Cartesian Continuous Sampling with Unequal Gradient Strengths

C. A. Bookwalter[1], M. A. Griswold[2], J. L. Sunshine[2], and J. L. Duerk[1,2]

[1]Department of Biomedical Engineering, Case Western Reserve University, Cleveland, OH, United States, [2]Department of Radiology, University Hospitals of Cleveland and Case Western Reserve University School of Medicine, Cleveland, OH, United States

Introduction: Continuous sampling (CS) sequences have previously been shown to increase SNR without significantly increasing acquisition time [1,2]. A balanced, symmetric CS sequence essentially samples every k-space location twice when the amplitudes of the dephase/rephase lobes are equal and opposite to the readout lobe (e.g., Figure 1a). However, fast imaging methods may require a shorter TR via dephase/rephase lobes designed under maximum gradient slew rate and/or amplitude constraints; under these conditions replication of every k-space data point may not occur. Further, rapid imaging often utilizes k-space undersampling (e.g. parallel imaging and asymmetric echoes) which can be applied to CS sequences in the form of unequal gradient amplitudes (Figure 1b). This study compares signal-to-noise ratio (SNR) improvement for several unequal gradient amplitude Cartesian CS sequences.

Theory: Partial averaging (i.e. extending the sampling window partially over dephase/rephase lobe) improves the time efficiency of radial CS sequences [1]. Although this method performs well in radial acquisitions, Cartesian partial averaging results in image texture [3,4]. Alternatively, shorter, higher amplitude dephase/rephase lobes (Figure 1b) may be used to further increase the efficiency of CS. Like partial averaging, fewer points will be collected and the gain in SNR will be a fraction of the original CS case. The SNR gain can be described by

$$SNR_{improvement} = \frac{\Delta x_{CS}\sqrt{T_{CS}}}{\Delta x_{TS}\sqrt{T_{TS}}} \qquad (1)$$

where, T_{CS} and T_{TS} are the sampling time of the CS and traditional sampling windows, respectively, while Δx_{CS} and Δx_{TS} are the respective pixels sizes.

Only the read gradients (G_{RD}) are shown in Figure 1; for simplicity, we restrict this discussion to examples where no other gradients are applied during this time. Assuming that the dwell time (i.e. interval between sampled points) is constant, the relative amplitude of the gradients will determine the total number of sampled points. The unequal gradient factor (n) describes the relationship between the maximum gradient amplitude of the readout gradient (G_{read}) and the dephase/rephase lobes ($-n^*G_{read}$). For $n > 1$, fewer points will be collected and therefore will result in a lower SNR gain compared to n=1, yet still better than conventional sampling. Alternatively, if time is not a factor, a low amplitude gradient ($n < 1$) results in additional SNR gain beyond the n=1 case.

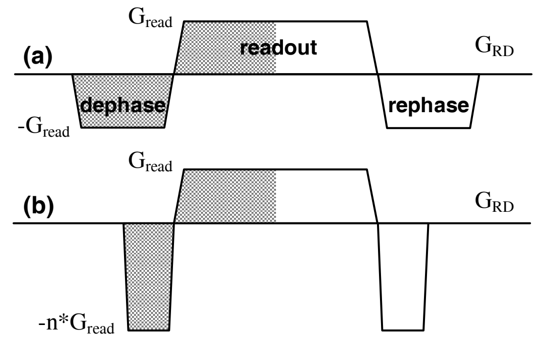
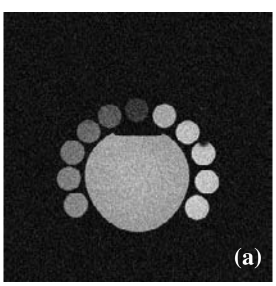


Figure 1. Partial sequence diagrams depicting equal gradient amplitude TST (a) and unequal gradient amplitude TST (b) sequences where G is the gradient strength and n can be any positive value limited only by maximum gradient strength.

Methods: A Cartesian CS FLASH pulse sequence with equal gradient amplitudes (Figure 1a) was modified to allow unequal gradient amplitudes (Figure 1b) where n equals any positive number, limited only by the maximum gradient amplitude. A volume head coil was used to collect images of a doped phantom for n = 0.75, 1.0, 1.5, 2.0 and 2.3. Imaging parameters were TE = 5.6 ms, TR = 12 ms, FOV = 300x300 mm, FA = 15°, bandwidth per pixel = 390 Hz/px, and slice thickness = 10 mm for all scans. All imaging experiments were performed on a 1.5 T Siemens Espree scanner. All reconstruction was performed offline with Matlab using linear interpolation to a measured trajectory [5]. SNR was estimated by dividing the mean of a region of interest inside the phantom by the background standard deviation.



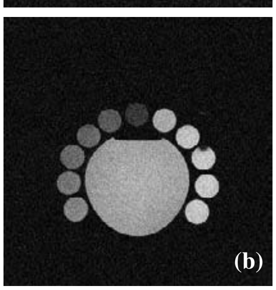


Figure 2: Traditional (a) and CS n=2 (b) phantom images.

Results: Phantom images are shown in Figure 2. SNR from the uniform phantom was computed to be 29.6, 27.2, 25.1, 22.9 and 23.1 for n = 0.75, 1, 1.5, 2, and 2.3, respectively. This is an SNR improvement over traditional Cartesian (SNR = 19.2) sampling of about 53.4%, 40.9%, 30.0%, 18.8%, and 19.6%. Theoretical predictions of SNR improvement were 56.1%, 44.2%, 31.1%, 24.1%, and 21.1%, respectively. Theoretical predictions for these and other values of n are shown in Figure 3.

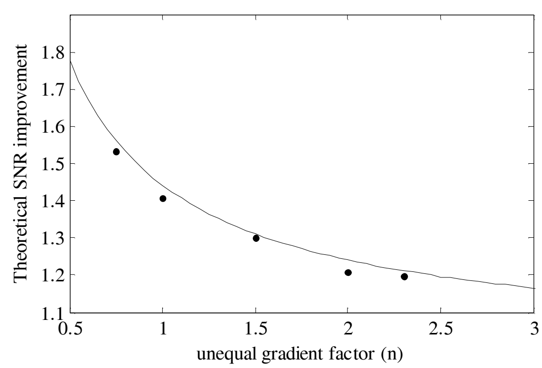


Figure 3: SNR improvement versus unequal gradient factor (n). The solid line shows the simulated SNR improvement and the solid circles show the measured SNR improvement at n = 0.75, 1, 1.5, 2, and 2.3.

Discussion and Conclusions: The measured SNR improvement is within experimental accuracy (~2%) to theoretical predictions, allowing demonstration of the versatility of the Cartesian CS sequences. Additionally, this study describes a faster implementation of an already efficient method of improving SNR which is applicable to any CS sequence.

References: [1] Winkelmann et.al., IEEE TMI, 24, 254-262, 2005. [2] Bookwalter et.al., Proc. ISMRM 2005, #2371. [3] Mugler, MRM, 19, 170-174, 1991. [4] Ortendahl, IEEE TNS, 41, 1634-1638, 1994. [5] Duyn et. al., JMRI, 132, 150-153, 1998.