A SHORT-TE COMPUTED DIFFUSION IMAGING (CDWI)

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Target Audience: Researchers and clinicians who are interested in body DWI imaging for tumor or neurography.

Purpose: A technique named computed diffusion imaging (cDWI), allowing to provide high b-value (b) equivalent DWI images using relatively low b DWI images, was proposed and applied as a useful technique for improving contrast between tumors and the background tissue especially in body diffusion imaging, compared to actually measured DWI (mDWI) with high b [1-3]. Since the clinically available DWI sequence has relatively longer TE (80-100ms) to give b=500~1000 s/mm^2 necessary for cDWI, the base (b0) image is basically T2-weighted. Thus, it is difficult to suppress longer T2 components such as water or CSF signals without using relatively high b, and thus T2 shine-through effects is sometimes problematic. The purpose of this study was to propose a short-TE cDWI technique to solve those problems by increasing the CNR for short T2 and low ADC tissues, and to assess for phantom and volunteer.

Methods: The spin echo (SE)-based mDWI signal intensity at TE and b for tissue of T2 and ADC is denoted by using arbitrary coefficient k as:

$S(TE,b)=k*\exp[-TE/T2]*\exp[-b*ADC]$ ---- (1).

In this study, following three cDWI methods were compared.

A) *Same-TE cDWI* [1-3]: By using 2-points aDWI signals at the same TE, TE_2 and different b-value ($b_1<b_2$). ADC image is obtained by:

$ADC=-\ln[S_2(TE_2,b_2)/S_1(TE_2,b_1)]/(b_2-b_1)$ ---- (2).

The cDWI image of the same TE=TE$_2$ at $b=b_c$ is obtained using the ADC as

$S_c(TE_2,b_c)=S_1(TE_2,b_1)*\exp[-(b_c-b_1)ADC]$ ---- (3).

B) *Short-TE cDWI*: cDWI image of $TE=TE_1$ ($TE_1<TE_2$,) and $b=b_c$ was obtained by using 3-points by adding separately acquired $S_3(TE_1,b_1)$ instead of S_1 as:

$S_c(TE_1,b_c)=S_3(TE_1,b_1)*\exp[-(b_c-b_1)ADC]$ ---- (4)

C) *Zero-TE cDWI*: After additionally calculating T2 by

$1/T2=-\ln[S_1(TE_2,b_1)/S_3(TE_1,b_1)]/(TE_2-TE_1)$ ----- (5),

$S_c(TE_c,b_c)=S_3(TE_1,b_1)*\exp[-(TE_c-TE_1)/T2]*\exp[-(b_c-b_1)ADC]$ ----- (6).

By this method, cDWI images of T2-effects free (TE_c=0) becomes available.

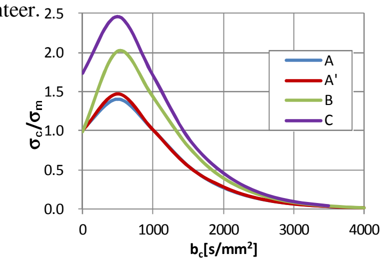

Fig. 1 Simulated noise SD ratio to mDWI vs. b-value (b_c) for several cDWI methods. Parameters were b_1=0, b_2=1000s/mm^2, TE$_1$=28ms, TE$_2$=100ms, TE$_c$=0ms, ADC=2x10^{-3} mm^2/s and T2=200ms. cDWI noise SD was increased in the order of A, A', B,and C due to noise propagation..

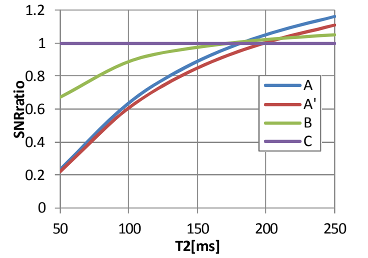

Fig. 2 Simulated SNR for several cDWI methods at b_c=2000 as a function of tissue T2. The SNR was shown by the ratio to that in the method-C (TE$_c$=0). When T2<200ms (background T2), the SNR for method-B and C were better than the method-A'. The SNRratio is independent of tissue ADC.

***Monte-Carlo simulation*:** Assuming Rician distribution of noise on the magnitude DWI signals, the mean and the SD of cDWI signals were measured after 5000 times each trial as parameters of b-value, TE, ADC, and T2 [3]. The SNR was defined as the ratio of tissue cDWI signal to the background SD. A method-A' of setting TE$_1$=100ms in equation (3) was added to compare only the noise correlation effects with the method-A. Added Gaussian noise SD for mDWI was σ_m=0.02.

***Phantom and Volunteer Study*:** A phantom including several celery, carrot, and welsh onions in doped water, and a volunteer brain axial images were assessed. Imaging was performed on 3T MR imager of ToshibaVantage Titan^{TM} 3T with a single-shot SE-EPI of b_1=0, b_2=1000s/mm^2, TE$_1$=28ms, and TE$_2$=100ms. Motion probing gradient (MPG) was applied to a direction perpendicular to the running direction of targeted fibers (vascular in celery or corpus callosum (CC)). The cDWI signals of b_c=1000 and 2000 s/mm^2 were calculated then the mean and SD in the ROI were measured. Here noise SD was measured on the phantom each water portions using the subtraction method [4] then commonly used for SNR measurements on both studies.

Results and Discussion: For simulations, the background noise SDs were increased in the order of method A,A',B,C (**Fig. 1**) reflecting the noise propagation effects; nevertheless, the SNRs for tissues were increased in the same order when the tissue T2 is shorter than the background (**Fig. 2**). For MRI experiments (phantom: **Fig. 3** and **Table 1**; brain: **Fig. 4** and **Table 2**), SNRs for vegetable or cerebral parenchyma were increased compared to the water or CSF in TE$_1$=28ms (method-B) than the TE$_2$=100ms (method-A) among the same b-value cDWI images, and the method-C was better than the method-B except for the water. The CNRs for the fiber portions (celery vascular, carrot cortex, or CC in brain)-to-background were enhanced and T2 shine-thorough effects in water or CSF were reduced in short-TE cDWI images. Although the new methods requires 3 points images, it allows to provide T2-effects reduced (ADC dominant) DWI images, in addition to ADC and T2 maps. Instead of acquiring the third image, S$_3$ in method-B, routinely acquired short-TE FSE images can also be applied.

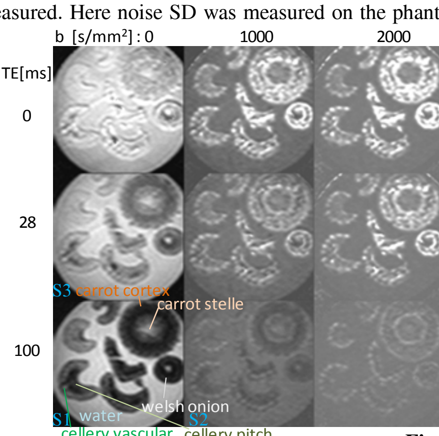

Fig. 3 Resulting Phantom images
MPG direction is R-L. Note that fiber (vascular) signals were enhanced in short-TE high b-value cDWI images.

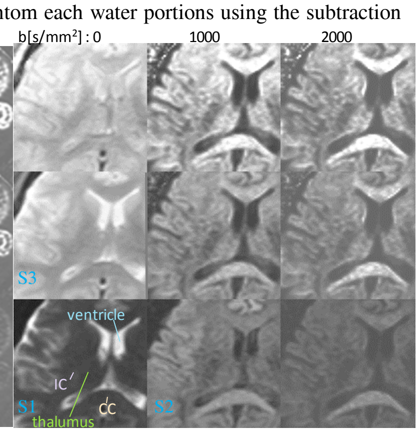

Fig.4 Resulting volunteer brain images
MPG direction is H-F. Note that the contrast of CC (corpus callosum) to background tissues was better in short-TE cDWI images, and CSF signals shown in (TE,b)=(100,1000) (red arrow) were reduced in short-TE cDWI images even at b_c=1000 s/mm^2.

Conclusion: Our proposed cDWI techniques are useful for improving CNRs for shorter T2 tissues with low ADC, compared to the conventional same-TE method; and thus expected to be clinically useful for enhancing neuronal fibers (neurography) or short-T2 tumors.

References: [1] *Blackledge MD et al. Radiology: 261,573-581(2011)*; [2]*Ueno et al. Eur Radiol 23,3509-16 (2013)*; [3]*Kimura T et al., Proc. of 20th ISMRM (2012), pp3574*; [4] *Miyati T et al. Proc. SPIE 6142, 61423o1-7*;

Table 1 Phantom results of SNR and CNR to water for different portions.

(TE[ms], b[s/mm^2])	SNR=S/noiseSD					CNR to water				noiseSD
	water	celery		carrot		celery		carrot		water
		vascular	pitch	cortex	stele	vascular	pitch	cortex	stele	
$S_c(0,0)$	45.5	73.1	55.3	52.4	58.6	27.60	9.84	6.98	13.15	6.16
C: $S_c(0,1000)$	7.4	50.7	22.7	28.3	17.5	43.26	15.27	20.86	10.09	4.42
C: $S_c(0,2000)$	3.9	116.3	32.1	52.2	16.7	112.47	28.25	48.27	12.87	1.00
$S_3(28,0)$	65.1	79.0	50.1	45.0	70.7	13.91	-14.97	-20.03	5.66	4.24
B: Sc(28,1000)	7.6	35.6	14.4	17.2	15.1	28.03	6.79	9.65	7.49	4.27
B: Sc(28,2000)	4.1	76.8	19.6	25.8	16.8	72.70	15.53	21.69	12.70	0.99
$S_1(100,0)$	60.8	37.4	15.0	11.9	43.3	-23.37	-45.78	-48.90	-17.49	4.36
$S_2(100,1000)$	7.9	17.1	4.6	5.0	10.2	9.25	-3.29	-2.89	2.38	3.94
A: Sc(100,2000)	4.0	34.4	5.8	8.5	9.4	30.45	1.82	4.49	5.42	0.93
ADCx10^{-3}[mm^2/s]	2.15	0.88	1.29	0.97	1.54	0.88	1.29	0.97	1.54	-
T2 [ms]	1738	100	61	55	155	100	61	55	155	-
A, B, C: cDWI method; S_1,S_2,S_3: measured data, Sc: cDWI data										

Table 2 Brain results of SNR and CNR to thalamus for different portions.

(TE[ms], b[s/mm^2])	SNR=S/noiseSD(water)				CNR to thalamus	
	thalamus	CC	IC	ventricle	CC	ventricle
$S_c(0,0)$	46.1	40.8	37.9	51.1	-5.4	5.0
C: $S_c(0,1000)$	36.4	48.9	16.6	9.7	12.4	-26.7
C: $S_c(0,2000)$	93.7	188.6	24.7	15.4	94.9	-78.2
$S_3(28,0)$	41.7	37.9	37.5	65.3	-3.8	23.6
B: Sc(28,1000)	23.2	32.3	11.7	7.4	9.1	-15.8
B: Sc(28,2000)	58.1	120.2	16.8	10.1	62.1	-48.0
$S_1(100,0)$	12.1	11.8	13.8	49.4	-0.3	37.2
$S_2(100,1000)$	7.4	11.2	4.7	4.3	3.8	-3.1
A: Sc(100,2000)	18.0	40.6	6.6	3.9	22.6	-14.1
ADCx10^{-3}[mm^2/s]	0.60	0.16	1.17	2.55	0.16	2.55
T2 [ms]	60	63	74	284	63	284
CC: corpus callosum, IC: internal capsule						