

A gyral coordinate system predictive of fibre orientations

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When axonal fibres approach or leave the cortex, their trajectories tend to closely follow the cortical convolutions. To quantify this tendency, we propose a three-dimensional coordinate system based on the gyral geometry. For every voxel in the brain, we define a “radial” axis orthogonal to nearby surfaces, a “sulcal” axis along the sulcal depth gradient that preferentially points from deep white matter to the gyral crown, and a “gyral” axis aligned with the long axis of the gyrus.

When compared with high-resolution, in-vivo diffusion MRI data from the Human Connectome Project, we find that in superficial white matter the apparent diffusion coefficient (at $b=1000$) along the sulcal axis is on average 16% larger than along the gyral axis and twice as large as along the radial axis. This is reflected in the vast majority of observed fibre orientations lying close to the tangential plane (median angular offset < 7 degrees), with the dominant fibre orientation typically aligning with the sulcal axis.

In cortical grey matter, fibre orientations transition to a predominantly radial orientation. We quantify the width and location of this transition and find strong reproducibility in test-retest data, but also a clear dependence on the resolution of the diffusion data. The ratio of radial to tangential diffusion is fairly constant throughout most of the cortex, except for a decrease of the diffusivity ratio in the sulcal fundi and the primary somatosensory cortex (Brodmann area 3) and an increase in the primary motor cortex (Brodmann area 4).

Although only constrained by cortical folds, the proposed gyral coordinate system provides a simple and intuitive representation of white and grey matter fibre orientations near the cortex, and may be useful for future studies of white matter development and organisation.

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31 The cerebral cortex of the human brain is highly convoluted, and the
32 pattern of cortical folding is reflected in the orientations of axonal fibres (Figure
33 1). In myelin-stained histological sections, the dominant axonal orientation in the
34 gyral white matter runs parallel to the sulcal walls, and points towards the gyral
35 crowns (Van Essen et al. 2014; Budde and Annese 2013). This implies that axons
36 mostly cross the gyral crowns at an angle perpendicular to the surface, but
37 approach the sulcal walls at oblique angles before turning 90 degrees to become
38 radial within the cortex (Figure 1). Furthermore, predominantly tangential axons
39 have been found in the white matter below the sulcal fundi, which is consistent
40 with the expected trajectory of U-fibres connecting neighbouring gyri (Van Essen
41 et al. 2014; Budde and Annese 2013; Reveley et al. 2015; Schilling et al. 2017).
42 Despite the predominant tangential orientations found in superficial white
43 matter, at least some axons cross the U-fibres in the sulcal fundi (Reveley et al.
44 2015) and some cross the gyral white matter to connect the opposite gyral banks
45 (Van Essen et al. 2014). These results from myelin-stained sections present a
46 good initial hypothesis of the axonal orientation distribution, even though the
47 interpretation of these images is complicated due to the projection of a three-
48 dimensional geometry on a two-dimensional plane.

49 Diffusion MRI allows us to investigate such patterns in three dimensions
50 over many subjects in-vivo and non-invasively, albeit at a much lower resolution.
51 Using high-resolution diffusion MRI, fibre bundle orientations are mostly radial
52 within the cortex (McKinstry et al. 2002; Deipolyi et al. 2005; Leuze et al. 2014;
53 Truong, Guidon, and Song 2014; Kleinnijenhuis et al. 2015; Bastiani et al. 2016),
54 although at least some cortical regions have predominantly tangential fibre
55 orientations such as the primary somatosensory cortex (Anwander, Pampel, and
56 Knosche 2010; McNab et al. 2013; Calamante et al. 2017). One limitation of these
57 investigations is that they typically do not extend below the cortex, although
58 some do report predominantly tangential orientations just below cortex
59 (Kleinnijenhuis et al. 2015; Reveley et al. 2015).

60 Here we extend these basic analyses of radially beyond the cortex to the
61 underlying white matter. We introduce a three-dimensional gyral coordinate
62 system of white matter orientation that is fully specified by the cortical folding
63 pattern. We define three axes: radial, sulcal, and gyral, which are defined relative
64 to the white/grey matter boundary surface, and linearly interpolated to deep and
65 superficial white matter, as well as different intra-cortical depth levels.

66 Compared with previous approaches, our analysis has two distinct
67 advantages. First, we propose a novel interpolation scheme, which allows us to
68 define the gyral coordinate system in the center of gyral folds by interpolating
69 between the sulcal walls, as well as in the rest of the superficial white matter.
70 Secondly, the three axes allow us to further subdivide tangential fibres into those

that are aligned with, or orthogonal to, the sulcal depth gradient. The code to generate the gyral coordinates has been made available online⁴.

Using fibre orientations inferred from high-resolution diffusion MRI from the Human Connectome Project (HCP; Van Essen et al. 2013; Glasser et al. 2013; Sotiropoulos et al. 2013) dataset, we find that the best-fit diffusion tensors tend to align well with this gyral coordinate system. We confirm quantitatively that the dominant fibre orientations inferred from diffusion MRI are almost exclusively aligned with the tangential (sulcal/gyral) plane in white matter, and with the radial axis in the cortical grey matter.

Moreover, we propose that the transition of white matter orientation from the tangential plane to the radial axis (in the cortex) can be described using a sigmoidal function that parameterizes the location and width of the transition. We fitted this model to diffusion MRI-derived orientations using data acquired at multiple spatial resolutions. We found high reproducibility of the transition boundary across subjects, but also a notable dependence of this transition on spatial resolution.

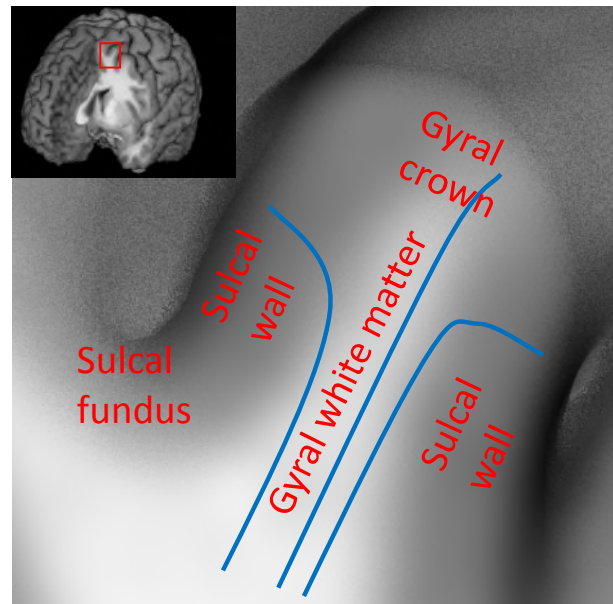


Figure 1 Illustration of the convoluted cortical surface consisting of protrusions called gyri separated by troughs called sulci. Concave sulcal fundi and convex gyral crowns are connected by relatively straight sulcal walls. Axons from the other parts of the brain have to follow the shape of the gyral white matter to reach the gyral crown and sulcal walls (e.g. blue lines). This suggests that a gyral coordinate system based on the shape of the gyri might be predictive of fibre orientation in gyral white matter.

⁴ A github repository containing code for generating gyral coordinates is available at <https://git.fmrib.ox.ac.uk/ndcn0236/gyralcoord>.