximizing the separation distance among the main lobes of the point spread function (denoted as *d* in Fig. 1). Once the favorable point spread function is selected, the corresponding *k-t* sampling pattern can be obtained by Fourier transform.

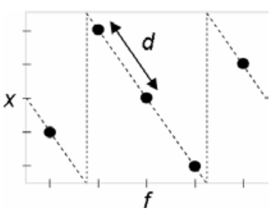

Fig. 1 Point spread function in *x-f* space for 5x acceleration in 2D. Due to the lattice structure, main lobes (black dots) are regularly spaced along *x* and *f*, lying along a periodically wrapped line. *d* denotes the minimum main-lobe separation distance.

MATERIALS AND METHODS Real-time 2D cardiac imaging was performed with either an optimized or an unoptimized (linear interleaved) *k-t* sampling pattern at 8x acceleration. A balanced steady-state free precession (SSFP) sequence was used on a Philips Intera 1.5T scanner (Philips, Best, the Netherlands) with a 5-element phased-array coil, TE/TR/flip = 1.49ms/3.00ms/60° and 27.1 frames/sec.

RESULTS Fig. 2 shows the minimum main-lobe separation distance *d* for 2 or 3 spatial dimensions at acceleration factors up to 9x. *d* is normalized to the field of view and effective temporal bandwidth. Compared to an unoptimized linear interleaved order, the optimized sampling patterns significantly increase *d* at higher acceleration factors, thereby reducing the potential amount of signal overlap. For example, the optimized pattern for 5x acceleration in 2D achieves a farther separation than even the 4x sampling pattern. For both optimized and unoptimized patterns, *d* is increased in 3D compared to 2D due to the availability of an extra dimension for information packing. Fig. 3 shows exemplary images acquired with an unoptimized (left) and optimized (right) sampling pattern, reconstructed using *k-t* BLAST (top) and *k-t* SENSE (bottom). The use of an unoptimized pattern led to overpacking of signals in *x-f* space, which resulted in some residual aliasing artifacts. The use of an optimized pattern led to farther signal separation, thereby minimizing the amount of signal overlap and eliminating the residual artifacts.

CONCLUSION We have presented an approach for optimizing lattice sampling patterns for typical image series. This is achieved without specific knowledge about the image series itself. The proposed approach reduces the astronomical number of choices to a handful, which can be searched efficiently to generate optimized sampling patterns in both 2D and 3D. These patterns can significantly increase the separation distance among the main lobes of the point spread function, thereby minimizing the potential amount of signal overlap and improving image quality. Such patterns are particularly important for the higher acceleration factors that are achievable, for example, with *k-t* BLAST and *k-t* SENSE.

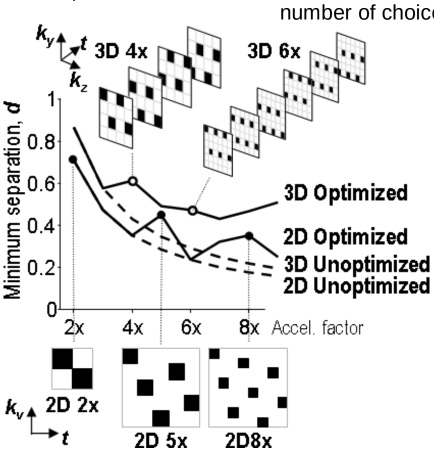

Fig. 2 Minimum main-lobe separation distance *d* at various acceleration factors for optimized and unoptimized (linear interleave) patterns. Several examples of optimized sampling patterns in 2D and 3D are shown.

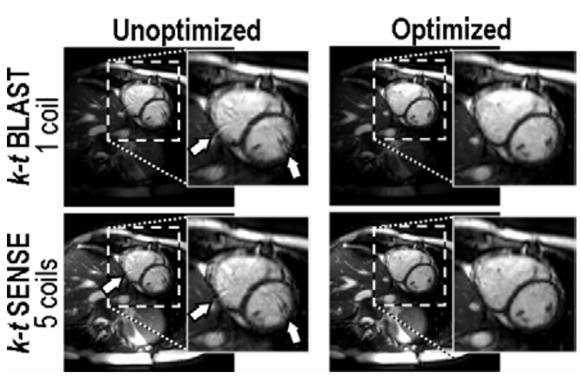

Fig. 3 2D real-time cardiac images at 8x acceleration using an unoptimized (left) or an optimized (right) sampling pattern, with *k-t* BLAST (top) or *k-t* SENSE (bottom). Arrows point to residual artifacts.

REFERENCES [1] Madore B, et al. Magn Reson Med 1999; 42:813-828. [2] Kellman P, et al. Magn Reson Med 2001; 45: 846-852. [3] Tsao J, et al. Magn Reson Med 2003; 50:1031-1042. [4] Xiang QS & Henkelman RM. Magn Reson Med 1993; 29: 422-428. [5] Willis NP & Bresler Y. IEEE Trans Image Process 1995; 4:654-666. [6] Tsao J. Magn Reson Med 2002; 47:202-207. [7] Fuderer M. IEEE Trans Med Imaging 1988; 7:368-380. [8] Doyle M, et al. Magn Reson Med 1995; 33:163-170.