**REVIEW**

**Recent advances in diffusion neuroimaging: applications in the developing preterm brain [version 1; referees: 2 approved]**

Diliana Pecheva¹, Christopher Kelly¹, Jessica Kimpton¹, Alexandra Bonthrone¹, Dafnis Batalle¹, Hui Zhang², Serena J. Counsell¹

¹Centre for the Developing Brain, School of Biomedical Engineering & Imaging Sciences, King's College London, London, UK
²Department of Computer Science & Centre for Medical Image Computing, University College London, London, UK

---

**Abstract**

Measures obtained from diffusion-weighted imaging provide objective indices of white matter development and injury in the developing preterm brain. To date, diffusion tensor imaging (DTI) has been used widely, highlighting differences in fractional anisotropy (FA) and mean diffusivity (MD) between preterm infants at term and healthy term controls; altered white matter development associated with a number of perinatal risk factors; and correlations between FA values in the white matter in the neonatal period and subsequent neurodevelopmental outcome. Recent developments, including neurite orientation dispersion and density imaging (NODDI) and fixel-based analysis (FBA), enable white matter microstructure to be assessed in detail. Constrained spherical deconvolution (CSD) enables multiple fibre populations in an imaging voxel to be resolved and allows delineation of fibres that traverse regions of fibre-crossings, such as the arcuate fasciculus and cerebellar–cortical pathways. This review summarises DTI findings in the preterm brain and discusses initial findings in this population using CSD, NODDI, and FBA.

**Keywords**

infant, brain, diffusion magnetic resonance imaging
Corresponding author: Serena J. Counsell (serena.counsell@kcl.ac.uk)

Author roles: Pecheva D: Writing – Review & Editing; Kelly C: Writing – Review & Editing; Kimpton J: Writing – Review & Editing; Bonthrone A: Writing – Review & Editing; Batalle D: Writing – Review & Editing; Zhang H: Funding Acquisition, Supervision, Writing – Review & Editing; Counsell SJ: Funding Acquisition, Project Administration, Supervision, Writing – Original Draft Preparation, Writing – Review & Editing

Competing interests: No competing interests were disclosed.

Grant information: The authors receive funding from the Medical Research Council (MRC) UK (MR/L011530/1), the Biotechnology and Biological Sciences Research Council (grant number BB/J014567/1), the British Heart Foundation (FS/15/55/31649) and are supported by the Wellcome EPSRC Centre for Medical Engineering at King’s College London (WT 203148/Z/16/Z), MRC strategic grant MR/K006355/1 and by the National Institute for Health Research (NIHR) Biomedical Research Centre based at Guy’s and St Thomas’ NHS Foundation Trust and King’s College London. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Copyright: © 2018 Pecheva D et al. This is an open access article distributed under the terms of the Creative Commons Attribution Licence, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

How to cite this article: Pecheva D, Kelly C, Kimpton J et al. Recent advances in diffusion neuroimaging: applications in the developing preterm brain [version 1; referees: 2 approved] F1000Research 2018, 7(F1000 Faculty Rev):1326 (doi: 10.12688/f1000research.15073.1)

First published: 21 Aug 2018, 7(F1000 Faculty Rev):1326 (doi: 10.12688/f1000research.15073.1)
Introduction
Diffusion-weighted magnetic resonance imaging (dMRI) is a non-invasive imaging technique that measures the displacement of water molecules in tissue over time. As such, dMRI offers the opportunity to investigate tissue microstructure in vivo and provides quantitative measures that relate to brain injury and development. The most widely used dMRI analysis approach in the developing brain is diffusion tensor imaging (DTI), which has proven to be extremely useful for investigating brain development and injury. More recent approaches have moved beyond the tensor model to incorporate biophysical models to study tissue microstructure more specifically.

The aim of this review is to briefly describe studies assessing white and grey matter in the developing brain using advanced analysis approaches that have been used widely in the adult brain, such as neurite orientation dispersion and density imaging (NODDI), fixel-based analysis (FBA), and constrained spherical deconvolution (CSD). These approaches require high b-value (typically >2,000 s/mm²), high angular resolution dMRI data which pose additional challenges in neonatal imaging including longer acquisition times, which may lead to motion corrupt data, reduced signal-to-noise ratio, and increased distortions. However, recent advances in data acquisition approaches and hardware, coupled with imaging at 3 Tesla, mean it is now possible to acquire high-quality HARDI data in the neonatal brain. We believe these techniques will be increasingly used to improve our understanding of the neural substrate associated with impaired brain development in this population.

Diffusion-weighted imaging
Diffusion is the constant motion of molecules due to thermal energy. Given an environment without restrictions, water molecules will traverse a random walk, with direction changes following collisions with other particles. However, in the brain, the presence of axons, neuronal cell bodies, glial cells, and macromolecules comprise a heterogeneous environment which hinders and restricts diffusion. In the presence of these impediments, the measured root-mean-square displacement will be lower than predicted for water at room temperature. The term “apparent diffusion coefficient” is used to convey that the observed measure is influenced by the tissue microstructure. Diffusion is restricted if it is confined by physical boundaries, such as the diffusion of molecules in the intra-axonal space, causing the diffusion to become non-Gaussian²³.

Diffusion tensor imaging
The organisation of tissue microstructure will affect how water molecules diffuse. In a homogenous medium, the diffusion of water molecules is equal in all directions; this is isotropic diffusion. However, in a coherently organised microstructure, such as in white matter, diffusion is anisotropic⁴–⁶. Within white matter, water molecules diffuse more slowly perpendicular to the fibres than parallel to them (Figure 1). Under these conditions, the apparent diffusion coefficient will be different depending on the direction in which it is measured. To account for this, Basser et al.⁷ proposed that diffusion is characterised using a mathematical tensor model. To examine water molecular motion in a tissue with an ordered microstructure using the tensor model, a minimum of six non-collinear directions of diffusion sensitisation is required, in addition to one with no diffusion weighting, although usually at least 30 unique sensitised directions are recommended to robustly estimate the tensor model parameters.

The diffusion tensor provides scalar, rotationally invariant indices⁸. Indices derived from \( \lambda_1, \lambda_2, \lambda_3 \) (Figure 1) are, by definition, independent of orientation. The magnitude of the diffusivity along the main fibre orientation as estimated by DTI is given by \( \lambda_1 \), termed the axial diffusivity (AD). The average of the other

![Figure 1. Isotropic and anisotropic diffusion in the brain.](image)

In the white matter of the corpus callosum (red), diffusion occurs preferentially along the axonal fibres, resulting in anisotropic diffusion (b). In the ventricular cerebrospinal fluid (CSF; green), diffusion is unhindered and can be described as isotropic (c). Diffusion tensor ellipsoids representing anisotropic and isotropic diffusion are shown in b and c, respectively. Reproduced with permission from 9.
two eigenvalues, the radial diffusivity (RD), describes the magnitude of diffusivity across the fibres. The mean diffusivity (MD) is the average of all three eigenvalues and provides a measure of the overall diffusivity within a voxel. Fractional anisotropy (FA) is the variance of the three eigenvalues normalised by the magnitude of the tensor and takes values between 0 and 1.

**DTI studies in the infant brain**

The perinatal period is characterised by a pattern of decreasing MD, RD, and AD and increasing FA in the cerebral white matter in preterm infants\(^ {13,14} \) and term infants\(^ {5,16} \). White matter maturation follows a heterogeneous spatiotemporal pattern, with different fasciculi maturing at different times and different rates\(^ {16,23} \) in a posterior-to-anterior and a central-to-peripheral direction of maturation. The increase in FA takes place before myelin is evident histologically and is attributed to changes in white matter structure which accompany the remyelinating state including an increase in axonal membrane maturation and microtubule-associated proteins, a change in axon caliber, and an increase in oligodendrocyte number\(^ {24–29} \). At this stage, the highest FA values are seen in the unmethylated but highly organised commissural fibres in the splenium and genu of the corpus callosum. The second stage is associated with the historical appearance of myelin and subsequent maturation, with the earliest signs observed in the projection fibres of the posterior limb of the internal capsule around term\(^ 27 \).

Lower FA and increased MD are found across the white matter in preterm infants compared with term-born infants\(^ {24,28–30} \), and increased prematurity is associated with lower FA and higher MD\(^ {13,31–35} \). Furthermore, infants with white matter injury identified on conventional MRI show reduced anisotropy and increased MD and RD across the white matter in comparison to preterm infants with normal MRI\(^ {14,36–40} \). White matter diffusion measures in preterm infants at term equivalent age have been related to subsequent neurodevelopmental performance. Increased FA and decreased MD and RD in the white matter at term equivalent age are associated with improved motor, cognitive, and language performance in early childhood\(^ {40–47} \) and improved visual function\(^ {48–50} \).

In addition to assessing white matter, DTI studies of cortical gray matter have identified altered cortical development in infants born preterm. Cortical maturation up to term equivalent age is characterised by decreasing FA and MD, reflecting increased dendritic arborisation and synapse formation\(^ {53,31–33} \). FA and MD are elevated in preterm infants at term equivalent age compared to infants born at term, suggesting impaired cortical development in this population\(^ {32} \).

**Limitations of DTI**

While DTI has proven to be a powerful technique for studying the brain, a major limitation is that it is only able to depict a single fibre population within a voxel. DTI fails to represent appropriately the tissue microstructure in the presence of crossing fibres and DTI-derived measures lack tissue specificity, as these measures can be affected by multiple microstructural features. Moreover, in a restricted environment, diffusion is no longer Gaussian and the tensor model deviates from the signal.

The use of more advanced analysis approaches, such as those that enable microstructure to be studied with greater specificity, require high angular resolution diffusion imaging (HARDI) acquisitions at a higher b-value than has typically been used in the neonatal brain. These approaches have long acquisition times and so their use in unsedated neonates has been limited. However, advances in MRI acquisition techniques, such as the use of protocols designed specifically for neonates using neonatal head coils and multiband MRI coupled with modern gradient coil systems, with maximum gradient amplitude, slew rate, and duty cycle\(^ {54–56} \), now enable HARDI data to be acquired in a clinically feasible time.

**Compartment models of microstructure**

Compartment models provide a biophysical interpretation of the diffusion-weighted signal and attempt to characterise the complexity of cerebral tissue by decomposing the signal into compartments describing diffusion within distinct microstructural constituents.

Stanisz et al.\(^ {57} \) first introduced the three-compartment model comprising a restricted intra-axonal compartment, anisotropic hindered extra-axonal compartment, and a restricted isotropic compartment describing diffusion within cellular structures such as glial cells. Behrens et al.\(^ {58} \) presented a method to account for multiple fibre populations using the ball and stick model where diffusion along axons is represented by sticks and outside the axons diffusion is an isotropic ball. CHARMED\(^ {57} \) models the intra-axonal space using cylinders with a distribution of radii given by the F-distribution and extra-axonal space as tensor with a principle direction aligned with the cylinders. This was extended to provide an estimate of axon diameter in the AxCaliber framework\(^ {59,60} \). Alexander\(^ {60} \) simplified CHARMED by using a single axon radius and symmetric tensor that was used in the ActiveAx framework to estimate axon diameter in biological tissue\(^ {51,61} \) and axon diameter mapping in the presence of orientation dispersion\(^ {62} \). However, recent work shows that the gradient amplitudes attainable with current clinical scanners are not able to estimate axon diameter accurately\(^ {63,64} \).

NODDI\(^ {65} \) provides measures of neurite density index (NDI) and orientation dispersion index (ODI). The model consists of three compartments modelling the intracellular, extracellular, and cerebrospinal fluid (CSF) environments. The intraneurite compartment captures the diffusion inside dendrites and axons, collectively termed neurites. The intraneurite compartment is modelled using sticks to represent unhindered diffusion along the neurites and highly restricted diffusion perpendicular to the neurites. The orientation distribution can vary from being highly parallel, reflecting the coherent organisation of white matter fibres such as in the posterior limb of the internal capsule or the corpus callosum, to highly dispersed, such as in regions of crossing fibres like the centrum semiovale or the complex configuration of the cortex. The extraneurite compartment represents the space occupied by glial cells and neuronal somas where diffusion is hindered and is modelled as an anisotropic Gaussian distribution using a zepelin. The CSF compartment is modelled as isotropic Gaussian diffusion.
The NODDI model has been applied to investigate white and grey matter maturation in the preterm brain.\textsuperscript{14,67,68} NDI increases in the white matter with increasing maturation, with the highest NDI values observed in primary motor and somatosensory tracts and lower values observed in association fibres.\textsuperscript{67,69} Combined with graph theoretical approaches and network-based analysis, both FA- and NDI-weighted connections were highly correlated with age at MRI in a widespread pattern encompassing most white matter connections between 25 and 45 weeks post-menstrual age (PMA). Lower gestational age (GA) at birth was significantly correlated with lower FA and NDI, and we observed a consistent negative correlation of relative NDI-weighted global efficiency with GA at birth, suggesting an alteration in network topology with increased prematurity at birth.\textsuperscript{67} Cortical grey matter maturation is characterised by increasing ODI (accompanied by decreasing MD and FA), reflecting increased dendritic arborisation. At around 38 weeks’ GA, this increase in ODI plateaued, but after this period NDI increased in primary motor and sensory regions (Figure 2), suggesting that cortical development up to 38 weeks’ PMA shows a predominant increase in dendritic arborisation and neurite growth, while after 38 weeks’ PMA it is dominated by increasing cellular and organelle density.\textsuperscript{34}

The DIAMOND model\textsuperscript{70} combines compartmental and statistical modelling to represent restricted, hindered, and isotropic compartments using three peak-shaped matrix-variate distributions. DIAMOND estimates the number of tissue compartments in each voxel and provides compartment-specific measures of FA, AD, RD, and MD and a measure of heterogeneity within...

\textbf{Figure 2. Correlation between cortical diffusion characteristics and age at scan.} Hot colours indicate increase and cool colours indicate decrease in diffusion measure. Abbreviations: FA, fractional anisotropy; MD, mean diffusivity; NDI, neurite density index; ODI, orientation dispersion index; PMA, post-menstrual age. Reproduced from\textsuperscript{34}. 

Page 5 of 12
the compartment. This model was recently applied to assess cortical maturation in the preterm cortex, demonstrating a decrease in the radial organisation of the cortex\(^7\).

Approaches to model the diffusion signal have limitations, including assuming non-exchanging tissue compartments and fixed compartmental diffusivities\(^7\), and, to date, there have been no studies validating these measures with human preterm or neonatal tissue samples. However, ODI measures have recently been correlated with changes in neurite geometrical configuration assessed with histology in a population with spinal cord multiple sclerosis\(^7\), suggesting that model indices are relevant proxies of underlying microstructure.

**Constrained spherical deconvolution**

CSD estimates the fibre orientation distribution (FOD) in the presence of multiple fibre orientations\(^7\)–\(^9\). It was initially introduced for single-shell HARDI data\(^7\) and is able to estimate FODs regardless of the number of fibre populations within a voxel. It is assumed that each fibre bundle has the same diffusion properties, apart from the orientation, and that no exchange occurs between bundles over the time-scale of DWI acquisition. The signal emanating from each fibre bundle is independent and they can be summed. The diffusion-attenuated profile for an anisotropic fibre bundle is represented by a response function. The response function is low amplitude along the axis, where diffusion is high, and high amplitude in the radial plane, where diffusion is low. Recently, multi-tissue CSD has been introduced, which exploits the different diffusion dependencies of different tissues at multiple b-values (b-value refers to the degree of diffusion weighting which is related to the amplitude and duration of the diffusion gradients and the time interval between the leading edges of the two pulsed gradients) to derive tissue-specific response functions, where grey matter and CSF response functions are both isotropic, leading to improved estimation of the FOD\(^8\).

CSD-based tractography has been used in a limited number of studies in the infant brain to visualise fibre bundles that are not readily delineated using DTI-based approaches. In Pieterman et al.\(^8\), we were able to visualise cerebellar–cortical pathways crossing in the mid-brain (Figure 3). In another recent study, we were able to delineate the arcuate fasciculus, which traverses regions of fibre crossings in the centrum semiovale and we observed that FA values of the arcuate fasciculus in preterm infants at term equivalent age correlated with language performance at 2 years (Figure 4)\(^8\).

**Fixel-based analysis**

CSD has led to the development of fibre bundle-specific measures. Raffelt et al.\(^8\) introduced a measure of apparent fibre density (AFD) of individual fibre populations estimated from the FOD. A fixel describes an individual different fibre bundle within an imaging voxel where fibre bundles of different orientations may be present in an imaging voxel. AFD is based on the assumptions that the intra-axonal water diffusion is restricted in the direction perpendicular to the fibre orientation, the extra-axonal diffusion-weighted signal is attenuated at high b-values (>2,000 s/mm\(^2\)), and the diffusion-weighted signal from the restricted compartment is preserved under

---

Figure 3. Reconstruction of cerebello–thalamo–cortical tract (CTC, red-yellow) and cortico–ponto–cerebellar tract (CPC, blue-green) in an infant born at 33 weeks and imaged at 40 weeks post-menstrual age with fibre orientation distribution plots overlaid on the diffusion data. (a) Crossing fibres of the CTC tract at the level of the mesencephalon. (b) Crossing fibres of the CPC tract at the level of the pons. (c) 3D reconstruction of both tracts. Reproduced from 81.
typical diffusion-weighted gradient pulse durations used \textit{in vivo}. Consequently, the radial diffusion-weighted signal is approximately proportional to the volume of the intra-axonal compartment\textsuperscript{83}. Since the FOD amplitude is proportional to the radial diffusion-weighted signal, it provides a measure of fibre density (FD) determined as a proportion of the volume occupied by the fibre population\textsuperscript{83}, as illustrated by Figure 5. This measure would detect within-voxel changes related to the volume of restricted water along a specific direction. AFD also accounts for differences in macroscopic white matter structure across subjects. FODs are modulated according to changes in local volume, such as expansion or contraction, that occur during registration. This presents a measure pertaining to both microscopic changes in FD and macroscopic morphological changes that occur across voxels.

Raffelt \textit{et al.}\textsuperscript{84} make a distinction between the changes in microstructure that occur within a voxel and the macroscopic changes in morphology that occur across voxels. They introduced a measure of FD derived solely from unmodulated FOD amplitude so as to describe changes in white matter microstructure without the effects of macroscopic morphological changes. Changes in white matter microstructure which would result in a reduction in FD can be visualised in Figure 6. Nonetheless, macroscopic alterations in morphology are likely to occur across white matter during development and need to be accounted for. Raffelt \textit{et al.}\textsuperscript{84} provide, in addition to FD, a measure of macroscopic differences in morphology based on the local deformations that are applied during registration. Changes in brain morphology have previously been investigated using voxel-based morphometry (VBM)\textsuperscript{85} and tensor-based morphometry\textsuperscript{86,87}. Local changes

![Figure 5](image)

\textbf{Figure 5.} A single fibre population within a voxel (A, B), the expected diffusion-weighted signal profile (C), and the associated fibre orientation distribution (FOD) (D) The FOD amplitude is proportional to the radial signal profile and therefore the fibre density of the fibre population.

Image adapted from \textsuperscript{88}.
in volume can be investigated using the information from a subject’s nonlinear deformation to a template. At each voxel, the determinant of the Jacobian describes the expansion or contraction of the subject image relative to a target. This method focuses on the changes in fibre bundle that occur perpendicular to the main fibre orientation, as a reduced fibre bundle cross-section would imply a reduced number of axons. Using FOD registration, it is possible to assess changes in volume with respect to specific fibre orientations. This provides a fibre bundle-specific measure of fibre cross-section (FC) based on the Jacobian determinant following registration of FOD images.

To date, there have been few studies assessing white matter in the preterm brain using FBA. Pannek et al. demonstrated reduced FD, FC, and FD multiplied by FC (FDC) in the corticospinal tract and corpus callosum in preterm infants at term equivalent age compared to healthy controls[89]. We have observed a significant negative correlation between FC and FDC and duration of mechanical ventilation and parenteral nutrition in preterm infants at term equivalent age, suggesting that aberrant white matter development previously attributed to microstructural changes may be due to alterations in the size (fibre cross-sectional area) of specific fibre bundles at the macroscopic scale[90].

**Summary**

Recent advances in diffusion acquisition and analysis approaches enable white and grey matter microstructure to be probed in detail, demonstrating increases in NDI and FC in white matter and increasing ODI in cortical grey matter with increasing maturation. CSD-based tractography facilitates the delineation of complex fibre bundles that have not been clearly depicted using DTI approaches. Large-scale studies (such as the developing Human Connectome Project, http://www.developingconnectome.org) are now underway and are obtaining high b-value HARDI data in the neonatal brain with the aim of improving our understanding of human brain development and the impact of environmental and genetic factors on brain development. It is likely that the acquisition and analysis techniques outlined in this review will be confined to the research environment in the short term. However, the ultimate aim of neonatal neuroimaging is to facilitate early diagnosis and prognosis, and innovations in image acquisition including multiband techniques to reduce acquisition time are likely to facilitate the increased use of these advanced methods in the neonatal brain in the future.

**Grant information**

The authors receive funding from the Medical Research Council (MRC) UK (MR/L011530/1), the Biotechnology and Biological Sciences Research Council (grant number BB/J014567/1), the British Heart Foundation (FS/15/55/31649) and are supported by the Wellcome EPSRC Centre for Medical Engineering at King’s College London (WT 203148/Z/16/Z), MRC strategic grant MR/K006355/1 and by the National Institute for Health Research (NIHR) Biomedical Research Centre based at Guy’s and St Thomas’ NHS Foundation Trust and King’s College London.

The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.
1. Hutter J, Tourrier JD, Price AN, et al.: Time-efficient and flexible design of optimized multishell HARDI diffusion. Magn Reson Med. 2018; 79(3): 1276–92. Published Abstract | Publisher Full Text | Free Full Text | F1000 Recommendation
2. Assaf Y, Freidlin NZ, Rohde QK, et al.: New modeling and experimental framework to characterize hindered and restricted water diffusion in brain white matter. Magn Reson Med. 2004; 52(5): 965–78. Published Abstract | Publisher Full Text
3. Basser PJ: Inferring microstructural features and the physiological state of tissues from diffusion-weighted images. NMR Biomed. 1995; 8(7–8): 333–44. Published Abstract | Publisher Full Text
4. Hajnal JV, Doran M, Hall AS, et al.: MR imaging of anisotropically restricted diffusion of water in the nervous system: technical, anatomic, and pathologic considerations. J Comput Assist Tomogr. 1991; 15(1): 1–18.

5. Moseley ME, Cohen Y, Kucharczyk J, et al.: Diffusion-weighted MR imaging of anisotropic water diffusion in cat central nervous system. Radiology 1990; 176(2): 439–45. Published Abstract | Publisher Full Text
6. Thomsen C, Henriksen O, Ring P, et al.: Evaluation of the white matter maturation. J Neuroradiol. 2009; 26(2): 65–95. Published Abstract | Publisher Full Text
7. Basser PJ, Mattiello J, LeBihan D: MR diffusion tensor spectroscopy and imaging. Biophys J. 1994; 66(1): 259–67. Published Abstract | Publisher Full Text | Free Full Text
8. Pierpaoli C, Basser PJ: Quantitative MRI in the very preterm: application to normal neonate development analysis. NeuroImage. 2001; 13(4): 214–24. Published Abstract | Publisher Full Text
9. van Puij C, van Kooi BJ, de Vries LS, et al.: Quantitative fiber tracking in the corpus callosum and internal capsule reveals microstructural abnormalities in preterm infants at term-equivalent age. AJNR Am J Neuroradiol. 2012; 33(1): 678–84. Published Abstract | Publisher Full Text
10. Partridge SC, Mukherjee P, Henry RG, et al.: Diffusion tensor imaging: serial quantitation of white matter tract maturity in premature newborns. Eur Radiol. 2011; 21(3): 538–47. Published Abstract | Publisher Full Text | Free Full Text
11. Koenigsknecht MJ, Leeman A, Groenendaal F, et al.: Microstructural brain development between 30 and 40 weeks corrected age in a longitudinal cohort of extremely preterm infants. Neuroimage. 2014; 103: 214–24. Published Abstract | Publisher Full Text
12. van Puij C, van Kooi BJ, de Vries LS, et al.: Quantitative fiber tracking in the corpus callosum and internal capsule reveals microstructural abnormalities in preterm infants at term-equivalent age. J Magn Reson Imaging. 2002; 16(6): 621–32. Published Abstract | Publisher Full Text
13. Partridge SC, Mukherjee P, Henry RG, et al.: Diffusion tensor imaging: serial quantitation of white matter tract maturity in premature newborns. Neuroimage. 2004; 22(3): 1300–14. Published Abstract | Publisher Full Text | Free Full Text
14. van Puij C, van Kooi BJ, de Vries LS, et al.: Quantitative fiber tracking in the corpus callosum and internal capsule reveals microstructural abnormalities in preterm infants at term-equivalent age. AJNR Am J Neuroradiol. 2012; 33(4): 678–84. Published Abstract | Publisher Full Text | Free Full Text
15. Dubois J, Hertz-Pannier L, Dehaene-Lambertz G, et al.: Assessment of the early organization and maturation of infants’ cerebral white matter fiber bundles: a feasibility study using quantitative diffusion tensor imaging and tractography. Neuroimage. 2006; 30(4): 1121–32. Published Abstract | Publisher Full Text | Free Full Text
16. Oishi K, Mori S, Donohue PK, et al.: Multi-contrast human neonatal brain atlas: application to normal neonate development analysis. Neuroimage. 2011; 56(1): 8–20. Published Abstract | Publisher Full Text | Free Full Text
17. Braga RM, Roze E, Ball G, et al.: Development of the Corticospinal and Callosal Tracts from Extreme Prematurity Birth up to 2 Years of Age. PLoS One. 2015; 10(5): e0125681. Published Abstract | Publisher Full Text | Free Full Text
18. Dubois J, Dehaene-Lambertz G, Perrin M, et al.: Asynchrony of the early maturation of white matter bundles in healthy infants: quantitative landmarks revealed noninvasively by diffusion tensor imaging. Hum Brain Mapp. 2008; 29(1): 14–27. Published Abstract | Publisher Full Text | Free Full Text
19. Gao W, Liu W, Chen Y, et al.: Temporal and spatial development of axonal organization and maturation of white matter in the developing brain. AJNR Am J Neuroradiol. 2009; 30(2): 290–6. Published Abstract | Publisher Full Text | Free Full Text
20. Kulkova S, Hertz-Pannier L, Dehaene-Lambertz G, et al.: Multi-parametric evaluation of the white matter maturation. Brain Struct Funct. 2015; 220(6): 3657–72. Published Abstract | Publisher Full Text | Free Full Text
21. Nocein-Manor R, Card D, Morris D, et al.: Quantitative MRI in the very preterm brain: assessing tissue organization and myelination using magnetization transfer, diffusion tensor and T imaging. Neuroimage. 2013; 64: 505–16. Published Abstract | Publisher Full Text
22. Rosin-Maron R, Card D, Raybaud C, et al.: Cerebral maturation in the early preterm period- A magnetization transfer and diffusion tensor imaging study using voxel-based analysis. Neuroimage. 2015; 112: 30–42. Published Abstract | Publisher Full Text
23. Rose J, Vassar R, Cahill-Roxley K, et al.: Brain microstructural development at near-term age in very-low-birth-weight preterm infants: an atlas-based diffusion imaging study. Neuroimage. 2014; 86: 244–56. Published Abstract | Publisher Full Text | Free Full Text
24. Hüppi PS, Warfield S, Kikinis R, et al.: Quantitative magnetic resonance imaging of brain development in premature and mature newborns. Ann Neurol. 1998; 43(2): 224–35. Published Abstract | Publisher Full Text
25. Wimberger DM, Roberts TP, Barkovich AJ, et al.: Identification of “premyelination” by diffusion-weighted MRI. J Comput Assist Tomogr. 1995; 19(1): 28–33. Published Abstract | Publisher Full Text | Free Full Text
26. Neil JJ, Shiran SI, McLaren KC, et al.: Normal brain in human newborns: apparent diffusion coefficient and diffusion anisotropy measured by using diffusion tensor MRI imaging. Radiology. 1998; 201(1): 57–66. Published Abstract | Publisher Full Text | Free Full Text
27. Brody BA, Kinney HC, Koman AS, et al.: Sequence of central nervous system myelination in human infancy. I. An autopsy study of myelination. J Neuropathol Exp Neurol. 1987; 46(3): 283–301. Published Abstract | Publisher Full Text | Free Full Text
28. Anjari M, Srinivasan L, Alspoir J, et al.: Diffusion tensor imaging with tract-based spatial statistics reveals local white matter abnormalities in preterm infants. Neuroimage. 2007; 35(3): 1021–7. Published Abstract | Publisher Full Text | Free Full Text
29. Rose SE, Hatzipanos G, Shadbolt MW, et al.: Altered white matter diffusion anisotropy in normal and preterm infants at term-equivalent age. Magn Reson Med. 2008; 60(4): 761–7. Published Abstract | Publisher Full Text | Free Full Text
30. Thompson DK, Inker TE, Fazeghi N, et al.: Characterization of the corpus callosum in very preterm and full-term infants utilizing MRI. Neuroimage. 2011; 55(2): 479–90. Published Abstract | Publisher Full Text | Free Full Text
31. Ball G, Counsell SJ, Anjari M, et al.: An optimised tract-based spatial statistics protocol for neonates: applications to prematurity and chronic lung disease. Neuroimage. 2010; 53(1): 94–102. Published Abstract | Publisher Full Text | Free Full Text
32. Hasegawa T, Yamada K, Morimoto M, et al.: Development of corpus callosum in preterm infants is affected by the prematurity: in vivo assessment of diffusion tensor imaging at term-equivalent age. Pediatr Res. 2011; 69(3): 249–54. Published Abstract | Publisher Full Text | Free Full Text
33. Huang H, Zhang J, Wakana S, et al.: White and gray matter development in human fetal, newborn and pediatric brains. Neuroimage. 2006; 33(1): 27–38. Published Abstract | Publisher Full Text | Free Full Text
34. Goutouzis A, Paulos A, et al.: Delineation of early brain development from fetuses to infants with diffusion MRI and beyond. Neuroimage. 2018; pii: S1053-8119(18)30649-0. Published Abstract | Publisher Full Text | Free Full Text
35. Ouyang M, Dubois J, Yiu Q, et al.: Specific relations between neurodevelopmental abilities and white matter microstructure in children born microstructural alterations in normal and preterm infants at term-equivalent age. AJNR Am J Neuroradiol. 2012; 33(3): 839–45. Published Abstract | Publisher Full Text | Free Full Text
36. Counsell SJ, Edwards AD, Chew AT, et al.: Specific relations between neurodevelopmental abilities and white matter microstructure in children born microstructural changes in preterm neonates at term-equivalent age: a diffusion tensor imaging and probabilistic tractography study. AJNR Am J Neuroradiol. 2012; 33(3): 839–45. Published Abstract | Publisher Full Text | Free Full Text

References
86. Gaser C, Nenadic I, Buchsbaum BR, et al.: Deformation-based morphometry and its relation to conventional volumetry of brain lateral ventricles in MRI. NeuroImage. 2001; 13(6 Pt 1): 1140–5. PubMed Abstract | Publisher Full Text

87. Leow AD, Klunder AD, Jack CR Jr, et al.: Longitudinal stability of MRI for mapping brain change using tensor-based morphometry. NeuroImage. 2006; 31(2): 627–40. PubMed Abstract | Publisher Full Text | Free Full Text

88. Raffelt D, Tournier JD, Crozier S, et al.: Reorientation of fiber orientation distributions using apodized point spread functions. Magn Reson Med. 2012; 67(3): 844–55. PubMed Abstract | Publisher Full Text

89. Pannek K, Fripp J, George JM, et al.: Fixel-based analysis reveals alterations in brain microstructure and macrostructure of preterm-born infants at term equivalent age. NeuroImage Clin. 2018; 18: 51–9. PubMed Abstract | Publisher Full Text | Free Full Text | F1000 Recommendation

90. Pecheva D, Tournier JD, Pietsch M et al. Fixel based analysis of white matter fibre density and morphology in the preterm brain. Proceedings of the International Society for Magnetic Resonance in Medicine. 2018; 0843. Reference Source
Open Peer Review

Current Referee Status: ✔ ✔

Editorial Note on the Review Process
F1000 Faculty Reviews are commissioned from members of the prestigious F1000 Faculty and are edited as a service to readers. In order to make these reviews as comprehensive and accessible as possible, the referees provide input before publication and only the final, revised version is published. The referees who approved the final version are listed with their names and affiliations but without their reports on earlier versions (any comments will already have been addressed in the published version).

The referees who approved this article are:

Version 1

1 Hao Huang Qinlin Yu Department of Radiology, Perelman School of Medicine, University of Pennsylvania, Pennsylvania, USA
   Competing Interests: No competing interests were disclosed.

2 Risto A Kauppinen School of Experimental Psychology and Clinical Research and Imaging Centre, University of Bristol, Bristol, UK
   Competing Interests: No competing interests were disclosed.

The benefits of publishing with F1000Research:

- Your article is published within days, with no editorial bias
- You can publish traditional articles, null/negative results, case reports, data notes and more
- The peer review process is transparent and collaborative
- Your article is indexed in PubMed after passing peer review
- Dedicated customer support at every stage

For pre-submission enquiries, contact research@f1000.com