PROSPECTIVE SNR OPTIMIZATION IN K-T-BASED SENSITIVITY-ENCODED DYNAMIC IMAGING USING A FAST GEOMETRIC ALGORITHM

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Introduction MR data acquisition and image reconstruction are typically formulated using Fourier transform (FT) theory, i.e., the classical k-space transform. However, in dynamic MR imaging (e.g., 2D Cartesian sampling) it takes a few milliseconds from collecting one k-space phase-encode (PE) line to the next, i.e., sampling in the PE direction is time-sequential and not instantaneous [1]. Hence, a more accurate model for MR data acquisition is the so called “k-t-space perspective” (k=spatial frequency, t=frame) [1,2]. Most well known k-t-based schemes use k-t sampling patterns that are restricted to a lattice (generalized sheared grid) [1-3]. Based on sampling theory, k-t sampling on a lattice will result in aliasing of the object’s spectrum in the reciprocal domain, referred to as dual k-t lattice [4-6] or the x-f-space (x=PE direction, f=temporal frequency) [3]. The replication pattern is on the corresponding point-spread function (PSF) which is the FT of the sampling lattice [2,4]. The acceleration in k-t-based techniques results from multifold undersampling that the k-t lattice provides relative to the Nyquist rate. In UNFOLD [3] and PARADIGM [4], the k-t lattice is designed so that there is no overlap of the support region in x-f-space. On the contrary, in UNFOLD-based parallel imaging (e.g., TSENSE), the k-t sense, and PARADISE [5-6], there is overlap in x-f-space which can potentially be undone using sensitivity encoding (SE) and prior information (signal model). The prior information is in form of statistics for k-t SENSE, cross-shaped x-f support model (Fig 1a) for UNFOLD [3], and multi-banded patient-adaptive x-f support model (Fig 1b) for PARADIGM [4-6]. Optimizing the reconstruction SNR in this context has been previously introduced and its significance has been demonstrated in-silico for PARADISE [5]. A similar study has been conducted for k-t SENSE [7]. We focus on nongated cardiac MR techniques that use x-f support models and SE, namely, PARADISE [5-6] or UNFOLD-based parallel imaging. We propose a novel algorithm for designing the SNR-optimal k-t sampling pattern and study its performance in vivo. The proposed algorithm is geometric, i.e., it is based on geometry of overlap patterns in x-f-space and does not require any knowledge of coil sensitivities.

Theory Fig 1a depicts a x-f support model B similar to the one used in UNFOLD [3] characterized by a dynamic FOV (DFOV) and a temporal bandwidth that is varying in x. Fig 1b shows a more refined x-f support used in PARADISE [6], referred to as the banded support model [4], which formulates the approximate heart motion periodicity (hence the gap between bands) and also models heart-rate (HR) variability [6]. Given a fixed spatial resolution, a k-t lattice Λ shown in Fig 2a is parameterized by (Δx, Δk) and can be expressed as sum of delta functions located on a sheared grid [2,5]. The PSF for Λ, denoted by Λ*, is given by its 2D FT (inverse FT in k and forward in x). Fig 2b depicts two representative replicas of the x-f support (Fig 1a), one centered at the origin and another on a grid point Λ*(m,n) of the PSF lattice Λ. As a result of this replication, pixels within B overlap with each other and hence need to be un-mixed. The reconstruction task is to collect all recovery pixels within support B by un-mixing the overlapped pixels in x-f-space. This overlap pattern is depicted in Figs 3a and 3b for two PSF lattices. In parallel k-t-based techniques that only use x-f support information (unlike k-t SENSE), this procedure relies on the SE along x (no encoding along f) provided by multiple receiver channels. If two overlapping pixels have close x-coordinates, as shown in Fig 3a, then they are experiencing almost similar SE. Hence, the underlying SENSE equations in x-f-space would be closely dependent which will result in an ill-conditioned matrix equation for un-mixing of the overlapped pixels. Therefore, compared to Fig 3a, the overlap pattern in Fig 3b is expected to have a better conditioning (lower spatial-temporal g-factor [5,7]) and result in a better SNR. Motivated by this observation, for a pixel (x0,f0) in B, we denote by ps(x0,f0) the minimum x-coordinate distance between the set of pixels that overlap onto (x0,f0). Let ρ(Δx,Δk) denote the minimum of ps(x,f) among all pixels within B resulting from sampling on Λ parameterized by (Δx, Δk) (Fig 2a). We postulate that by designing Λ so that ρ(Δx,Δk) is maximized, the resulting overlap patterns will correspond to well-conditioned (low g-factor) SENSE matrix equations for x-f-space reconstruction. Eq. (1) provides a functional form for the optimization problem. Fig 4 summarizes the computational steps for evaluating the cost function for a set of feasible (Δx,Δk) choices.

Methods MR imaging with informed consent was performed under the NHLBI IRB using a 1.5T Siemens Avanto scanner with a 32-element cardiac array. Initially, a gated segmented SSFP cine scan was acquired (iFOV=±40mm square, matrix=256x224, 30 phases, TR=3.5ms, temporal resolution=28ms, GRAPPA rate 4). A customized SSFP pulse sequence was developed to allow for operator-defined TR and ordering of phase-encodes -- hence capable of acquiring a general k-t lattice (Fig 2a). MR data for the non-gated PARADISE scheme [5] with a 320x256 image matrix (1.3x1.6mm resolution) was collected during a single breathhold (scan time=16.4s). The x-f support model was chosen to be the banded model [5] as in Fig 1b with 11 bands (DC centered) and the following parameters: (1) DFOV location was estimated from localizer scans (DFOV=0.32*iFOV) (2) Average HR during the gated scan was used as an estimate for f0 (=1.1Hz) (3) The thickness of the bands (Fig 1b) was set to 0.33f0 to account for HR mis-estimation and variability during the scan. The proposed k-t lattice design algorithm (Fig 4) was run to find the SNR-optimal lattice by maximizing p (result: p*=0.24*iFOV). For comparison, a suboptimal lattice was computed so that its p would satisfy p=p*/3 (result: p=0.09*iFOV). The search space for (TR,Δk) was limited according to the acquisition and SSFP pulse sequence specifications (resolution, min TR, etc.). Computation time was less than 30s and each k-t lattice was immediately preceded by a conventional coil-profile calibration acquisition (128 Nyquist-spaced phase-encodes) to provide the final k-t sampling schedule.

Discussion & Conclusion Fig 5 shows the end-diastolic (ED) frame for the gated cine. Reconstructed ED frames for PARADISE acquired (non-gated) according to the SNR-optimized and suboptimal k-t lattices are shown in Figs 5a and 5b, respectively. The optimized lattice acquisition results in a much better reconstruction SNR (Fig 5h) because its underlying SENSE equations (in x-f space [5]) are better conditioned (have lower g-factor). In conclusion, the SNR difference seen in Fig 6 demonstrates the effectiveness and significance of the proposed k-t lattice design technique. In contrast to previous k-t acquisition design techniques [5-7], all computations in the proposed algorithm are geometric-based and independent of coil sensitivities. This feature enables fast computation of the SNR-optimal k-t sampling schedule for k-t-based parallel imaging prior to running the MR scan.