Integrated parallel reception, excitation, and shimming (iPRES) with split DC loops for improved B0 shimming

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Introduction: MRI image quality is dependent on the homogeneity of the main magnetic field, B_0. Traditionally, B_0 inhomogeneities are corrected by using whole-body spherical harmonic shim coils. However, such coils are located far from the subject and are typically limited to the 2nd or 3rd order, so that they cannot effectively correct for localized B_0 inhomogeneities, such as those induced by susceptibility differences at air/tissue interfaces. To address this limitation, a novel technique, termed integrated parallel reception, excitation, and shimming (iPRES), has recently been proposed[1-3]. It uses a new coil design that allows an RF current and a direct current (DC) to flow in the same coil simultaneously, thereby enabling parallel RF excitation/reception and B_0 shimming with a single coil array. Such an integrated RF/shim coil array can be placed close to the subject to maximize both the signal-to-noise ratio (SNR) and shimming performance. In vivo human experiments have demonstrated that the iPRES coil array can provide a much more effective local B_0 shimming and EPI distortion correction than conventional spherical harmonic shim coils, in particular in the frontal brain region, which suffers from large susceptibility-induced B_0 inhomogeneities. The B_0 root-mean-square error (RMSE) in that region was reduced by 60% with iPRES.

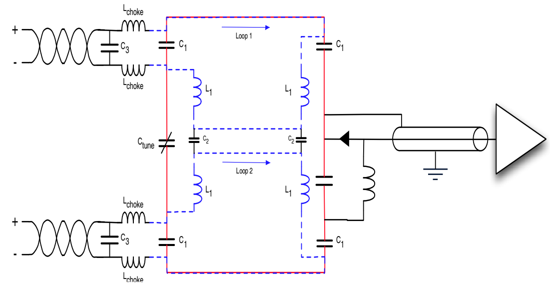

Figure 1. Schematic of an iPRES(2) RF/shim coil (red: RF-isolated path, blue: two independent DC shim loops).

A limitation of the current iPRES implementation, however, is that each DC shim loop is constrained to have essentially the same size and geometry as the RF coil element onto which it is integrated. As a result, localized B_0 inhomogeneities with spatial variations smaller than the size of the RF coil element cannot be fully corrected. Here, we propose to address this lack of spatial resolution by increasing the number of independent magnetic fields available for B_0 shimming within each RF coil element. Specifically, the original RF coil is split into multiple smaller DC loops, each of which uses an independent DC current to generate different magnetic fields, while maintaining the SNR of the RF coil. The higher number of degrees of freedom and spatial resolution for B_0 shimming offered by the additional DC loops can provide a more effective shimming of localized B_0 inhomogeneities than the original iPRES design. The modified integrated RF/shim coil design with additional DC loops is termed iPRES(N), where N represents the number of split DC loops within each RF coil. The advantages of the iPRES(N) approach are demonstrated in the following proof-of-concept experiments.

Methods: Experiments were performed on a GE MR750 3T scanner. A single RF coil elements of a GE 32-channel head coil array was modified to have an iPRES(2) (2-loop) design (**Fig. 1**). Each DC loop was driven by its own DC power supply. Inductor and capacitor values were chosen to ensure RF isolation from the DC supplies and maintain the Q factor of the RF coil (C_1 = 1000 pF, $C_2 = C_3$ = 100 pF, $L_1 = L_{choke}$ = 1.2 μH).

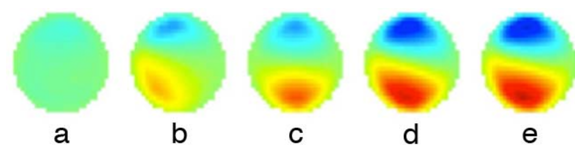

Figure 2. B_0 maps with no DC current (a), with 0.9 A applied to each DC loop separately (b,c), and with 0.9 A applied to both DC loops simultaneously (d). (e) sum of (b) and (c).

A first experiment was performed to demonstrate the ability of the iPRES(2) coil to simultaneously perform RF reception and generate two independent B_0 fields from the two split DC loops. A spherical phantom was positioned such that it was aligned with the center of one of the DC loops, while the other one was slightly left. Coronal B_0 maps were acquired using a multi-echo gradient-echo sequence (TR = 530 ms, TE = 1.5, …, 11.2 ms, voxel size = 4x4x4 mm) with a 0.9 A DC current applied to each loop separately or to both loops simultaneously (**Fig. 2**).

A second experiment was conducted to demonstrate that the iPRES(2) coil can perform B_0 shimming and correct for geometric distortions more effectively than the original single-loop iPRES(1) design. To induce localized B_0 inhomogeneities, two additional RF-isolated DC perturbation loops were inserted between the phantom and the iPRES(2) coil. DC currents of +0.9 A and -0.9 A were applied to each perturbation loop to produce asymmetric B_0 inhomogeneities across the RF coil. Using the iPRES(2) coil, a B_0 map was acquired with the perturbation applied, but no DC currents in the split DC loops. Next, two basis B_0 maps were acquired with 0.9 A applied to each split DC loop separately, but no perturbation. The optimal DC currents to apply to the split DC loops were determined by minimizing the RMSE between the perturbation B_0 map and a linear combination of the basis B_0 maps. The iPRES(2) coil was then modified into an iPRES(1) coil. Using this iPRES(1) coil, a B_0 map was acquired with the perturbation applied, but no DC current in the single DC loop. Next, a basis B_0 map was acquired with 0.9 A applied to the single DC loop, but no perturbation. The optimal DC current to apply to the single DC loop was then computed by minimizing the RMSE between the perturbation B_0 map and the basis B_0 map. Spin-echo EPI images were also acquired using the iPRES(2) or iPRES(1) coil with no perturbation, with the perturbation applied, and with the perturbation corrected (TR = 2 s, TE = 30 ms, FOV = 25.6 cm, matrix size = 128x128, slice thickness = 4 mm) (**Fig. 3**).

Results: **Figs. 2b** and **2c** show that the iPRES(2) coil can generate two independent and spatially distinct B_0 fields from the two split DC loops. **Figs. 2d** and **2e** further show that these B_0 fields are additive, as expected.

Fig. 3 shows that when the perturbation is applied, the EPI images acquired with either the iPRES(2) or iPRES(1) coil are stretched on the left and compressed on the right because of the asymmetric B_0 inhomogeneities (**Fig. 3**, middle). These distortions are greatly reduced when shimming with the iPRES(2) coil (circled region in **Fig. 3**, top right), but not with the iPRES(1) coil (**Fig. 3**, bottom right), as expected. The B_0 RMSE was reduced by 25% with the iPRES(2) coil, but only by 1% with the iPRES(1) coil.

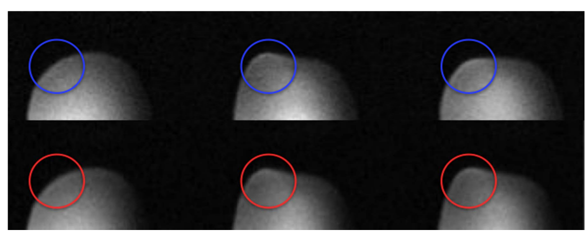

Figure 3. EPI Images acquired using the iPRES(2) (top) or iPRES(1) (bottom) coil, with no perturbation (left), with the perturbation applied (middle), and with the perturbation corrected (right).

Discussion: Both the EPI images and B_0 RSME reduction demonstrate that the iPRES(2) coil can provide a more effective shimming of localized B_0 inhomogeneities than the single-loop iPRES(1) coil due to the larger number of degrees of freedom (DC loops) and ability to achieve a more flexible spatial control of the magnetic field used for shimming. Even though there are still residual distortions in the EPI images after shimming with the iPRES(2) coil, because these proof-of-concept experiments were only performed with a single coil rather than a coil array, the results nevertheless demonstrate the advantages of this new design. Implementing the iPRES(2), or more generally iPRES(N), design into each coil element of a coil array (e.g., a 32-channel head coil array) is straightforward and will enable an even more effective B_0 shimming of localized B_0 inhomogeneities than an equivalent iPRES(1) coil array.

Conclusion: Our initial results demonstrate that the novel iPRES(N) design can greatly improve the shimming performance of the original single-loop iPRES(1) design, while maintaining its RF performance, by increasing the number of degrees of freedom and spatial resolution for B_0 shimming.

References: 1. Han H et al. MRM 2013:70:241-247 2. Truong TK et al. Neuroimage 2014;103:235-240. 3. Stockmann JP et al. Proc. ISMRM 22, 400.