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Automated assessment of the quality of diffusion tensor imaging data using color cast of color-encoded fractional anisotropy images

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ABSTRACT

Diffusion tensor imaging (DTI) data often suffer from artifacts caused by motion. These artifacts are especially severe in DTI data from infants, and implementing tight quality controls is therefore imperative for DTI studies of infants. Currently, routine procedures for quality assurance of DTI data involve the slice-wise visual inspection of color-encoded, fractional anisotropy (CFA) images. Such procedures often yield inconsistent results across different data sets, across different operators who are examining those data sets, and sometimes even across time when the same operator inspects the same data set on two different occasions. We propose a more consistent, reliable, and effective method to evaluate the quality of CFA images automatically using their *color cast*, which is calculated on the distribution statistics of the 2D histogram in the color space as defined by the International Commission on Illumination (CIE) on *lightness and a and b* (LAB) for the color-opponent dimensions (also known as the CIELAB color space) of the images. Experimental results using DTI data acquired from neonates verified that this proposed method is rapid and accurate. The method thus provides a new tool for real-time quality assurance for DTI data.

1. Introduction

Diffusion tensor imaging (DTI) has become a useful tool for noninvasive study of tissue organization in the brain. It provides insights on various aspects of tissue organization based on the property of local anisotropic diffusion of water molecules in the living tissue. Diffusion anisotropy is modeled by estimating a diffusion tensor at each spatial location in the brain from a series of measures from diffusion-weighted images (DWIs). The DWIs are acquired by applying diffusion gradients along many non-collinear orientations in 3D space. Signal differences across DWIs acquired under differing diffusion gradients are assumed to derive from the diffusion of water. By fitting a diffusion tensor to the observed measurements using a linear least squares method, the principal direction of the tensor is expected to reflect the direction of local diffusion of these water molecules. Various useful diffusion anisotropy indices (DAIs), such as fractional anisotropy (FA) [1], ellipsoidal area ratio (EAR) [2], and mean diffusivity (MD), each characterizing a different aspect of tissue organization, can subsequently be derived from the calculated tensor.

However, DWI data often suffer from artifacts. Some are caused by "physiological noise," such as cardiac pulsation, some are from "system-related artifacts," such as thermal radio frequency noise and distortions induced by eddy currents [3], and some are from head movements. Erroneous DWI measures resulting from these artifacts introduce errors into the estimation of diffusion tensors and the indices calculated from them, thereby undermining the validity of inferences about tissue organization. Sometimes artifacts are not visually perceptible but will propagate nevertheless throughout the entire data analytic stream. Therefore, detecting and removing corrupted images and outliers are important steps in maintaining the quality of the imaging data, the validity of the findings, and the physiological inferences based on them.

Various methods have been proposed to prevent corruption of DTI data during acquisition. The use of parallel imaging to support a full k-space acquisition of data can reduce vibration artifacts [4]. The navigator technique is also used to detect and correct motion in DTI data [5-7]. External devices have also been developed to track and correct head motion [8-11]. These techniques may provide very precise motion information down to the micrometer scale. Landmarks, typically markers attached to the skin or bite bars, are also used to track bulk head motion, but that requires complicated setup and additional computational time. Consequently, these methods are

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not always practical to implement, and they do not obviate the need for quality control of the DTI data once acquired.

Post-processing techniques can help to improve data quality retrospectively, by detecting and then removing or correcting outliers in the imaging data. Ding and Gore [12] developed a technique of anisotropic smoothing for reducing noise in DTI data. This extended the traditional method for filtering anisotropic diffusion images by allowing isotropic smoothing within homogeneous regions and anisotropic smoothing along structure boundaries. Hasan [13] proposed a theoretical framework for quality control and parameter optimization in DTI. This approach is based on the analytical error propagation of the MD obtained directly from the DWI data acquired using rotationally invariant and uniformly distributed icosahedral encoding schemes. Moreover, error propagation of the cylindrical tensor model has been further extrapolated to spherical tensor cases (diffusion anisotropy close to 0) in order to analytically relate the precision error in FA to the mean diffusion-to-noise ratio. Mangin and Poupon [14] presented a method to correct distortion and robustly estimate diffusion tensors. The distortion correction relies on maximizing mutual information to estimate the three parameters of a geometric distortion model based on the basic physics of DTI data acquisition. In order to reduce outlier-related artifacts, Mangin et al. used the Geman-McLure M-estimator instead of the standard least squares method for tensor estimation. Chang et al. [15] proposed an approach for robust tensor estimation by rejecting outliers. This regression-based method iteratively reweights least squares to identify potential outliers and subsequently excludes them during tensor estimation. Liu et al. [16] presented a full DWI preprocessing framework for automatic DWI quality control. They used the normalized correlation between successive slices and across all the diffusion gradients to screen for artifacts. Dubois and Poupo [17] proposed a method to generate a schema of diffusion gradient orientations that allow the diffusion tensor to be reconstructed from partial clinical DTI data sets. A general energy-minimization electrostatic model was also developed in which the interactions between orientations are weighted according to their temporal order during acquisition. Jiang et al. [18] proposed an outlier detection method for DTI by testing the consistency in the apparent diffusion coefficient (ADC). The detection criterion uses the smoothness of the fitted surface of the peanut-shaped ADC directional profile. Error maps are then created based on this criterion and a cluster analysis is performed on the error maps. The potential outliers are excluded from subsequent tensor fitting process. Zhou et al. [19] proposed an automated approach to artifact detection and removal for improved tensor estimation in motion-corrupted DTI data sets using a combination of local binary patterns and 2D partial least squares. Rohde et al. [10] proposed a comprehensive approach for correction of motion and distortion in DTI. This approach uses a mutual information-based registration technique and a spatial transformation model which contains parameters that correct for eddy current-induced image distortion as well as rigid body motion in three dimensions. Liu et al. [20] also proposed an improvement over the iterative cross-correlation algorithm [21] for correcting eddy-current-induced distortion in DWI data by pre-excluding cerebrospinal fluid (CSF) from the DWI data to maximize mutual information between DWI and baseline imaging data. Lauzon et al. [22,23] proposed a parallel processing pipeline for quantitative quality control of MRI data using DTI as an experimental test case. Assessment of variance and bias in DTI contrasts was implemented by modern statistical methods (wild bootstrap and SIMEX). The final quality of DTI data was assessed by FA power calculation.

Despite the progress in detecting DTI data outliers or artifacts, most of these approaches emphasize only on outlier detection and robust tensor estimation, while they fail to provide a definite and quantitative measure for the quality of DTI data. For example, some of these approaches have shown that the percentage of definiteness of the tensors increased with implementation of the post-processing algorithm, but whether the tensors thus estimated were correct or not remained unclear. Therefore, the questions of how to evaluate the effectiveness of these post-processing algorithms and how to assess the quality of the estimated tensor remain open issues. In this paper we propose an efficient and automated method for assessing the quality of DTI data. We focus primarily on the efficacy of assessing the quality of DTI data using color-encoded fractional anisotropy (CFA) images, which we believe will form the basis for a supplemental tool to automatically evaluate the quality of DTI data in real time, during data acquisition.

2. Methods

2.1. Motivation

FA images provide information only on the magnitude, and not the direction, of diffusion anisotropy at each location in the brain. Without this directional information, motion-corrupted data can generate FA maps that appear nearly normal (e.g., Fig. 1b). Maps of color-encoded direction (e.g., CFA), however, retain directional information because they are constructed explicitly to encode, with color, the spatial direction of each tensor's primary eigenvector. Our lab uses red to encode diffusion along *x*-axis, green along the *y*-axis, and blue along the *z*-axis, following the coordinate-system in an image volume (Fig. 1a). Diffusion along a particular direction is thus shown as a mixture of the three color elements corresponding to the *x*, *y*, and *z* components. Therefore, assessing the color scheme in a CFA image can provide information regarding possible subject motion, because, in general, their motion produces a signal change in the relevant DWI volume along the given measuring direction of diffusion gradient (if they are not perpendicular to each other), as the signal directly reflects the diffusion of the water molecules in the tissue, which is also motion and contributes to the estimation of the tensor's spatial orientation. The presence of a tint affecting the entire image is termed a *color cast*. For example, a red cast in Fig. 1a, green in Fig. 1e, and blue in Fig. 1i suggests the possible presence of motion. Difference in CFA images for motion-corrupted and motion-free DTI data—i.e., a color cast—can serve as a metric for assessing the quality of DTI data.

In practice, the quality of DTI data is often assessed after tensor estimation by inspecting the CFA image visually on a slice-wise basis [16,19], which is inherently subjective, time-consuming, and unreliable across different data sets and observers. Assuring the quality of DTI data in real time using an objective and automated approach is therefore important to prevent errors from propagating to subsequent steps of processing and data analysis. This is especially important for imaging data from populations that tend to move frequently, such as infants and neuropsychiatric patients with tics.

2.2. Detecting color cast in CFA images

We hypothesize that if tensor estimation suffers from motion artifact in the DWI data, CFA images calculated from the estimated tensors will be color cast. We know that the color space, as defined by the *International Commission on Illumination* (CIE) on lightness and a and b (*LAB*) for the color-opponent dimensions (also known as CIELAB color space) [24], is perceptually uniform and can effectively quantify color differences as seen by human eyes. We thus map the RGB values of a CFA image into CIELAB space [25,26] and then examines a 2D histogram formed by considering only the a and b color aspects of the image to assess image quality [27]. For a motion-free CFA image, its 2D histogram generally contains clustered peaks

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