INTRODUCTION – Images obtained with gradient-echo echo planar imaging (GRE-EPI) suffer from magnetic field variations within the brain, such as in regions adjacent to air-tissue interfaces. In these regions, magnetic field inhomogeneities cause spins to dephase more rapidly, resulting in signal dropouts. Thus, conventional GRE-EPI pulse sequences used for dynamic susceptibility-contrast perfusion-weighted imaging (DSC-PWI) or blood oxygenation-dependent functional MRI (BOLD-fMRI) usually confine image analysis to homogeneous brain regions. Compensation mechanisms based on z-shimming (originally proposed in [1]) apply additional field gradients prior to repeated signal readouts of the same imaging plane, with the drawbacks of prolonging scan time ([2],[3]) or increasing image distortions ([4],[5]). Extending PERMEATE [6], a multi-echo EPI pulse sequence developed for DSC-perfusion quantification, z-shimming gradients were added prior to the first and second echo train, to restore $T_2^*$-related signal dropouts in the first echo train, while maintaining regular contrast for the following echo trains. Using this technique, functional brain activity could be successfully detected in typical dropout regions close to the auditory canals in a breath-holding fMRI experiment [7], therefore facilitating whole-brain EPI-based BOLD-fMRI with unchanged acquisition time and low spatial image distortions due to parallel imaging accelerated acquisition. In this study, we propose adding a similar z-shimming approach to a combined gradient-echo/spin-echo (GRE-/SE-) EPI sequence [8], in which each EPI train is preceded by different z-shim gradients (see Fig. 1) in order to restore susceptibility-induced signal-dropouts and facilitate full-brain coverage in combined gradient- and spin-echo measurements, for application in DSC-PWI and fMRI.

METHODS – Fig. 1 shows the pulse sequence design used for the present study. Following an $\alpha$-$\beta$ pulse combination to form a Hahn spin echo ($\alpha = 90^\circ$, $\beta = 180^\circ$), a spin-echo signal is sampled by an EPI readout train at $T_E$GRE. Additional gradient-echo readouts acquired at $T_E$GRE and $T_E$GRE fit into the time between the $90^\circ$ and $180^\circ$ pulse, combined gradient-echo/spin-echo readouts measured at $T_E$GRE and $T_E$GRE were placed between the $180^\circ$ pulse and the spin-echo readout at $T_E$GRE. Individual z-shim gradients $G_{\text{zshim}}$ were added prior to each gradient-echo EPI readout train. In order to acquire four gradient-echo EPI trains followed by a spin-echo signal at $T_E$GRE = 100 ms ($\approx T_2$ of gray matter), a parallel imaging reduction factor of $R = 3$ and an in-plane resolution of $84 \times 84$ voxels were used on our 3T system with gradient strength = 50 mT/m and gradient slew rate = 200 T/m/s. The experiments were carried out using the following acquisition parameters: $TR = 2000$ ms, $T_E$GRE = 14.6, 37.0, 65.6, 84.1 ms, $FOV = 24$ cm, slice thickness = 3 mm, number of slices = 16. Z-shimming gradients $G_{\text{zshim},1-4}$ in the present version of the pulse sequence can be adjusted so that $G_{\text{zshim}2}$ compensates for $G_{\text{zshim}1}$, and $G_{\text{zshim}3}$ compensates for $G_{\text{zshim}2}$. Thus, EPI trains 2 and 4 were acquired on-resonance, while EPI trains 1 and 3 were acquired at different off-resonance settings in order to correct for susceptibility-induced off-resonance effects.

RESULTS – Fig. 2 shows the results achieved in a female volunteer using the abovementioned acquisition parameters and z-shimming values of $G_{\text{zshim}1} = -G_{\text{zshim}2} = -0.75 \cdot G_{\text{GRP}}$ and $G_{\text{zshim}3} = -G_{\text{zshim}4} = 0.75 \cdot G_{\text{GRP}}$, with $G_{\text{GRP}}$ the slice-selective refocusing gradient. Square-root-sum-of-squares images were produced from the gradient-echo EPI trains (Fig. 2a-b) as well as from combined gradient-echo/spin-echo EPI trains (Fig. 2c-d). Fig. 2e shows the spin-echo image acquired at $T_E$GRE.

DISCUSSION – Signal dropouts caused by susceptibility effects could be compensated for in the square-root-sum-of-squares images (Fig. 2f-g) in areas close to the ear canals as well as above the nasal cavities, therefore approaching the spin-echo image in terms of signal dropouts. The presented technique is particularly promising for applications in functional imaging, with the possibility to simultaneously acquire a GRE-signal, a combined GRE/SE-signal, as well as a SE-signal, all of them with minimal signal dropouts. Multi-echo simultaneous GRE- and SE-EPI acquisitions with z-shimming benefit from reduced signal contributions from large vessels in order to increase signal specificity through SE-EPI readout, while increased sensitivity in typical signal dropout regions can be achieved in the GRE-EPI readouts. Together, a powerful tool for BOLD-fMRI and DSC-PWI is presented with minimal signal dropout artifacts, and fast image acquisition in order to achieve the high temporal resolution necessary for functional imaging.