Sliding Window SENSE Calibration for Reducing Noise in fMRI

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Introduction. We propose a self-calibrated parallel imaging fMRI method in which sensitivity profiles are calculated dynamically using a sliding window approach: averaging a small number of consecutive fully-sampled multishot images. This technique provides an SNR gain over conventional SENSE reconstruction. For conjugate gradient CG-SENSE reconstruction (1,2) used here, profiles are updated at every time frame. No spatial smoothing is performed so as to retain thermal noise in sensitivity profiles. Sliding window width determines similarity between thermal noise in sensitivity profiles and thermal noise in the windowed raw data. Narrower window width yields more similarity and provides better noise cancellation in the reconstructed image time-series. This *sliding window* technique is especially applicable to acquisition of high spatial-resolution images (where thermal noise dominates over physiological noise). Activation from visual stimulation is revealed where conventional sensitivity calculations falter.

We compare this proposed *sliding window* parallel imaging technique with a conventional *reference frame* method and an *all-frame* method, as well as with the conventional fully-sampled two-shot reconstruction. In the *reference frame* method, four image time frames from the beginning of a time series are averaged and smoothed with spline interpolation. In the *all-frame* method, data acquired over the whole time-series is averaged to calculate coil sensitivity. In all comparisons, our proposed technique demonstrates enhanced BOLD activation and less noise. The improvement is most significant for high resolution, thin slice, and low SNR cases.

Theory. **k**-space data acquired can be expressed in matrix form as $\mathbf{d} = \mathbf{ES}(\mathbf{m} + \mathbf{p}) + \boldsymbol{\varepsilon}$ where $\mathbf{m}$ is a vector containing the original image, $\mathbf{p}$ is a vector of physiological noise, $\boldsymbol{\varepsilon}$ is a thermal noise vector, $\mathbf{S}$ is a coil sensitivity matrix, and $\mathbf{E}$ is the Fourier kernel matrix. $\hat{\mathbf{m}} = (\hat{\mathbf{S}}^H \mathbf{E}^H \mathbf{E} \hat{\mathbf{S}})^{-1} \hat{\mathbf{S}}^H \mathbf{E}^H \mathbf{d}$ where $\hat{\mathbf{S}}$ is the calculated coil sensitivity matrix. A reconstructed image, under *sliding window* method, can be expressed $\hat{\mathbf{m}} \approx \mathbf{m} + \mathbf{p} + (\mathbf{S}^H \mathbf{E}^H \mathbf{E} \mathbf{S})^{-1} \mathbf{S}^H \mathbf{E}^H (\boldsymbol{\varepsilon} - \overline{\boldsymbol{\varepsilon}})$. When $\boldsymbol{\varepsilon} = \overline{\boldsymbol{\varepsilon}}$, $\hat{\mathbf{m}}$ is free of thermal noise. But that would occur only when R=1, which is not of interest since no acceleration is provided. When sliding window width is minimal (R=2), then $\overline{\boldsymbol{\varepsilon}}$ is the closest approximation to $\boldsymbol{\varepsilon}$ and so $\hat{\mathbf{m}}$ will contain the least amount of noise. As the sliding window width becomes wider, $\overline{\boldsymbol{\varepsilon}}$ resembles $\boldsymbol{\varepsilon}$ to a lesser degree which results in $\hat{\mathbf{m}}$ having more thermal noise. When the *all-frame* method is used, $\overline{\boldsymbol{\varepsilon}}$ is averaged to zero under a Gaussian noise assumption; thermal noise sampled in **k**-space is therefore propagated to $\hat{\mathbf{m}}$. (Similarly, smoothing sensitivity maps would also result in thermal noise propagation to $\hat{\mathbf{m}}$.)

Methods. We demonstrate *sliding window* with a two-shot spiral-in/out trajectory providing an acceleration factor R=2. For every two repetition times (TR), two fully-sampled two-shot images (one spiral-in and one spiral-out) are reconstructed for each coil. The sensitivity profile of each coil is the ratio of the fully sampled two-shot image of that coil to the square root of the pixel-wise sum of squares of all coils. Separate sensitivity profiles are generated for spiral-in and spiral-out data. For *sliding window* (window width = 2 TRs), a new fully sampled two-shot image of each coil is formed after every TR. The sensitivity profile of each coil is then updated at every TR and used for CG-SENSE image reconstruction at that TR. For the *all-frame* method, all fully sampled two-shot images of each coil over the entire time series are first averaged for sensitivity profile calculation. The resulting sensitivity profiles are used for CG-SENSE reconstruction of the entire time series. We also compare *sliding window* to a *reference frame* method. The same CG-SENSE program is used for reconstruction regardless of sensitivity profile calculation methods; it generates one spiral-in image and one spiral-out image for every TR.

Six subjects participated in fMRI experiment at four slice thicknesses (2mm, 3mm, 4mm, and 5mm) on a GE 3T whole-body scanner (GE Signa, WI). An 8-channel head coil (MRI Devices Corp., WI) was used for all image acquisitions. The TE was set to be minimal allowed by the spiral-in trajectory (35.4 ms), TR/α/matrix size/FOV = 2s/70°/128x128/20cm. The scan time was 248 seconds (data from the first 8 seconds discarded). T2-weighted fast spin-echo scans were obtained for anatomic reference (TR/TE/ETL=4000ms/68ms/12). The fMRI task consisted of 6 cycles of an on/off block having a period of 40s. During the on-block, subjects saw a checker board flashing at 8Hz. Subjects were told to stare at a fixation-cross to reduce eye movement during the off-block. This experiment was performed once for each slice thickness; slice thickness order was randomized among subjects. Standard spiral trajectory gridded-reconstruction is used to make two-shot images from each coil's data. (3) Activation maps are created by correlation analysis after image reconstruction; *i.e.*, cross-correlation of image time-sequence per pixel with sine and cosine functions at the fundamental task frequency, followed by projection onto the in-phase axis.

Results. Figure 1 shows ratios of activation volumes with the *sliding window* method to those using the *all-frame* method for 2mm and 5mm thickness spiral-out images. Bars indicate averaged ratios for all six subjects. Standard deviations among subjects are indicated by error bars. For comparison, ratios of activation volumes using fully-sampled 2-shot reconstruction to those using the *all-frame* method, and volume ratio of *reference frame* method to *all-frame* method are also shown. The activation threshold is set to p<0.005 in all cases. *Sliding window* gives the same statistical performance to 2-shot reconstructed images and better than both *reference frame* and *all-frame* methods, especially at small voxel size where thermal noise dominates. Figure 2 shows correlation coefficient maps from spiral-out images of a typical volunteer using *all-frame, reference frame, and sliding window* methods as well as with conventional 2-shot reconstruction. From these figures, it is clear that the *sliding window* method is able to detect activation under high noise when conventional sensitivity calculation methods falter.

Discussion. Using conventional methods for calculating sensitivity maps, fMRI sensitivity is preserved only when voxel size is large enough that physiological noise predominates thermal noise. (4) Spatial resolution is thereby limited. By instead using *sliding window* sensitivity maps for CG-SENSE reconstruction, thermal noise is significantly reduced. The *sliding window* method is therefore recommended for use to detect fMRI activation at high spatial resolution. Elsewhere, we have shown the *sliding window* method to be applicable to other fMRI acquisition sequences, including echo-planar imaging. Though demonstrated with fMRI, we expect this technique to directly benefit other dynamic SENSE applications such as cardiac and flow imaging.

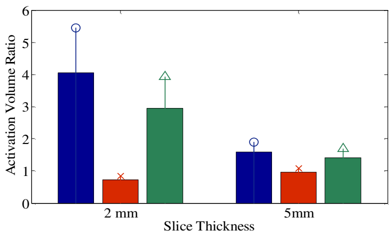

Fig. 1 Ratios of numbers of activated pixels from using *sliding window* to those from using *all-frame* (o), volume ratio of *reference frame* to *all-frame* (x), and volume ratio of 2-shot to *all-frame* (Δ) .

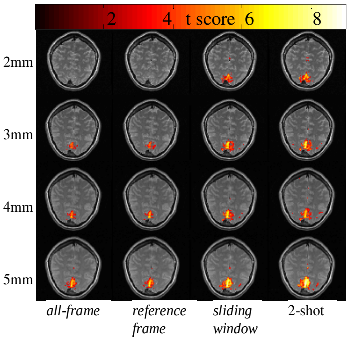

Fig. 2 Activation maps for one volunteer (p<0.005). Same data was processed using different sensitivity profile calculation methods. *Sliding window* yields greater activation than *all-frame* and *reference frame*; especially at thin slices. Results from *sliding window* is statistically the same as those using 2-shot reconstruction.

Reference. 1. Pruessmann KP et al., Magn Reson Med. 2001; 46(4):638-651. 2. Liu et al., Magn Reson Med. 2005 ; 54(6) :1412-1422. 3. Jackson et al, IEEE Trans. Med. Imag. 1991; 10(1):473-478. 4. de Zwart et al., Magn Reson Med. 2002; 48(6):1011-1020.

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