Eddy Currents in MT Asymmetry Imaging with Alternate Ascending/Descending Directional Navigation (ALADDIN)

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Introduction : Even after active shielding of gradient coils and programming gradient pre-emphasis, small residual eddy currents (typically < 1%) may negatively affect some imaging sequences such as diffusion-weighted imaging [1] and balanced steady state free precession (bSSFP) [2]. Recently a new imaging technique, alternate ascending/descending directional navigation (ALADDIN), was developed and used for perfusion-weighted (PW) imaging [3] and also magnetization transfer (MT) asymmetry imaging [4]. The ALADDIN technique sensitizes interslice blood flow (perfusion) and MT effects induced in 2D sequential multislice acquisitions without requiring a separate ratio frequency (RF) pulse for spin preparation. The ALADDIN PW and MT asymmetry imaging techniques share a common data acquisition process but require two separate data reconstruction methods that result in two distinctive ALADDIN image sets. However, these two ALADDIN image sets may not be uniquely determined when the MR gradient system is interfered by eddy currents. A bSSFP sequence has been used for ALADDIN, in which the gradient is balanced (i.e., null zero-th moment) along each of the three directions. The phase encoding gradient, which is balanced between the positive and negative intensities within each period of time to repeat (TR), induces little eddy currents with the linear phase-encode (PE) order [2]. On the other hand, intensities of the positive and negative portions for the slice-select and readout gradients are not equal, thereby inducing eddy currents that are constant across multiple TR periods. Although contributions of these slice-select and readout eddy currents to conventional bSSFP imaging are negligible [2], they may generate mismatched MT frequencies leading to residual signals in the subtraction images of ALADDIN. In this study, we investigated the effects of eddy currents on ALADDIN signals and proposed a new acquisition scheme that can suppress eddy current induced errors.

Material and Methods : All experiments were performed on a 3T whole body scanner (Siemens Medical Solutions, Erlangen, Germany) with a body coil transmission and a 12-element head matrix coil reception. Three normal male volunteers were scanned in this IRB-approved study.

ALADDIN MT asymmetry images [4] were acquired on a distilled water phantom (no MT), 4% agarose phantom (symmetric MT), and *in vivo* brain and skeletal muscle (asymmetric MT). For eddy current suppression, we acquired four datasets from alternating ascending/descending acquisitions and positive/negative slice-select gradients using positive readout gradient followed by the same four data acquisitions using negative readout gradient. The same acquisition of these 8 datasets was repeated once (total 16 repetitions). Imaging parameters were flip angle = 50°, matrix size = 128 × 128, FOV = 230 × 230 mm^2, thickness = 5 mm, gap = 7 mm, scan direction = axial, PE order = linear, PE direction = anterior-posterior, delay time between repetitions = ~4 sec, and scan time per dataset = ~4 min. To test the effect of readout eddy current, we varied TR (from 3.76 ms to 4.18 ms with increment of ~0.05 ms) and acquisition BW (from 698 Hz to 528 Hz with decrement of ~19 Hz). The echo time was set to the half of the TR value in each case. Datasets were reconstructed as percent signal changes (PSC) between datasets of positive and negative MT frequencies [4]. ROI analysis was performed in a region covering 90% of signal regions for phantom and a whole white matter region manually segmented from the center slice.

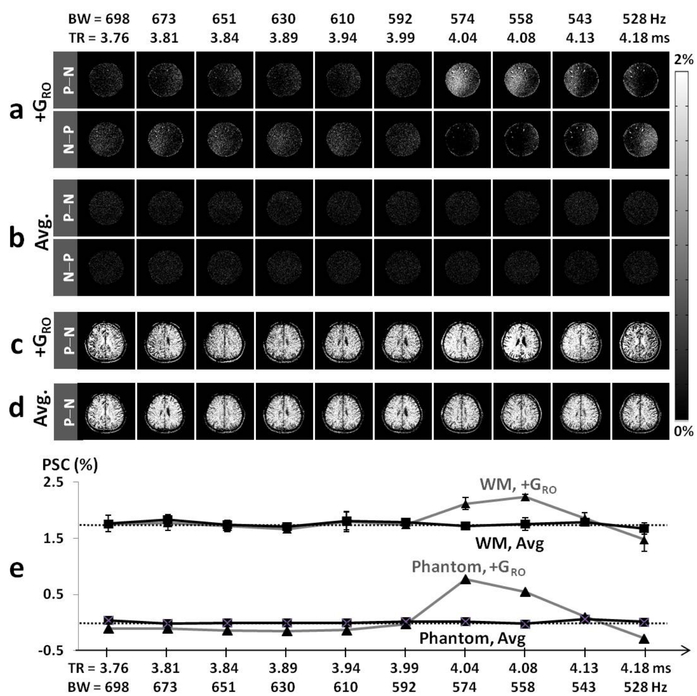

FIG. 1. Experimental results for TR-dependent studies performed on phantom (**a**,**b**) and human brain (**c**,**d**) and their region of interest analyses (**e**). The "+G_{RO}" and "Avg." represent datasets acquired with positive readout gradient only and with positive and negative readout gradients averaged, respectively

Results and Discussion : Figure 1a shows the TR-dependent ALADDIN signals acquired for the agarose phantom. When only the positive readout gradient was used (+G_{RO}), residual signals were detectable in MT asymmetry images (Fig. 1a). Within the tested TR range, the residual signals became negative or positive depending on TR values and sometimes the polarities were mixed within a slice varying along the readout direction (e.g. second column from the right in Fig. 1a), presumably due to the spatially varying frequency offsets from the first order readout eddy current. Overall the residual signals were stronger at lower TR values, presumably due to increased discrepancy between positive and negative gradients along the readout direction. With the new acquisition scheme (Avg.), the residual signals were suppressed independent of TR values and spatial locations (Fig. 1b,e). When the TR-dependent study was applied to human brain, the signal modulation as a function of TR was similar to that of the agarose phantom (Fig. 1c,e). The MT asymmetry signals varied less with TR by using the new averaging scheme (Fig. 1d,e). In human brain, MT asymmetry signals in WM were ~1.8%, which was higher than those from the agarose phantom (~0%) (Fig. 1e). Unlike the agarose phantom and human brain, the distilled water phantom showed no signal or signal changes as a function of TR, confirming that all the signal modulations in Fig. 1 are associated with MT effects and gradient system imperfections.

Under our experimental conditions, the strengths of the readout gradient and the readout dephasing gradient were ~0.78 G/cm and −2.73 G/cm, respectively, yielding summation of 1.95 G/cm. A long-term readout eddy current of 0.3% (i.e., 0.0059 G/cm) would induce a frequency offset of 249 Hz (corresponding to 2.0 ppm at 3T) at a position of 10 cm offset from the isocenter. According to a previous study (Fig. 1b in the reference [5]), the slope of the tangential line for the MT-induced longitudinal magnetization (M_0=1) versus saturation offset frequency is about 0.1 per 40 ppm (i.e., 0.25% of signal change per ppm) at a 30-ppm frequency offset and 1.0-μT saturation power, which were close to our experimental conditions. This indicates that the frequency deviation of 2.0 ppm may induce signal changes of about 0.5%, comparable to maximal PSC variations along the readout direction (horizontal) within a slice (e.g. the second image from the right in Fig. 1c).

All the experimental results and the theoretical calculations indicate that readout eddy currents induces deviations in MT frequencies causing artifactual signals in ALADDIN MT asymmetry images, which can be suppressed by averaging over alternating readout gradient polarities. More extensive studies are necessary to understand MT effects of bSSFP in consideration of the periodic off-resonance responses of bSSFP.

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