Dual-Echo Gradient Echo (DEGE) Phase Contrast (PC) Imaging for High Temporal Resolution Flow Studies in Flow Phantom, Aneurysm Models and In vivo Human Carotid Artery

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OBJECTIVES

Two flow-sensitized images, each in a separate sequence repetition, are acquired in conventional PC imaging. This and the addition of flow sensitizing gradients more than double the pulse sequence length, reducing the temporal resolution of cine flow quantification. High temporal resolution is important particularly for hemodynamic studies in structures such as intracranial aneurysms. In this study, a dual-echo gradient echo cine PC imaging was developed for in-plane flow quantification with high temporal resolution. Its feasibility was examined in experiments (i) using a sinusoidal flow phantom, (ii) in anthropomorphic intracranial aneurysm models of middle cerebral artery (MCA) and basilar artery (BA) tip aneurysm and finally, (iii) in in vivo human carotid artery.

METHODS AND MATERIALS

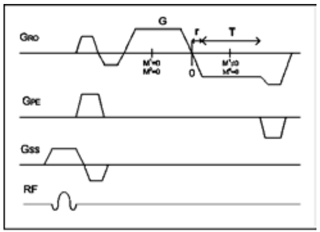

Figure 1. DEGE PC pulse sequence diagram.

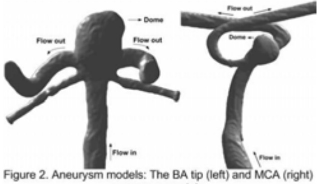

Figure 2. Aneurysm models: The BA tip (left) and MCA (right) aneurysm models

Two phase images were acquired from two echoes in a single pulse sequence (Fig. 1). The first echo was motion-compensated while the second echo was flow-encoded. Subtraction of the two phase images produced velocity-encoded phases mixed with phase evolution between the two echo times. Further subtraction between two cardiac phases removed this phase evolution and an average velocity during the cardiac cycle as well. This average velocity was estimated rapidly by running in a few seconds, an un-gated standard PC sequence with identical geometric scan parameters. The first gradient moment, M^1 was achieved by changing a receiver bandwidth and the read-out resolution instead of having additional flow-sensitizing gradients. A similar scheme, so-called gradient inversion has been reported to encode flow velocity (1, 2). In this study, v_{enc} was calculated from the following two equations, [1] $v_{enc}\,(cm/\sec) = \frac{1174.43}{\Delta M^1\,(\frac{mT}{m} m\sec^2)}$ and [2] $M^1 = G(\frac{1}{4}T^2 + Tr + \frac{2}{3}r^2)$. Eqn. [2] could be further revised into the direct relationship between M^1 and the scan parameters, [3] $M^1 = \frac{1}{\gamma\delta_{RO}}(\frac{1}{4bw} + \frac{r_{\min}bw}{\gamma\delta_{RO}} + \frac{2r_{\min}^2 bw^3}{3(\gamma\delta_{RO})^2})$ where, bw is a receiver bandwidth per pixel, δ_{RO} is a pixel size along the read-out direction and r_{min} is a gradient minimum rise time. All experiments were performed on a 1.5 T MR scanner (Avanto, Siemens). 1 Hz sinusoidal flow was imaged using body and spine array coils with 3mm slice thickness (sl thk), TE1/TE2/TR=3.63/5.46/8.3ms, 220x220mm FOV, 256x256 matrix, 20^0 FA, 675Hz/pixel BW, v_{enc} =80 cm/sec, and 3 views/segment (VPS). Two anthropomorphic aneurysm models were created from 3D CT angiography obtained from patients with intracranial aneurysms (Fig. 2: volume rendered 3D images). These models have been previously used for laser Doppler velocimetry (3). 1 Hz physiologic pulsatile flow was generated using a computer-controlled pump system and delivered into the models. The aneurysm models were then imaged with 3mm sl thk, TE1/TE2/TR= 3.8/6.22/11ms, 150x150mm FOV, 192x192 matrix, 20^0 FA, 490 Hz/pixel BW, v_{enc} = 60 cm/sec, and 3 VPS. Human carotid artery was also scanned using neck and head coils with 3mm sl thk, TE1/TE2/TR= 3.32/5.15/9.7ms, 200x200mm FOV, 192x192 matrix, 20^0 FA, 650 Hz/pixel BW, 3 VPS, and v_{enc} = 100 cm/sec for IS direction. Identical parameters were used for AP direction except: TE1/TE2/TR= 4.39/6.48/9.7ms, 192x384 matrix, 620 Hz/pixel BW and v_{enc} = 40 cm/sec. The images obtained from both the directions were reconstructed into 384x384 matrices for in-plane flow quantifications after zero-padding in the k-space. To evaluate performance of the proposed sequence, standard PC imaging has been performed with similar scan parameters for each experiment.

RESULTS AND DISCUSSIONS

Fig. 3 shows comparison of in-plane velocity measurements of the sinusoidal flow. The DEGE PC showed overall velocity difference of 1.8 cm/sec compared to standard PC with more than 3 times higher temporal resolution. Two measurements were highly correlated with the coefficient number of 97.2 %. Studies in the aneurysm models showed high correlation with standard PC (>90%). Fig. 4 shows in plane velocity measurements performed at common carotid artery (CCA). The DEGE PC showed 2.4 times higher temporal resolution with 89.1 % correlated with standard PC. Overall velocity difference between the two sequences was 3.62 cm/sec. DEGE PC showed about twice higher standard deviation than standard one. Phase image of DEGE PC (left bottom of Fig. 5) shows successful removal of background phase variation while manifesting velocity-encoded phase at the carotid artery. Fig. 6 shows flow path visualization superimposed onto the magnitude image calculated from velocity-encoded phase images along IS and AP directions. It demonstrated that DEGE PC imaging successfully tracked flow path using point velocities measured at each cardiac frame.

CONCLUSION

Dual-echo gradient echo PC sequence successfully quantified in plane flow velocity with 2~3 times higher temporal resolution, with flow values in good agreement with standard PC imaging. Its feasibility was examined on the sinusoidal flow phantom, in vivo human carotid artery and anthropomorphic aneurysm model studies. This high temporal resolution DEGE PC imaging may be useful in velocity quantifications studies in structures with complex and less steady flows.

REFERENCES [1] Grinstead et al, MRM 2006;54:138-145. [2] Markl et al, MRM 2003;49:945-952 [3] Tateshima et al, Stroke 2003;34:187-192.

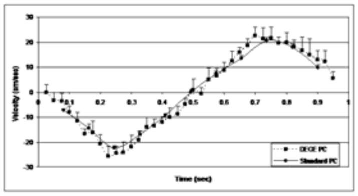

Figure 3. In-plane velocity measurements of a sinusoidal flow phantom

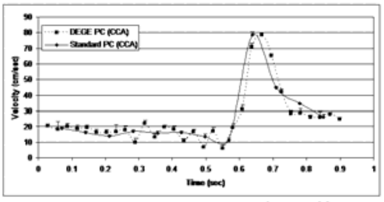

Figure 4. In-plane velocity measurements performed at CCA

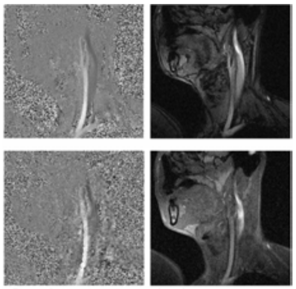

Figure 5. Magnitude images (right) and phase images (left) from DEGE PC (bottom) and the standard PC (bop).

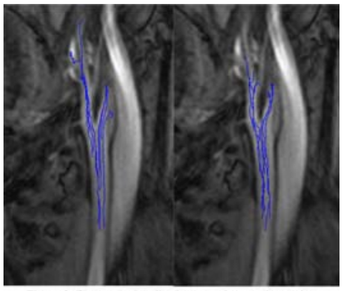

Figure 6. Flow path visualization superimposed onto the magnitude image: the standard PC (left) and DEGE PC (right)