Direct coupling of brain structural and functional information within white matter: a unified framework

Introduction

Integrative pattern of anatomy and physiology is crucial for understanding brain operational mechanisms. Precisely how the anatomical structure of the brain shape and constrains a repertoire of complex functions remains incompletely understood. A large number of neuroimaging studies have been keen to elucidate this relation in humans. Currently, macroscale human brain networks serve as the primary approach for investigating brain structure-function coupling (SFC). From simple correlations to harmonic analysis and modelling, various methods have been employed to uncover the subtle relationships between anatomical structural connectome (SC) and physiological functional connectome (FC). To some degree, alignments exist between these two types of network connectivity. Nevertheless, studying structure-function coupling from a network perspective (node-edge) is indirect, overlooking the procedural nature of inter-regional functional information transmission.

Biologically, the primary components of gray matter are neuronal somas, while white matter is mainly composed of axons. Signals from somas are conducted through myelinated axons. Glia support and protect neurons by providing nutrients, maintaining the cellular environment, and participating in information transmission. White matter anatomy scaffolds signal conduction within axons. The procedural nature of structure-function coupling involves two main steps: 1. 'Gray-white matter physiological connection': physiological activity initiated by somas in gray matter modulates the physiological processes occurring within white matter. 2. 'Structural-functional coupling within white matter': anatomic wiring of white matter sculpts axonal signal propagation, thereby regulating the intrinsic functional synchronization between gray matter regions. A two-step analysis of structure-function coupling has long been hindered by the gap in a pivotal link - assessment of physiological activity within white matter.

In the past decade, Ding and his colleagues have concentrated on the functional activity of white matter, undertaking substantial efforts to clarify its properties. Convergent evidences have expounded that bold signal observed in white matter is of physiological relevance. White matter fMRI facilitates refined and direct investigation of structure-function coupling. The first stage of the two-step analysis – 'gray-white matter physiological connection' has been explored by gray-white matter functional covariance connectivity, functional signal clustering et al, unveiling compelling results. However, the second step - 'structural-functional coupling within white matter' remains elusive.

Here we originally proposed a unified framework for direct coupling of brain structural and functional information within white matter. The framework was tensor FA-based -

The structural FA is the classical diffusion tensor FA while we also introduced a novel functional tensor based on signal co-fluctuation. Meanwhile, it was multiscale - Both voxel-wise and ROI-wise structure-function coupling patterns have been uncovered. Using this framework, we identified differential distribution of structural-functional coupling within white matter and pronounced heterogeneity in the corpus callosum. What's more, we validated repeatability of regions (both voxels and ROIs) with high structural-functional coupling using ICC. Aging effect, the relationship between coupling and behavioral measurements were examined. We observed that several regions significantly decouple with aging. Significant CCA brain-behavior correspondence was presented.

Our research provides fresh insights into the direct association between neuroanatomy and physiology. For the first time, the puzzle of structure-function coupling within the white matter has been uncovered, which means our study fills in an incomplete part of the structure-function coupling of the brain.