Tissue Specificity of Nonlinear Dynamics in Baseline fMRI

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Introduction

In the recent past there has been renewed interest in understanding the nature of fluctuations in BOLD data in the absence of a task [1,2]. In this work, nonlinear dynamical (NLD) techniques were applied to fMRI to examine the spatio-temporal properties of BOLD resting state fluctuations. Patterns of singularity in the complex plane (PSC) and Lempel-Ziv complexity (LZ) were used to study the deterministic nonlinearity in resting state fMRI. The results showed greater nonlinearity (higher PSC) and determinism (lower LZ) in gray matter (GM) compared to white matter (WM) and CSF. In addition, removal of respiratory and cardiac pulsations decreased the nonlinearity and determinism but did not alter the relative difference between GM and WM, suggesting that the tissue-specificity may be attributed to differences in native physiological and metabolic fluctuations.

Materials and Methods

Resting EPI data were acquired on a 3T Siemens Trio scanner in 5 subjects. In 3 subjects, 5 cortical axial slices were obtained and in the other two, 10 saggital slices were acquired. EPI scan parameters were: TR=750 ms, TE=34 ms, FA=50°, FOV=22cm, 5mm slice thickness and 1120 volumes. High resolution (512×512, FOV=22cm) T1-weighted anatomical images were acquired for three of the subjects, and were segmented into GM and WM based on their intensity. For the other two subjects, T1 MPRAGE anatomical images were obtained and subsequently segmented into GM, WM and CSF using SPM2 (http://www.fil.ion.ucl.ac.uk). The segmented anatomical images were down-sampled to match the resolution of EPI data. Physiological monitoring was done using a pulse-oximeter and nasal respiratory cannula during data acquisition to record cardiac and respiratory signals, respectively. Fluctuations in fMRI data related to these physiological activities were corrected retrospectively [1]. PSC captures the arrangement of singularities in the complex plane and the higher its value, the higher the nonlinearity [3]. It was calculated to assess nonlinearity. Because the nonlinearity revealed by PSC may arise from both deterministic and random processes, we used LZ to assess the underlying determinism. LZ is zero for a fully deterministic signal and one for a completely random signal [4]. Data analysis consisted of calculating PSC and LZ for each voxel and finding the mean for each of the tissue types. The statistical significance of the difference in means was assessed using the non-parametric Wilcoxon rank sum test [5] as the parameter distributions were not Gaussian.

Results and Discussion

Table 1 and Figs.1 and 2 indicate that deterministic nonlinearity in GM is significantly higher than that in WM and CSF. Figs. 3(a), (b) and (c) show the difference maps obtained by subtracting the PSC, LZ and fMRI time course variance, respectively, before and after physiological correction. The similarity between the three figures suggests that the deterministic nonlinearity contributed by physiological rhythms have been accounted for by retrospective correction. Table 2 shows the mean PSC and LZ changes in WM with addition of Gaussian noise to WM time series so as to match their standard deviation with that of GM. While PSC increased slightly, it is much less than the PSC of GM in Table 1. LZ increased with increasing noise intensity and moved further away from GM LZ values. Therefore higher noise intensity in GM, as reported by Kruger et al [2], may not be a factor contributing to higher nonlinear determinism in GM reported here.

PSC	GM	WM	CSF	Wilcoxon Rank Sum Test: p-value		
				GM-WM	GM-CSF	WM-CSF
Sub 1	765	457	-	8.68×10^{-12}	-	-
Sub 2	1065	634	-	2.39×10^{-12}	-	-
Sub 3	1080	645	-	0	-	-
Sub 4	962	716	841	6.9×10^{-5}	1.5×10^{-5}	4.8×10^{-4}
Sub 5	940	771	618	3.1×10^{-5}	3.2×10^{-4}	3.1×10^{-5}

LZ	GM	WM	CSF	Wilcoxon Rank Sum Test: p-value		
				GM-WM	GM-CSF	WM-CSF
Sub 1	0.82	0.91	-	2.28×10^{-12}	-	-
Sub 2	0.60	0.72	-	3.05×10^{-7}	-	-
Sub 3	0.64	0.82	-	3.89×10^{-25}	-	-
Sub 4	0.56	0.69	0.75	2.5×10^{-6}	8.9×10^{-4}	8.5×10^{-7}
Sub 5	0.65	0.70	0.73	3.7×10^{-4}	2.2×10^{-3}	5.3×10^{-5}

Table 1. PSC and LZ mean and p- values for all the tissue types

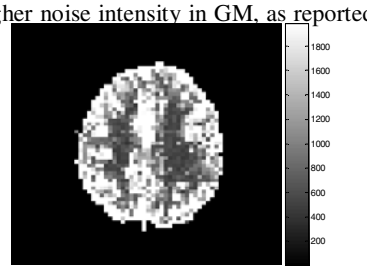

Fig. 1 PSC map of an axial slice

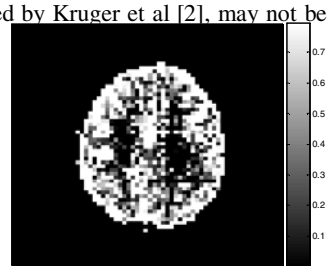

Fig. 2 LZ map of an axial slice

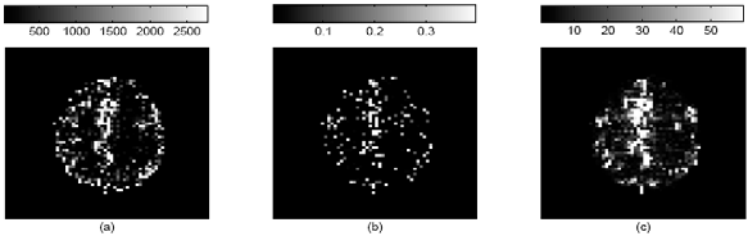

Fig. 3 (a) PSC difference map (original value- corrected value) for an axial slice. (b) LZ difference map for the same slice. (c) Percentage reduction in fMRI time course variance

Conclusions

This work has demonstrated the utility of NLD techniques in understanding the resting-state fMRI fluctuations. We have shown that determinism and nonlinearity are tissue-dependent, being higher in GM than in WM and CSF. We have also demonstrated that the tissue-specificity is unlikely due to cardiac/respiratory fluctuations or noise intensity differences. Hence, we conclude that the tissue-specificity of nonlinear dynamics seen in Table 1 can be mostly attributed to differences in underlying physiology and neural processing.

Sub	After Noise Addition	
	PSC	LZ
1	481	0.98
2	684	0.90
3	676	0.98
4	737	0.82
5	789	0.84

Table 2 WM PSC and LZ after addition of noise

References

1. Hu X et al, MRM 34: 201-212. **2**. Kruger G et al, MRM 46: 631-637. **3**. Di Garbo A et al, Intl J Bif Chaos 8:1831-183. **4**. Zhang XS et al, IEEE BME 46(5): 548-555. **5**. Wilcoxon F. Biometrics 1: 80-83.

Acknowledgement This work was supported in part by National Institutes of Health