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Investigating the need of triggering the acquisition for infant diffusion MRI: A quantitative study including bootstrap statistics

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ABSTRACT

Diffusion weighted magnetic resonance imaging is increasingly being used for neonatal and young pediatric subjects. Our purpose was to investigate a) whether cardiac triggering was needed to reduce variability of diffusion (tensor) imaging data, b) how pulsation artifacts affect the fitted diffusion tensor when triggering is not used and c) the feasibility of triggered data acquisition in neonates and young children.

Data were collected from 11 infants and 7 adults. In seven infants and seven adults, diffusion encoding was applied solely along the z gradient direction with and without cardiac triggering. Non-parametric bootstrap statistical methods were applied to investigate the dependence of variance on triggering. One infant and all adults served as test–retest controls. From the remaining three infants diffusion tensor imaging data were acquired with and without triggering.

Our findings that used the repeated measurements in a single diffusion-encoding direction indicated that without triggering the variability in the data was increased significantly both in infants and adults. When collecting diffusion tensor data in infants, this increased variability results in erroneous fractional anisotropy values and artifactual fiber direction estimates. Contrary to previous reports but supported by our findings involving adults, pulsation artifacts were present in a larger extent of the brain in the infant population.

In conclusion, triggering is feasible in young subjects and is preferred when acquiring diffusion MRI data. In doing so, the amount of erroneous estimations due to image artifacts will be minimized, which in turn will lead to more specific and less ambiguous interpretations. Although fitting the pulse-monitoring device requires additional set-up time, the total imaging time is usually shorter than acquiring multiple data sets to compile a single, artifact-free set.

Introduction

Magnetic resonance imaging (MRI) is increasingly being used for neonatal and young pediatric subjects (Barkovich et al., 1988; Rutherford, 2002; Woodward et al., 2006). Often the examination protocol includes diffusion-weighted imaging (DWI) (Le Bihan et al., 1986) to examine the white matter microstructure both in normal development (Lebel et al., 2008; Miller et al., 2003; Mukherjee et al., 2002; Neil et al., 1998) and in injured states (Huppi et al., 1998, 2001; Rutherford et al., 1991; van der Aa et al., 2011). However, diffusion weighted images (DWIs) are susceptible to several types of image artifacts which can be divided depending on whether the source is systematic or physiological (Tournier et al., 2011). Often, these artifacts are signal drop-outs (Fig. 1 and Video 1) and may occur due to cardiac pulsation (Wirestam et al., 1996). It has been shown in adults that pulse- or cardiac triggering (henceforth referred to as 'triggering' for brevity) improves the quality of diffusion-weighted data acquisition (Dietrich et al., 2000; Skare and Andersson, 2001).

Imaging neonatal subjects is extremely challenging because an awake baby will not stay still. Also, the heart rate of the newborns and young children can be consistently 120–160 beats/min (bpm) allowing little time for imaging between the heartbeats. Fitting sensors to detect heartbeats can also take precious examination time. For these reasons diffusion-weighted imaging of neonatal subjects usually proceeds without triggering.

For diffusion tensor imaging (DTI) the DWIs are usually collected along several non-collinear directions and used to estimate the apparent diffusion coefficient (ADC) (Le Bihan et al., 1986), diffusion anisotropy, e.g. fractional anisotropy (FA) (Basser and Pierpaoli, 1996), other measures of anisotropy (e.g., Frank, 2001), or carry out fiber tractography (Behrens et al., 2003; Conturo et al., 1999; Jeurissen et al., 2011; Jones

Abbreviations: ADC, apparent diffusion coefficient; bpm, beats/min; DTI, diffusion tensor imaging; DWI, diffusion-weighted imaging/diffusion weighted image; ECG, electrocardiogram; FA, fractional anisotropy; FOV, field of view; MRI, magnetic resonance imaging; NLLS, non-linear least squares fit; OLLS, ordinary linear least squares fit; (i)RESTORE, (informed) robust estimation of tensors by outlier rejection; SENSE, sensitivity encoding; SNR, signal-to-noise ratio; TR, repetition time; WLLS, weighted linear least squares fit.

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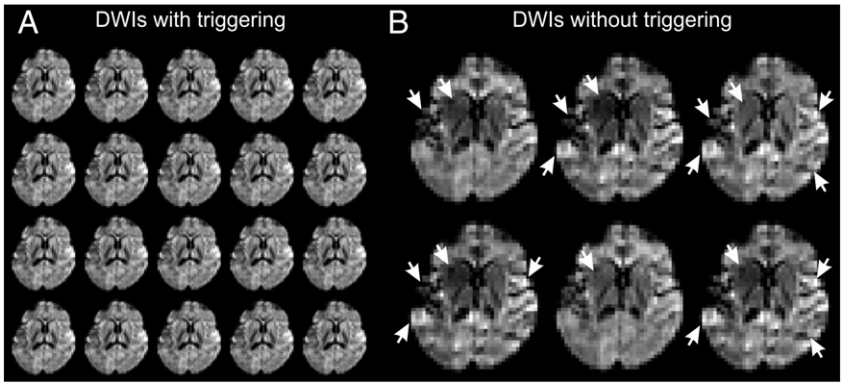

Fig. 1. The effect of triggering. Representative DWIs from a single slice of one subject (4.8 months, male). For the triggered series all 20 images are shown, for the non-triggered series only images with the largest differences are shown as examples. Intensity scaling is arbitrary, but constant across images shown. (A) Demonstration of triggered acquisition resulting in low volume-to-volume variance with 20 consecutive images without artifacts. (B) Without triggering the volume-to-volume variance increases resulting in visible positive and negative differences in signal intensities. Six representative examples are shown with the most prominent artifacts marked with arrows (altogether 10 out of 20 consecutive images showed some artifacts).

et al., 1999; Mori et al., 1999). If motion induced signal reduction results in an overestimation of the ADC along one or more diffusion encoding directions, the 3-dimensional diffusion profile, along with the above-mentioned measures (e.g. FA), will be estimated inaccurately. In addition to the erroneous estimation of the diffusion properties in a given individual, these biases can propagate to group level comparisons (Chung et al., 2010; Zhu et al., 2009) if, by chance, the images of one group suffer more pulsation artifacts than the images of the other group.

The aims of this paper were to (a) examine the presence and extent of pulsation artifacts in DWIs collected from young pediatric subjects; (b) investigate the effect of pulsation artifacts on the estimated diffusion measures; and (c) test feasibility of triggered acquisition in this patient group.

Patients and methods

Subjects

Fifteen young children and infants were involved (age range 1–13 months, 10 girls, 1 preterm girl), each of which was in need of a clinical MRI examination. With the approval of the local ethics committee and after written informed consent of a parent, the clinical scanning session was supplemented with one of two acquisition protocols (described below). Additionally, twelve young adults (age: 23.3 ± 2.3 years, 3 females) were scanned with the approval of the local ethics committee and after written informed consent, to provide comparative adult data. All of the collected MRI data were first visually checked by at least one of two of the co-authors (L.R.K., Z.N.) for gross subject motion artifacts. Four infants (3 girls) and 5 adults (1 female) were excluded from further analysis due to excessive movement, thus we only report the results obtained on the remaining 11 infants and 7 adults (see Table 1 for details).

Data acquisition

All images were collected on a 3 T Achieva Scanner (Philips Medical Systems, Best, The Netherlands) using an 8-channel receive-only head coil. According to local guidelines, the infants were sedated by qualified anesthesiologists using intra-venous propofol. The partial pressure of O_2 and the heart rate of the subjects were constantly monitored during the sedation. The adult volunteers were scanned awake and without sedation. The vector electrocardiograph available on the Philips MRI scanners was fitted before the examination and used for monitoring the electrocardiogram (ECG) and for triggering.

Table 1
Description of infants and adults involved.

		Age (months)	Sex	Start HR (bpm)	b-value	Reason for exam	Actual finding
Bootstrap (infant)	#1	4.8	M	146	1000	Orbital tumor	Normal
	#2	5.1	F	170	800	Epilepsy	Normal
	#3	7.8	F	121	800	Obstructive hydrocephalus	No obstruction
	#4	6.0	F	122	800	Ewing sarcoma	Progression
	#5	9.6	M	125	800	Oseomyelitis	Improvement
	#6	8.6	F	123	800	Hemiparesis	Left periventricular cyst, white matter loss
	#7	8.6	M	120	800	Orbital tumor	Bone metastasis of neuroblastoma
	#8	1.1	F	160	1000	Congenital malformation	Stroke
DTI	#9	10.1	F	132	800	Neuroblastoma follow-up	No progression
	#10	9.3	M	135	800	Neuroblastoma follow-up	Normal
	#11	13.3	F	137	800	Synovial sarcoma follow-up	Normal
		Age (years)	Sex	Start HR (bpm)	b-value	Reason for exam	Actual finding
Bootstrap (adult)	#1	21.3	M	85	1000	N/A	N/A
	#2	21.9	M	70	1000	N/A	N/A
	#3	22.4	F	70	1000	N/A	N/A
	#4	21.4	M	80	1000	N/A	N/A
	#5	26.9	M	70	1000	N/A	N/A
	#6	27.9	F	60	1000	N/A	N/A
	#7	24.9	M	70	1000	N/A	N/A