Reduced brain functional network dynamics in propofol sedation characterized by modularity and time delayed network mutual information analysis

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Target audience: neuroscientist, MRI physicist, fMRI analyst.

Purpose: Brain network dynamics is reflected by the nonlinear and non-stationary variation of network organization over time[1]. Studies have shown that a specific mental and cognitive state of the brain is associated with and characterized by its unique network dynamic properties[2-3]. The state of the brain experiences significantly changes during general anesthesia. However, anesthetic-induced network dynamics changes have only been examined by a handful of studies using neuroimaging techniques. Several algorithms have been proposed to assess brain network dynamics using the sliding window method[2-3]. However, the range of methods capable of quantitatively measuring the brain network dynamics is still quite limited. In this study, we proposed a measurement of time-delayed network mutual information (TD-NMI) to quantify network dynamics changes in different states of propofol sedation in a group of healthy volunteers.

Methods: Eight subjects (24 - 42 yo, 4 men) underwent functional magnetic imaging (fMRI) (1.5T GE scanner, TR/TE: 2s/40ms, 3.75×3.75×6 mm^3 voxel size) while listening to a set of English words during wakeful baseline (WB), deep sedation (DS) with propofol, and recovery (RC). In deep sedation, volunteers showed no response to verbal commands. Low frequency (0.015-0.1Hz) fMRI signals were obtained after standard preprocessing procedures. Individual 116-by-116-ROI cross-correlation matrices were constructed based on the AAL template[4] that covers the whole brain. Modularity analysis[5] was performed to separate the whole brain network of each group into several distinct functional modules. A dynamics index, TD-NMI, was computed for each module in each condition of all volunteers:

$$TD-NMI_{(N_1,N_{1+\tau})} = \sum_{C_1 \in N_1} \sum_{C_{1+\tau} \in N_{1+\tau}} P(C_1, C_{1+\tau}) log_2 \frac{P(C_1,C_{1+\tau})}{P(C_1)P(C_{1+\tau})}$$

where P(X) is the probability, and P(X,Y) is the joint probability. N_1 and $N_{1+\tau}$ are the cross correlation matrices calculated from time points $(t_1 \ldots t_{WS})$ and time points $(t_{1+\tau} \ldots t_{WS+\tau})$, respectively, where WS is the variant of window length and τ is the time delay. C_1 and $C_{1+\tau}$ are cross-correlation values between ROIs, with C_1 calculated from $(t_1 \ldots t_{WS})$ time points and $C_{1+\tau}$ calculated from $(t_{1+\tau} \ldots t_{WS+\tau})$ time points. This method is an extension of time delayed mutual information (TDMI) that measures information transferring rate (ITR) of a non-stationary time series. Here, a higher TD-NMI value indicates a lower variability of network dynamics.

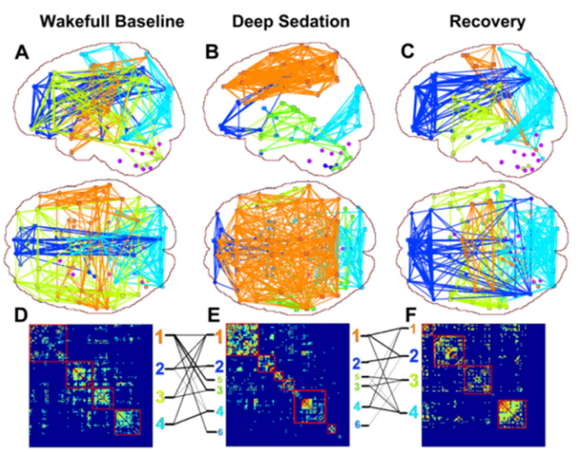

Figure 1: Brain modular patterns in three conditions: WB, DS and RC

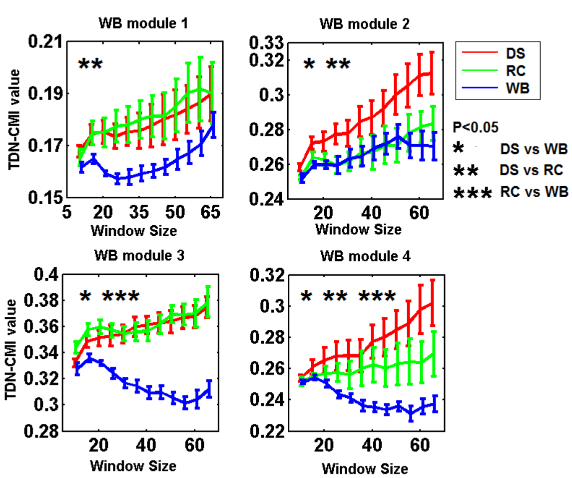

Figure 2: The relationship of TD-NMI values and the window size of each module in three conditions.

Results: The analysis revealed four distinct modules in WB and RC conditions and six modules in DS (Figure 1A-C). The ROI membership of modules was slightly different between WB and RC. The dependence of TD-NMI on window size is demonstrated in Figure 2 based on WB modules in the three states. The DS showed significantly lower dynamics (higher TD-NMI value) than WB in all modules. The computed TD-NMI value in the RC state showed no significant difference in comparison to DS with module 1 (motor-sensory module) and module 3 (default mode network module). With module 2 (fontal-posterior control module), TD-NMI value of RC recovered to the same level as seen in WB. With module 4 (visual module), TD-NMI value of RC was between the values obtained in DS and WB. The results also showed that TD-NMI value depended on the window size. DS and RC had increased TD-NMI values with increased window size, while WB did not.

Discussion: In comparison with WB and RC, DS modules showed locally clustered but globally segregated modular pattern. DS had a lower level of dynamics as quantified by TD-NMI in all modules. This indicates that the brain network had diminished level of dynamics and therefore reduced global information integration during sedation. During recovery, in comparison to WB and DS, the frontal-posterior control module showed fully recovered dynamics, the visual module showed partial recovery, while the default mode network and motor-sensory modules showed no sign of recovery. This observation suggested that different brain networks underwent different degrees of recovery after propofol sedation. This study shed light on modular dynamics changes in the brain during propofol sedation and revealed potentially different involvements of network modules in affecting state conditions of the brain during propofol sedation.

References:

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