Apodization and Smoothing Alter Voxel Time Series Correlations

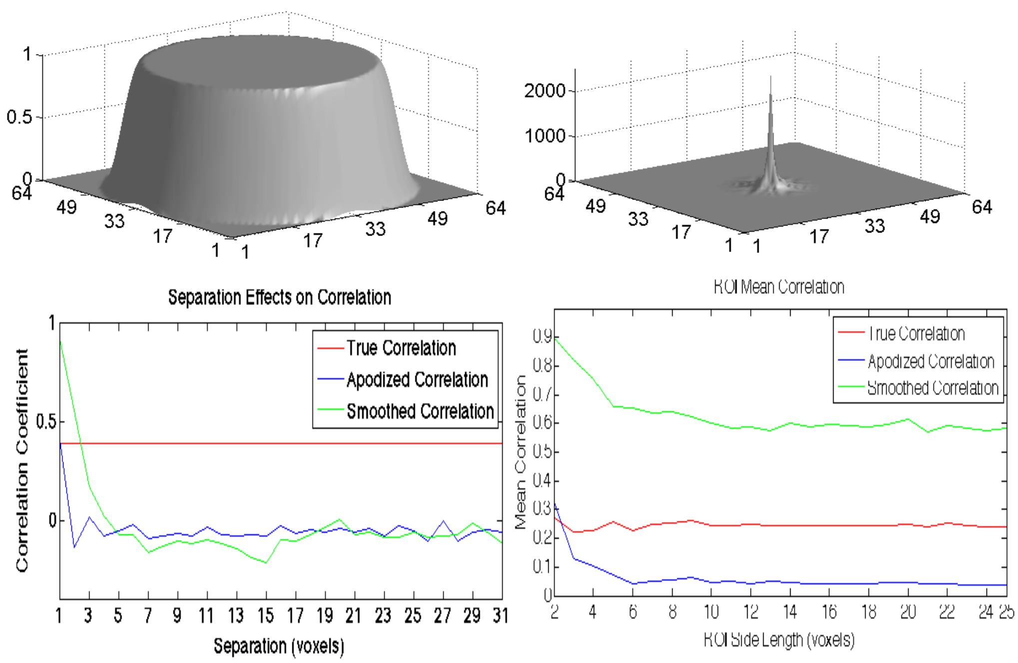
A. S. Nencka[1], and D. B. Rowe[1]
[1]Department of Biophysics, Medical College of Wisconsin, Milwaukee, WI, United States

Introduction: In an effort to account for un-collected data in pulse sequences where circular k-space measurements are made, like spiral or propeller sequences, or to reduce Gibbs ringing, k-space apodization is commonly performed.[1] Apodization is the point-wise multiplication of the k-space measurements with a window function which is unity over the center of k-space and which slopes to zero near the edges of the k-space measurements. A common apodization window is the Tukey function, shown in Fig. 1. Through the convolution theorem, this point-wise k-space multiplication is analogous to image space convolution of the reconstructed image with a kernel which is the Fourier transform of the window function, shown in Fig. 2. This process, similar to smoothing, leads to spatial correlation in the reconstructed data. This consistently added spatial correlation over a time series leads to correlation between voxel time series and thus can affect connectivity measurements. The effects of apodization on connectivity measurements are shown to be non-negligible.

Methods: Two separate simulations were performed. The first simulation examined the effects of apodization on the correlation between two voxels separated by different distances. A 64×64 matrix image time series was created in Matlab with the center element and one other element containing correlated time series. All other elements contained uncorrelated noise. The center element and other correlated element were varied from adjacent elements to 31 elements apart in steps of one element. The correlation coefficient between the two elements was measured with no apodization, with apodization using a Tukey window (critical frequency 24 pixel^{-1} and width 8 pixel^{-1}), and with Gaussian smoothing (kernel standard deviation 1.5 elements). The second simulation characterized the effects of apodization on the mean correlation between voxels in an ROI. A 64×64 image time series was created in Matlab with uncorrelated, random noise in all elements and an added correlated time series within a square ROI. The dimension of the square ROI was varied over the course of the experiment. For each ROI, the mean correlation coefficient for the elements within the ROI was computed with and without apodization using a Tukey window (critical frequency 24 pixel^{-1} and width 8 pixel^{-1}), as well as with Gaussian smoothing (kernel standard deviation 1.5 elements).

Results and Discussion: The results of the first simulation are shown in Fig. 3. Ringing, apparent in the Fourier transform of the window function in Fig. 2, is apparent in the correlation between the simulated elements. Thus, depending upon the distance between the correlated elements, the practice of apodization may either increase or decrease the measured correlation for the elements. When the elements are adjacent, the smoothing which results from apodization induces a greater correlation between the elements than is truly present. When the elements are separated by several elements, the Gibbs ringing from the apodization leads to lower measured correlations between the elements than are actually present. Additionally the inclusion of contributions from uncorrelated voxels from the spatial smoothing leads to lower correlations between elements when they are separated. The latter effect clearly dominates at the longer distances often used in connectivity studies, and therefore the practice of apodization likely reduces experimentally measured voxel correlations. The results of the second simulation are shown in Fig. 4. Once again, with adjacent voxels, the correlation is increased through apodization, while the mean correlation coefficient from the ROI is decreased when the ROI includes more than simply adjacent elements. The Fourier transform of the utilized Tukey window, which is equivalently convolved with the reconstructed image, includes ringing effects which lead to low correlations between elements which are not adjacent. Gaussian smoothing was also performed on the simulated data. With this smoothing and no Gibbs ringing, this leads to inflated mean correlation coefficients within a ROI.

Conclusion: Apodization clearly influences calculated element and mean ROI correlation coefficients. Researchers must be mindful of these effects when using apodization as part of reconstruction, as often is the case with spiral imaging, and suitably pre-whiten the reconstructed data or otherwise account for the processing induced correlations. Specifically, apodization and smoothing will markedly alter the results of applying ROI analysis techniques like COSLOF.[2] Of course, apodization window functions affect the correlation coefficient between two voxels and the ROI shape affects the mean ROI correlation coefficient.



Figures: (1) Top left. Tukey window with critical frequency of 24 pixels^{-1} and width of 8 pixels^{-1}. **(2)** Top right. Fourier transform of the Tukey window. **(3)** Bottom left. Correlation coefficient as a function of distance between voxels with no apodization (red) and with apodization (blue). **(4)** Bottom Right. Mean correlation coefficient within square ROIs significantly varies with processing techniques.

References: (1) Bernstein, M.A. et al. *Handbook of MRI Pulse Sequences*. Elsevier Academic Press: 2004. (2) Li, S.J. et al. Radiology 225: 253-259.

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