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Original contribution

A novel DTI-QA tool: Automated metric extraction exploiting the sphericity of an agar filled phantom

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ABSTRACT

Purpose: To develop a quality assurance (QA) tool (acquisition guidelines and automated processing) for diffusion tensor imaging (DTI) data using a common agar-based phantom used for fMRI QA. The goal is to produce a comprehensive set of automated, sensitive and robust QA metrics.
Methods: A readily available agar phantom was scanned with and without parallel imaging reconstruction. Other scanning parameters were matched to the human scans. A central slab made up of either a thick slice or an average of a few slices, was extracted and all processing was performed on that image. The proposed QA relies on the creation of two ROIs for processing: (i) a preset central circular region of interest (ccROI) and (ii) a signal mask for all images in the dataset. The ccROI enables computation of average signal for SNR calculations as well as average FA values. The production of the signal masks enables automated measurements of eddy current and B0 inhomogeneity induced distortions by exploiting the sphericity of the phantom. Also, the signal masks allow automated background localization to assess levels of Nyquist ghosting.
Results: The proposed DTI-QA was shown to produce eleven metrics which are robust yet sensitive to image quality changes within site and differences across sites. It can be performed in a reasonable amount of scan time (~15 min) and the code for automated processing has been made publicly available.
Conclusions: A novel DTI-QA tool has been proposed. It has been applied successfully on data from several scanners/platforms. The novelty lies in the exploitation of the sphericity of the phantom for distortion measurements. Other novel contributions are: the computation of an SNR value per gradient direction for the diffusion weighted images (DWIs) and an SNR value per non-DWI, an automated background detection for the Nyquist ghosting measurement and an error metric reflecting the contribution of EPI instability to the eddy current induced shape changes observed for DWIs.

1. Introduction

Diffusion tensor imaging (DTI) is demanding on MRI scanner hardware due to fast switching gradients required for fast imaging (i.e., echo-planar imaging, EPI) combined with strong diffusion sensitizing gradients to produce diffusion-weighted images (DWIs). As with all quantitative methods, the accuracy and sensitivity of the DTI metrics rely on good image quality. Furthermore, a large dataset is produced, made up of more than one non-diffusion weighted image, nDWI, and a large number of gradient directions (typically ≥30). This precludes visual inspection as a reliable form of monitoring the scanner performance. For these reasons, an automated, DTI-specific, phantom-based quality assurance protocol (QA) is of upmost importance both to track changes in performance at a given site as well as to assess inter-site differences in performance for multisite studies.

Due to the high incidence of image quality issues, it has become common practice to manually inspect and discard "bad" DTI images before computing DTI metrics, such as fractional anisotropy (FA) and apparent diffusion coefficient (ADC). However, the sporadic nature of many artifacts and the DTI data redundancy make such manual inspection tedious and unreliable. To mitigate these inconsistent practices, some DTI processing tools incorporate automated image rejection and

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distortion correction [1–3]. Because distortions are inevitable in EPI-based DTI data, all processing pipelines involve some form of distortion correction which can be accomplished using a variety of tools such as *FUGUE* and *eddy* [4] in FSL (FMRIB Software Library, Oxford, UK) [5]. Although necessary, these distortion correction tools may mask artifacts and hide scanner issues as they arise. Most quality control efforts focus on subject-specific in vivo effects and in many cases, the quality assurance/control is integrated with the DTI processing pipelines such as DTI studio [2], DTIprep [6], TORTOISE [1] and the work of Lauzon et al. [7]. However, the variable effectiveness of these methods at correcting image quality issues introduces another source of variability in DTI data [8]. Previous automated phantom-based QA approaches have focused primarily on the ability of the diffusion sensitizing gradients to perform as expected, measuring accuracy, repeatability and precision of ADC/FA measurements in a variety of isotropic phantoms. These methods offer gradient calibration routines [9] and other calibration metrics for multicentre studies [10–12]. Here, we present a phantom-based, automated quality assurance (QA) tool which incorporates both the assessment of artifacts and distortions present in DTI data, while measuring the performance of the diffusion sensitizing gradients as well. It is fast and simple and it can be used on a standardized spherical agar phantom.

To the best of our knowledge, only two similar DTI-QA protocols have been previously proposed [13,14]. Our approach is novel in three ways: (i) we produce similar DTI-QA metrics as previous studies but all are computed in a different way. In particular, our approach to distortion measurements is very different from that used in either previous DTI-QA protocol. We use a different phantom than Wang et al. [13] and hence do not have internal structures. Although we use the same agar phantom as Zhou et al. [14], we measure the distortions due to eddy currents and B0 inhomogeneity (not measured by ref. [14]) by exploiting the sphericity of the phantom. (ii) The image processing required to compute the metrics is fully automated and made publicly available. (iii) We expand the outcome metrics to capture the effects of parallel imaging (PAR) by scanning the phantom with and without PAR, as well as scanner stability *within* DTI scan time (e.g., SNR across nDWIs and SNR across DWIs) which indirectly measures the gradient performance; these were not available in either previous DTI-QA. This QA produces eleven relevant metrics that represent a comprehensive assessment of DTI data quality.

The focus of ref. [14] is on longitudinal HARDI (high angular resolution diffusion imaging) data quality for a multicentre trial. The metrics we propose can also be tracked in time, across sites and within site, following the criteria presented by Zhou et al. [14]. Therefore, this paper does not focus on the longitudinal aspect of the QA but rather on how the expanded set of metrics are computed, and what those metrics reflect, at a given time point, across scanners. The goal is to produce automated, sensitive and robust QA metrics. The code for the required processing is available for general use at https://github.com/josephdviviano/qa-dti. The output of the code is described in more details in the discussion.

2. Materials and methods

This DTI-QA was developed for purposes of intra- and inter-site monitoring in a multisite study called 'SPINS' which comprises three sites with different 3 T MRI scanners of different vendors/models. The sites are the Centre for Addiction and Mental Health (CMH, Toronto, CA), the Maryland Psychiatric Research Centre (MRC, Maryland) and the Zucker-Hillside Hospital (ZHH, NY) with the following 3T MRI scanners respectively: GE MR750 (GE Healthcare, WI), Siemens Trio (Siemens Medical Solutions, Erlangen, Germany) and GE HDx. For the GE sites, the 'dual spin echo' option was used [15] to minimize eddy currents as per human scans and the 8-channel head coil was used. For the Siemens site, a 12-channel head coil was used.

2.1. Phantom and image acquisition

The FBIRN (Function Biomedical Informatics Research Network) agar-filled phantom [16,17] is used for several reasons: (i) it is smaller (diameter = 17.5 cm) and more manageable than the ACR phantom so it fits in more head coils (ii) it allows for better consistency because of the agar; there is no need to wait for the liquid to settle, there will be no moving air bubbles and it is less prone to vibrational effects (iii) the diffusion in agar as well as the relaxation parameters (T1, T2) and RF load mimic the brain better than an aqueous phantom. Although the agar phantom diffusivity is expected to be a little higher than that in brain tissue (1.5×10^{-3} mm^2/s vs 0.5–1.4 $\times 10^{-3}$ mm^2/s) [14], we propose the use of this standard phantom because it has been used for many years in fMRI QA protocols [17] and has been shown to be temporally stable in diffusion measures (FA) as well spatially uniform [14]. It can be ordered from FBIRN so it is made in one location, following a consistent recipe and protocol, minimizing variability in production across sites. As for all phantom-based diffusion acquisitions, temperature is a possible source of contrast change because some scan parameters and diffusion are temperature dependent. For this reason, the temperature of the phantom is tracked and it is stored in a place with consistent temperature to ensure minimal variation within a given site; temperature may be a common source of inter-site differences which can be monitored.

The image acquisition parameters should match what is being run on subjects at the site to best capture the hardware/software performance at the given site. In particular, the b-value, the set of diffusion sensitizing gradient directions as well as the number of phase encode (PE) steps should match that used on brain scans because these values determine the size of the diffusion-sensitizing gradients and how they are played out. We can reduce the repetition time (TR) because a large value ($\gg$T1) is used for DTI in order to fit the number of slices required to cover the entire brain within one TR. For the purpose of this QA, we do not require full phantom coverage so we reduce the number of slices and shorten TR to the minimum. Although some signal loss is expected, we balance the need for good SNR with the need for a short scan time.

Due to the rather large b-value required for human scanning and the decrease in TR, a single central phantom slice may not have sufficient signal to perform the following QA reliably. In particular, the measurements that require well-defined edges of the phantom relative to the surrounding may be compromised, depending on the coil. The signal loss can be compensated for by either increasing the slice thickness or averaging over a few central slices. These operations will increase the absolute value of the signal without altering distortions or any other relative measures of interest: e.g., SNR of DWI relative to nDWI. As long as the same number of slices and slice thickness is used across different sites, the resulting values will be comparable across sites as well. The following calculations will be done on this central average slab, herein referred to as "the image". All QA metrics presented are derived from a set of such images, each one representing either a nDWI or the DWI for a particular diffusion direction. The number of nDWIs and DWIs will be denoted by N_0 and N_{DWI} respectively. For the SPINS multisite study, the following scan parameters were consistent across sites: TE/TR = Minimum Full/2000 ms, slice thickness 4 mm, 2 mm in-plane resolution (FOV = 25.6 cm, Nx $\times$ Ny = 128 $\times$ 128), 7 slices, $N_0 = 5$, $N_{DWI} = 60$ (same directions at all sites) and b = 1000 s/mm^2. The total scan time is kept below 15 min at all sites.

We propose to run the DTI-QA scan twice, once with no parallel imaging reconstruction (nPAR) and once *with* PAR (ASSET/iPAT factor 2). The changes in SNR and distortions can be used to assess the effectiveness of the PAR setting which is commonly used on all subject scans due to possible improvements to both of these measures. It is noteworthy to mention that there is a discrepancy across vendors in the implementation of PAR acquisitions: only for some cases PAR allows a reduction in minimum TE which results in signal recovery that can compensate for the reduction of data collection [18]. For other platforms, the