Quantification of 3D Radial Undersampling Artifact to Obtain High Quality Isotropic Resolution (0.36 mm) for Volumetric Cartilage Assessment

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INTRODUCTION The precision of cartilage volume measurements used in longitudinal studies of cartilage degeneration and treatment directly affects the number of subjects and length of the trial necessary to show significant changes. It has been suggested that these measurements require an in-plane resolution on the order of 0.3 mm [1]. While ten minute MR scans may be clinically infeasible, the increased resolution provided by longer scan times may be quite valuable in assessing cartilage volume. 3D radial steady-state methods, such as 3T VIPR-SSFP, have proven to be powerful for cartilage assessment by consistently providing 0.47 mm isotropic resolution which may be reformatted along any orientation while exhibiting the high signal characteristic of SSFP imaging in only five minutes [2,3]. Undersampling in the azimuthal and elevation dimensions of the *k*-space sphere can actually increase resolution with no increase in scan time. However, the effects of 3D undersampling are poorly understood and have not been previously quantified in vivo. In instances when the data are not sparse, such as in morphological musculoskeletal imaging, increasing undersampling can rapidly degrade the apparent image SNR. This work aims to quantitatively and qualitatively demonstrate the undersampling effects for a given resolution and scan time to gain insight into generating a protocol to obtain high isotropic resolution for cartilage volume measurements. Additional preliminary results utilizing new scanner technology that supports a 10 minute VIPR-SSFP scan, twice the previous limit on radial acquisitions, demonstrate higher image quality than previously attainable at high resolution.

METHODS Measuring the effect of 3D undersampling is difficult as the aliased energy is object dependent and appears as structured noise in the image. Signal variance within an ROI is the result of tissue variation, surface coil intensity, stochastic noise, and aliased energy, if any. To isolate the undersampling effects, scan time was held fixed while the number of unique projections was varied. Four successive 5 minute 3D radial knee scans acquired with a high resolution 416^3 image matrix were performed on a volunteer after obtaining IRB approval and informed consent. The first and second scans were acquired with the maximum number of unique projections possible. Stochastic noise was measured by analyzing the variance of the subtraction of the first and second image sets in a large ROI of adequate muscle signal in the axial, sagittal, and coronal planes. The stochastic noise contribution in all four scans should be equivalent as the total number of data points acquired in each experiment is constant. The third scan was altered to acquire half as many projections with two signal averages (2 NEX) while the fourth acquired a quarter of the projections with four signal averages (4 NEX). Corresponding variance measurements were individually obtained in the second, third, and fourth image sets using identically placed and sized ROIs. Tissue and surface coil variation should remain constant in successive scans. As the variance due to stochastic noise is independent of these and the undersampling effects, its measured value may be subtracted from the overall ROI variance. Thus, the remaining relative differences in ROI variance between the last three scans is a measure of the apparent noise due to undersampling.

Studies were conducted on a 3T Signa EXCITE HDx scanner (GE Healthcare, Milwaukee, WI) over a 15cm FOV using an 8 channel phased-array extremity coil and the VIPR-SSFP sequence. VIPR-SSFP is a 3D radial multi-echo sequence which utilizes the LCSSFP [4] technique to improve fat/water separation and optimize SNR. Efficient out and back radial encoding allows variable resolution, as low as 0.33 mm over 448^3 image matrix, with no increase in TR and thus no increase in sensitivity to off-resonance at 3T. The projection endpoints are selected uniformly on a sphere in *k*-space [5], with the number of unique projections normally determined by the scan duration. Until recently, 8 channel coil VIPR-SSFP acquisitions were limited to 5 minutes due to the prohibitively large datasets created. A 10 minute study has now been completed on the new3T Signa MR750 scanner with new RF, gradient, and data acquisition subsystems. High resolution images from both the 5 and 10 minute exams are provided for comparison in image quality.

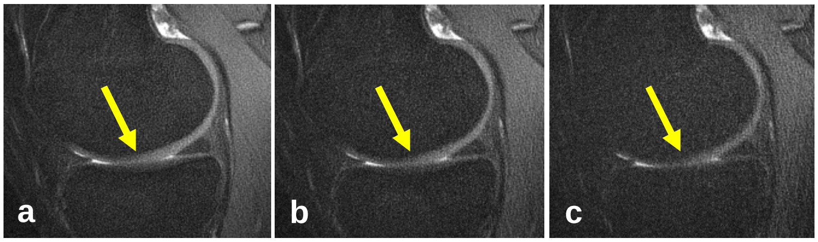

FIGURE 1 0.36 mm in-plane resolution sagittal knee images acquired with the maximum (a), half (b), and quarter (c) number of unique projections for a 5 minute exam. Note cartilage SNR degradation with increased undersampling.

RESULTS AND DISCUSSION The effects of reducing the number of unique projections while maintaining the same level of stochastic noise are shown in Fig 1. The apparent SNR degradation is especially evident in the articular cartilage as undersampling increases. This qualitative assessment is confirmed by the quantitative standard deviation measurements provided in Table 1. The measured stochastic noise is consistent in the three examples shown. With variation due to this effect removed and tissue and surface coil variation held constant, the remaining discrepancy between the standard deviation measurements of the multiple NEX image sets is due to undersampling. Note that SNR degradation due to undersampling is more severe in the sagittal and coronal planes due to the non-uniform VIPR-SSFP trajectory. Preliminary results comparing a 5 and 10 minute 0.36 mm isotropic resolution VIPR-SSFP exam are given in Fig 2. The ability to visualize the articular cartilage boundary is dramatically improved, especially in the areas indicated by the arrows.

Orientation	ROI Pixels	Subtraction Image Stochastic Noise	1 NEX Mean	1 NEX TV+U	2 NEX Mean	2 NEX TV+U	4 NEX Mean	4 NEX TV+U
Axial	868	269	3076	614	2793	613	2415	648
Sagittal	2080	229	2878	253	2714	302	2399	377
Coronal	2646	213	2655	257	2506	260	2164	315

TABLE 1 Standard deviation measurements due to tissue and surface coil variation and undersampling (TV+U) in knee images acquired with the maximum (1 NEX), half (2 NEX), and quarter (4 NEX) number of unique projections. Undersampling effect is most apparent in the sagittal plane, while less so in the axial plane.

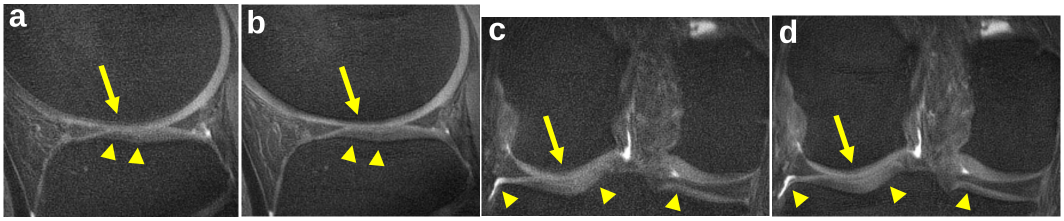

FIGURE 2 0.36 mm in-plane resolution sagittal/coronal knee images magnified to show details of cartilage, fluid, and bone interfaces. A 4 slice complex sum gives images an effective slice thickness of 1.44 mm. 10 minute exam images (b) and (d) show improved boundary clarity over 5 minute exam images (a) and (c).

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