Improved fMRI Slice Timing Correction: Interpolation Errors and Wrap Around Effects

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<u>Purpose</u>

We discuss a slice timing correction algorithm, a modification of the method of sinc interpolation, which reduces the slice dependent variability change and avoids wrap around effects.

<u>Introduction</u>

Event-related fMRI is a technique that is heavily dependent upon time-locking the stimulus to the data. To do so accurately requires one to account for the differential slice acquisition times, especially for longer TRs. Often slices are acquired in an interleaved manner, thus the 1st slice can differ in time from the 2nd by as much as TR/2. Correcting this phase shift requires one to interpolate the time series for each voxel, to a fixed reference time. However the interpolation error will vary considerably from slice to slice. We present methods for improving ideal (sinc) interpolation, which may also be applied to other types of interpolation (e.g. linear interpolation methods). We also discuss avoiding wrap-around artifacts when using sinc interpolation.

<u>Theory</u>

A common approach is to use an application of the Fourier Shift Theorem, which entails taking the Fourier transform of each time series and multiplying by a complex exponential to induce a phase shift [1]. The real part of the inverse Fourier transform is the resultant corrected data. This is equivalent to sinc interpolation in the time domain. There are two problems with this, however. 1) Because the data is discrete, interpolation artifacts will produce a ringing in the corrected data. This ringing is dependent upon the amount of phase shift induced, and is zero when you are at the reference slice. Often the temporal reference used is the first slice. Consequently, the largest difference is between the reference slice and all other slices, however there is still a significant difference between the other slices as seen in Figure 1. 2) Additionally, if the beginning of the time course has a significantly different value from the end, there will be *wrap around* artifacts as the Fourier method is equivalent to a circular convolution of the waveform with a sinc function as seen in Equation 1.

$$x\left(n-\frac{l}{N_z}\right)\otimes\frac{\sin 2p\,nN}{2p\,n} \qquad (1)$$

While one can get around this by doing a standard convolution in the time domain, it is desirable from a computation perspective to do this operation in the frequency domain.

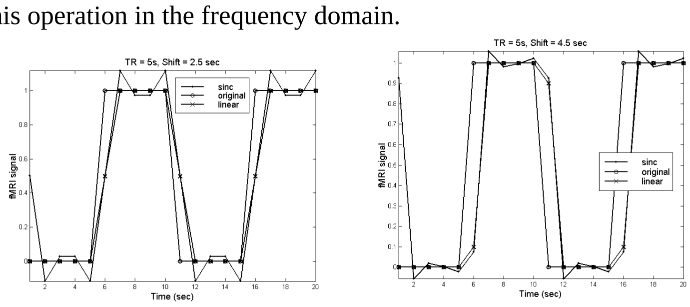

Figure 1: Sinc and linear interpolation of an ideal waveform for the fifth and ninth slices in an experiment with TR=5s. Note the very different interpolation errors, and the raised baseline due to wrap around at the beginning of the sinc interpolated time course.

<u>Methods</u>

The ringing artifact may be reduced by low pass filtering the spectrum (i.e. window in the frequency domain). If one chooses to window the spectrum, it is important not to smooth too much as this has the effect of reducing degrees of freedom in the data. We have found a hamming window to do a reasonable job of reducing interpolation artifacts and not over smoothing the data (see Figure 2). In many analysis, some smoothing will be desirable due to the band limited nature of the fMRI signal.

Removing the wrap around artifact is easily done by padding both ends of the time series with 2*TR zeros. This then just needs to be incorporated into any future modeling; or it may be truncated as well following the interpolation.

<u>Results</u>

We took the same ideal waveform as seen before and applied the frequency window to the interpolation stage, as well as the zero padding. The results are presented in Figure 2.

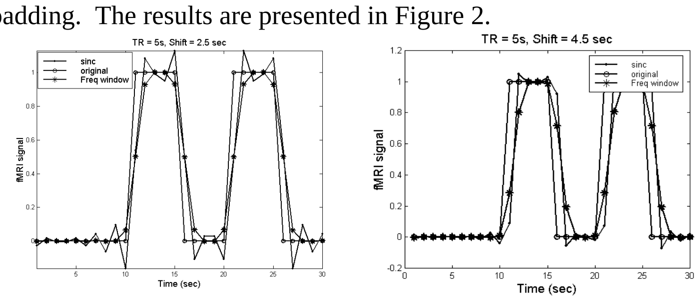

Figure 2: Windowed sinc interpolation of ideal box-car function for a shift of 2.5 seconds (left) and 4.5 seconds (right). The ringing has been attenuated by the hamming window.

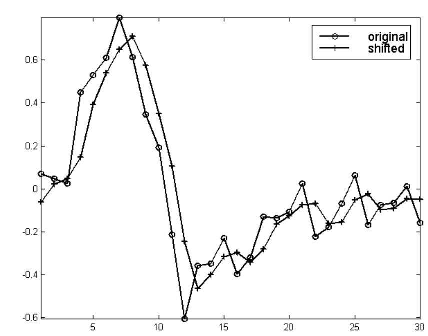

Figure 3: Data from event-related motor experiment, shifted by .9 second (TR = 1s). The subject moved their fingers briefly at t = zero seconds.

<u>Discussion</u>

Sinc interpolation is a good choice, provided you perform the smoothing, and pad with zeros to avoid the wrap around artifacts. This standardized smoothing is especially important if the subsequent fMRI analysis does not entail any temporal smoothing, or a low-pass filtering stage. The ringing artifacts are high frequency, and are thus attenuated by a smoothing filter. One must be careful not to over filter the data, but given that fMRI data are strongly band-limited, many analyses will include a low-pass filter in the processing anyway. Other types of interpolation (e.g. linear) induce a slice dependent low pass filtering on the data. We suggest that low pass filtering is also useful in these situations.

<u>References</u>

[1] Aguirre GK, Zarahn E, D'Esposito M. The variability of human, BOLD hemodynamic responses. Neuroimage 1998 Nov;8(4):360-9.

<u>Acknowledgment</u>

This research was supported by NIMH grants MH 43775, 43326 and 52286, AG11859 and to the Outpatient General Clinical Research Center, RR 00722, the Stanley Foundation, and the Schapiro Foundation. XG is supported by a grant from Phillips Medical