ANTHEM: Anatomically Tailored Hexagonal MRI

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Introduction: Several non-Cartesian k-space trajectories like spiral, rosette, radial have been proposed for MRI, which afford scan time reduction due to efficient coverage of k-space. We propose a novel strategy called ANTHEM (ANatomically Tailored HExagonal MRI) for reduction in k-space sampling density that uses a hexagonal sampling scheme and exploits anatomical geometries. Specifically, we optimized ANTHEM for two geometries: conical (breast) and cylindrical (abdominal cross sections, knee). We also developed an algorithm for reconstructing the hexagonally sampled data that is much simpler than those previously reported.

Theory: The FT of sampled k-space is the convolution of the desired image with the FT of the sampling comb. This results in image replicates, the locations of which depends on the sampling comb. Optimizing k-space sampling density can then be reduced to the problem of efficient tiling of these image replicates so as to avoid aliasing. Conventional MRI assumes a rectangular region of support. If the region of support is circular, then a hexagonal sampling grid (Fig 1) is optimal. It results in aliases that are also "hexagonally tiled". Since the aliases have been pushed out diagonally, FOV_x can be reduced by 13.4% without aliasing i.e. readout points can be reduced. Alternately, this can be viewed as more compact tiling.

However, hexagonal sampling in 2D as proposed in [2] can be achieved only along the readout direction, resulting in limited scan time reduction. Hexagonal sampling in 3D can lead to much higher savings and has hitherto been unexplored. We explored conical, spherical and cylindrical 3D geometries and found that significant reduction can be achieved using ANTHEM. For a spherical geometry, sampling along a body-centered cubic (BCC) grid can yield a 13.4% reduction in 2 directions. By judicious choice of the hexagonal sampling dimension, a reduction of 25% in **each** hexagonally sampled dimension (z and x) can be achieved for the conical geometry **without** changing the spatial resolution (Fig 3b). Equivalently, spatial resolution can be increased by 13-25% without increase in scan time.

Reconstruction: Standard 2D/3D FFTs are not directly applicable to hexagonally sampled data. Hexagonal FFTs proposed [1] compute it on a hexagonal grid that is then interpolated onto a rectilinear grid. Ehrhardt [2] proposed a 2D algorithm that involves an FFT along one dimension, application of a phase shift factor and then an FFT along the orthogonal direction. We propose a simpler Zero- Interspersed Reconstruction (ZIR) technique – a zero is inserted between each point along each hexagonally sampled dimension. A conventional 2D/3D FFT yields the original image along with hexagonal aliases outside the FOV, which can be cropped out. It can be shown theoretically that this is equivalent to the method proposed by [2] but involves only standard 2^N radix FFTs.

Methods: All simulations were performed using MATLAB (MathWorks, Natick, MA). Phantom and volunteer data (after informed consent) were collected on a 1.5 T GE Excite system (Waukesha, WI). For simulations, conical and spherical 3D objects were created and Fourier transformed to create 3D k-space data and then hexagonally sampled. Hexagonal sampling along x and z were implemented in a 3D Fast Gradient Recalled Echo (FGRE) sequence by modifying the x/z prephaser gradients on alternate TRs/k_y lines. For conical geometries, x was chosen parallel to the base plane whereas for the sphere it was immaterial.

Results: The ZIR method is shown in Fig 2a compared to the method of [2] (2b) for a 2D phantom. Note the "in-place" occurrence of the image in our ZIR method and the hexagonally distributed aliases whereas the algorithm in [2] requires complex shifting of quadrants/octants. Fig 3a shows 2D ANTHEM for a triangular phantom and 3b shows a surface rendered image of a conical phantom with hexagonal sampling and reducing the sampling density along x and z by 25%. The region inside the cone is alias free due to the staggering of the aliases caused by hexagonal sampling. Rectangular sampling with the same parameters would result in aliasing. Fig 4 shows hexagonally sampled (along z) and reconstructed images of a human knee reformatted to show an axial plane depicting the hexagonal aliasing pattern. Since the aliases have been pushed to the corners, the sampling be made more sparse along z to achieve reduction in scan time by 13.4% without any reduction in spatial resolution or aliasing. Fig 5 shows a hexagonally sampled breast image demonstrating the reduction in x and z by 25% due to its conical geometry. Note that the aliases correspond to the simulation. Since the aliases occur in known parts of the reconstructed images, they can be blanked out post reconstruction.

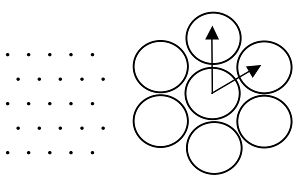

Fig 1. A hexagonal sampling grid and its aliasing pattern

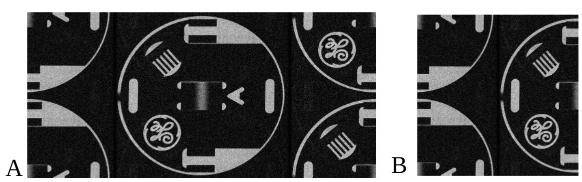

Fig 2. ZIR reconstruction of a 2D phantom hexagonally sampled along x. Note the location of the aliases. 2b shows the phase shift based reconstruction of [2] with its twisted output.

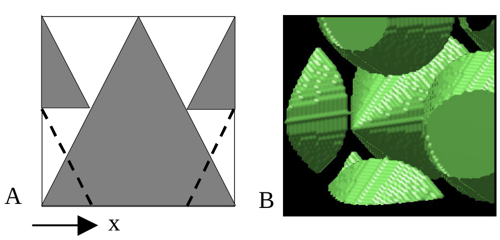

Fig 3a. 2D hexagonal sampling of a triangular region of support with reduction along x by 25%. The dashed lines are the rectangular sampling aliases. Fig 3b shows a surface rendering of hexagonal sampling of a 3D conical geometry along x and z. Note the absence of aliasing inside the main cone despite reduction of 25% along x and z

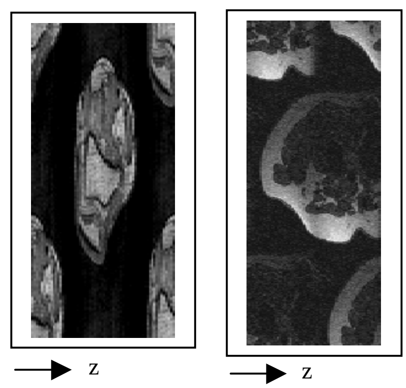

Fig 4,5 Hexagonally sampled images of a knee (left) and breast (right) sagittally obtained from human volunteers. Axial reformats are shown to highlight the location of the hexagonal aliases.

Conclusions: We have demonstrated a novel technique combining hexagonal sampling with anatomical constraints to reduce k-space sampling density. A new simplified reconstruction method has been derived which obviates the need for interpolation from hexagonal to rectilinear grids. For imaging organs with spherical, cylindrical or conical regions of support (e.g. brain, abdomen, breast, knee/leg), 13-25% reduction in density in each hexagonally sampled direction can be achieved. In practice, the FOV placement has to be done carefully to avoid unwanted aliasing. Reduction along x can be used, for example, to reduce T^*_2 blurring in echo-planar imaging and along y or z to reduce scan time. Hexagonal sampling is compatible with other data reduction strategies such as partial Fourier and parallel imaging.

References: 1. Mersereau RM. Proc IEEE, 67: 930-949 (1979) 2. Ehrhardt JC. IEEE TMI, 9: 305-309 (1990)