fMRI quality assurance using phase space reconstruction of SmartPhantom simulations of BOLD contrast

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INTRODUCTION

FMRI is a neuroimaging technique for the study of brain function based on blood oxygenation level dependent (BOLD) contrast. Quality assurance (QA) is important for fMRI because BOLD signal changes are small and noisy. Two common QA measures are signal-to-noise ratio (SNR [1]) and contrast-to-noise ratio (CNR). SNR reflects the ability of the scanning instrument to encode/decode spatial information in images, while CNR specifically measures fluctuations related to BOLD contrast. Accuracy in detecting functional activity of the brain depends on the CNR. SmartPhantom [2] provides controllable and reproducible simulated BOLD contrast signals which a static phantom does not. Thus, SmartPhantom was used for CNR measurement in the present study.

METHODS

The fMRI data were acquired from SmartPhantom with a 3T Siemens Allegra scanner using GE-EPI (TR=1700ms; TE=25ms; flip angle=70º; matrix=64×64; slice thickness=5mm, no gap). The SmartPhantom is a 7 inch diameter sphere ($NiCl_2*H_2O$ in solution of H_2O), having a pair of coils, one attached at each end in the z-direction. Direct current flowing in the coils induces dephasing effects as does the susceptibility difference of oxy- vs deoxyhemoglobin, and thus simulates the basis of BOLD signal changes. A triangle waveform, roughly approximating the temporal frequency content of a hemodynamic response, was generated by computer every 10 images with an amplitude approximating a 5% signal change. Each one-hour scanning session comprised three short scans (123 images, 3 min) and one long scan (1003 images, 30 min), in the sequence short, long, short, short. Figure 1 (left) shows a representative SmartPhantom signal collected during one 3 min scan. Multiple sessions took place in a time span of one month. Data processing was performed using AFNI.

For measurement of CNR, phase space reconstruction was employed based on the time delay embedding theorem [3]. Let a measured time series be denoted as $x(1), x(2), \cdots, x(N)$, where N is a total number of images. We construct a form of m dimensional vector, given as $\mathbf{X}_i = [x(i), x(i+d), \cdots, x(i+(m-1)d)]^T$, where m is the embedding dimension and d is the delay time. A certain trajectory in m-dimensional phase space is represented by $\mathbf{X}_i$, where $i=0, \cdots, L=(N-1)/\{(m-1)d\}$. Figure 1 (middle) shows SmartPhantom signals collected during one 30 min scan embedded in 2-dimensional phase space with time delay $d=2$. Ten points were recorded during each period of the triangle waveform; the 10 small clusters contain information about signal changes. The spread of points in each cluster indicates measurement noise. Thus, in each instance the noise can be defined as the distance (denoted R) between each point and the center within each cluster. Figure 1 (right) shows that the empirical probability density function (pdf) of the noise (R, solid line) is very well fitted by a Rayleigh distribution (dotted line) having mean $\alpha(\pi/2)^{0.5}$ and variance $(2-\pi/2)\alpha^2$, as previously reported [4]. For the present data $\alpha = 0.193$. CNR is defined as the ratio of signal contrast over the standard deviation of noise in the measured time series, which can be modified by substituting empirical $\alpha = 0.193$ into the definition of the Rayleigh distribution, to yield CNR = (maximum distance between cluster centers) / (1.52 * mean R).

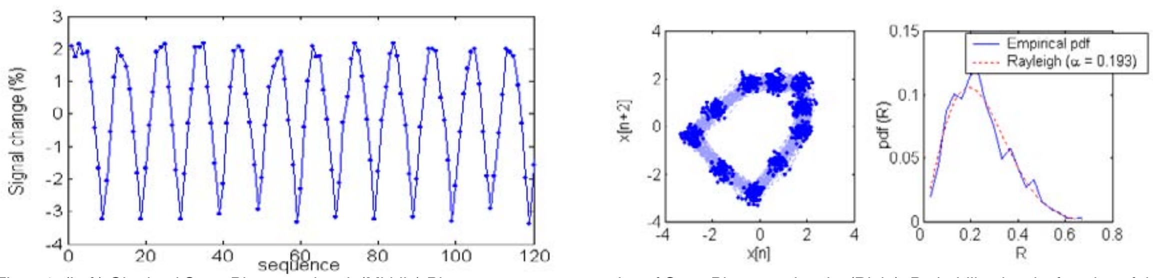

Figure1. (Left) Obtained SmartPhantom signal. (Middle) Phase space reconstruction of SmartPhantom signals. (Right): Probability density function of the noise estimates (R).

RESULTS AND DISCUSSION

Table 1 compares SNR [1] and CNR from four scans per session, over four sessions spanning one month. We selected signals in a region of interest, the central 5×5 pixels in the center slice of the SmartPhantom, for improved magnetic field homogeneity. As seen in Table 1, SNR within each session is very similar. CNR presents different information about QA within- and across-session. For example, the CNR for 3 min scans (Scan 1, 3 or 4) seems slightly higher than CNR for 30 min scans (Scan 2). CNR for scan 1 in session 2 is notably low, apparently due to an “outlier”, even though SNR for this scan is similar to that for other scans. In summary, the SmartPhantom enables QA for fMRI with controllable and reproducible simulated BOLD signals. The CNR calculation proposed here, based on phase space reconstruction, is effective for characterizing fMRI data.

Table 1: SNR and CNR measured in four sessions over a one month period.

Session	SNR_0				CNR			
	Scan1	Scan2	Scan3	Scan4	Scan1	Scan2	Scan3	Scan4
1	449	445	473	462	15.2	14.4	15.8	15.1
2	448	451	462	461	9.1	14.2	15.5	15.8
3	484	482	494	488	16.9	14.5	17.1	16.4
4	458	457	463	457	15.8	14.0	15.6	14.9

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