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Adaptive prior probability and spatial temporal intensity change estimation for segmentation of the one-year-old human brain

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HIGHLIGHTS

- We propose the intensity growth maps (IGM) to perform segmentation of one-year old data.
- The IGM captured intensity changes of 20–25% in immature WM regions.
- We generate adaptive tissue probability map of one-year old data using IGM.
- IGM-EM has a dice error ratio, GM: 9.75 and WM: 12.66.
- The results of IGM-EM show good performance in temporal and prefrontal lobe areas.

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ABSTRACT

The degree of white matter (WM) myelination is rather inhomogeneous across the brain. White matter appears differently across the cortical lobes in MR images acquired during early postnatal development. Specifically at 1-year of age, the gray/white matter contrast of MR T1 and T2 weighted images in prefrontal and temporal lobes is reduced as compared to the rest of the brain, and thus, tissue segmentation results commonly show lower accuracy in these lobes. In this novel work, we propose the use of spatial intensity growth maps (IGM) for T1 and T2 weighted images to compensate for local appearance inhomogeneity. The IGM captures expected intensity changes from 1 to 2 years of age, as appearance homogeneity is greatly improved by the age of 24 months. The IGM was computed as the coefficient of a voxel-wise linear regression model between corresponding intensities at 1 and 2 years. The proposed IGM method revealed low regression values of 1–10% in GM and CSF regions, as well as in WM regions at maturation stage of myelination at 1 year. However, in the prefrontal and temporal lobes we observed regression values of 20–25%, indicating that the IGM appropriately captures the expected large intensity change in these lobes mainly due to myelination. The IGM is applied to cross-sectional MRI datasets of 1-year-old subjects via registration, correction and tissue segmentation of the IGM-corrected dataset. We validated our approach in a small leave-one-out study of images with known, manual 'ground truth' segmentations.

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1. Introduction

Image segmentation methods are widely used in neurodevelopmental analyses to study anatomical differences and functionalities across all ages (Gilmore et al., 2007, 2010; Hazlett et al., 2011; Knickmeyer et al., 2008; Shaw et al., 2006). Many proposed methods segment MR images into tissue classes of white matter (WM), gray matter (GM) and cerebrospinal fluid (CSF). Common approaches for segmentation include Expectation Maximization (EM) (Roche et al., 2011), Artificial Neural Network (Perez de Alejo et al., 2003) and fuzzy classification-based algorithms (Shen et al., 2005). These methods work well on images from subjects older

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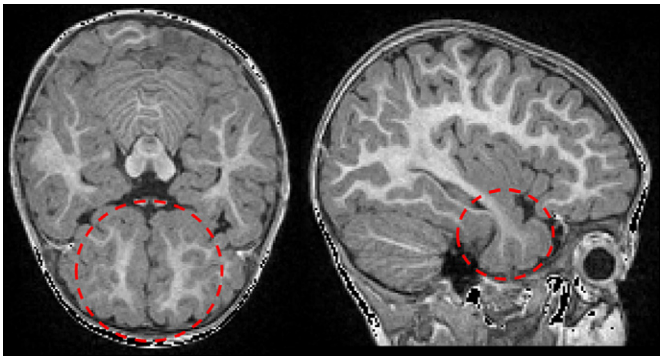

Fig. 1. WM in early postnatal stage undergoes myelination that strongly affects MR appearance. The intensity of immature WM (red circles) often appears similar to GM intensity within the temporal (left: sagittal slice) and prefrontal lobes (right: transverse slice). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

than 2 years of age, a point in development when the WM of the brain is mature enough to appear mostly homogenous across the brain. Consequently, volumetric studies evaluating GM and WM maturation changes in full-term children have been conducted mainly in subjects older than 2 years of age (Caviness et al., 1996; Giedd et al., 1996; Sowell et al., 2004). However, they fail to accurately represent WM around 1 year of age due to the progress of myelination in WM. The progress of WM maturation is inhomogeneous across the brain, following a pattern of posterior-to-anterior lobes and superior to inferior progression (Colby et al., 2011; Tzarouchi et al., 2009). The intensity of late myelinating WM often appears similar to GM intensity, strongly affecting MRI appearance. Consequently, at 1 year of age, the prefrontal lobes and inferior temporal pole show a reduced WM/GM contrast as compared to other lobes (Fig. 1). Not surprisingly, standard tissue segmentation methods, which assume homogeneous within-class appearance across the image produce incorrect results within the prefrontal and temporal lobes even after correcting intensity nonuniformity. Commonly, white matter is under-segmented in inferior temporal and prefrontal lobe. In order to address this issue, the addition of a mixed WM/GM class or the use of regional/lobar atlases was previously proposed, often with limited success, unless paired longitudinal datasets existed (Merisaari et al., 2009; Shi et al., 2010a,b). For the reminder of this paper, WM regions that are comparatively under-myelinated will be called immature WM.

1.1. Related studies

There are two main categories for methods compensating of immature WM in MRIs of 1-year-olds: a classifier-based approach and an atlas-based approach. Claude et al. (2004) proposed a classifier-based approach by segmenting immature WM parts of premature brain using a semi-automatic strategy including the pixel-wise region growing method and a novel method of image intensity gradient generation. The myelination intensity correction inside the WM was used to update Gaussian mixture model parameters for the WM cluster computation. After myelination correction, segmentation is achieved via combining several segmentation methods from a watershed segmentation-based method, rigid transformation and combination with prior probability images in the SPM2 package, and a Hidden Markov Random Field method. This method and most such classifier-based segmentation methods tend to overestimate the intensity compensation due to local over-fitting.

To reduce such overestimation, atlas-based approaches define spatial tissue priors for white matter regions at different stage of white matter maturation in a known brain atlas space. Such a brain atlas represent typical subjects at similar developmental age with a large number of often manually determined regional tissue class priors. The brain atlas image template, as well as the tissue priors, are registered and transferred to the subject image being segmented. In Weisenfeld and Warfield (2009), which focused on newborn MRI scans, the registration of atlas and priors are used to automatically learn subject-specific class-condition density functions, which are then fused to form an optimal estimate of the targets' segmentation. Shi et al. (2010a) applied an approach using atlas-based segmentation from a later time-point image of the same subject also for neonatal brain segmentation. This approach takes advantage of the fact that brain gyrification remains mainly stable during postnatal development for full-term infants. However, these segmentation results fully depend on availability of longitudinal datasets. To overcome this limitation Shi et al. (2010b) proposed a multi-region-multi-reference framework for atlas-based neonatal brain segmentation parcellating the average atlas into multiple regions, and applying an exemplar for image clustering into different sub-populations.

1.2. Motivation of current study

The white matter maturational process in the first few years of postnatal human life shows a relatively large degree of regional inhomogeneity (Murakami et al., 1999). At one year of age, the white matter in the prefrontal and inferior temporal lobes is at a reduced level of myelination and consequently shows reduced WM/GM contrast as compared to other cerebral regions. The purpose of this study is to develop a novel brain tissue segmentation method for cross-sectional 1-year-old MRI datasets using a novel spatial intensity growth map (IGM) that compensates for the white matter intensity appearance inhomogeneity. The proposed method is evaluated on selected T1-weighted images of 1-year-old subjects with manual 'ground truth' segmentations.

2. Method

The proposed segmentation procedure is based on a local intensity changes that captures expected intensity changes from 1 to 2 years of age (see Fig. 2 for an overview of the methods), The IGM is applied to MRI images by deformable registration and subsequent intensity correction (Section 2.3). The modified image is then segmented with an enhanced EM-based tissue segmentation method (Section 2.4). In order to achieve optimal tissue priors, we further employed an EM-like optimization of existing prior tissue probability maps to fit known expert rater segmentations (Section 2.5).

2.1. Training data

The subject population employed for the creation of the proposed IGM method consisted of fourteen subjects with paired longitudinal T1-(160 slices with TR = 2400 ms, TE = 3.16 ms, flip angle = 8, field of view 256 × 256) and T2-weighted (160 slices with TR = 3200 ms, TE = 499 ms, flip angle = 120, field of view 256 × 256) MR scans at 12 and 24 months. The subject scans were selected from scans acquired as part of the IBIS (Infant Brain Imaging Study) network (http://www.ibis-network.org) at 4 different sites (University of North Carolina, University of Washington at Seattle, Washington University at Saint Louis and the Children's Hospital of Philadelphia). All datasets were acquired on 3T Siemens Tim Trio scanners at 1 mm × 1 mm × 1 mm resolution.