Non-Linear Correction of 3D R2* Maps with Fast through-Plane Gradient Mapping Computation

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Target audience: MR physicists and researchers interested in MRI methodology

Introduction

In 3D gradient echo (GRE) imaging, strong macroscopic B0 field gradients (Gr) are observed at air/tissue interfaces and in the presence of metallic objects. In particular at low spatial resolution, the respective field gradients lead to an apparent increase in the intravoxel dephasing [1,2] and subsequently to signal loss or inaccurate R2* estimates [3]. If Gr is measured [5] their influence can be removed in post processing [1]. Proposed correction strategies usually assume a linear phase evolution with time [1]. However, for large Gr, [>~ 40 Hz/cm] e.g. near the edge of the brain, the para-nasal sinus and temporal lobes, this assumption is often broken [2,3], Moreover, when relying on central difference approximation for field gradient estimates from the in-plane gradients, remaining artifacts are observed after correction [1-3,7]. Existing solutions based on field map extrapolation beyond the air/tissue interfaces [2] or including the through plane gradients have been demonstrated to improve the field characterization, but may still lead to inaccurate field estimates and are computational expensive. In this work, we explore a model that considers a non-linear dependence of the phase evolution with echo time in the presence of strong Gr [3] and allows a fast estimate of a more accurate field map. We tested the performance of the model for correction of artifacts at large Gr in phantom and in vivo field map and R2* computations.

Materials and methods

The measured signal decay ($S_m(t)$) is a product of the true decay (S(t)) and the signal loss F(t) due to $B0_{macro}$. Standard approaches assume the phase evolution is linear, and that a 3D-linear-Sinc-correction (LSC) [1] adequately describes F (t). However, it has been demonstrated that in the presence of large $B0_{macro}$ the linear phase evolution becomes inaccurate [2-3]. Consequently, we describe the phase evolution as combination of a linear term and an error term: $\varphi(TE_N, r) = \Delta\varphi(TE, r) + \aleph(TE, r)$ [Eq.1], suggesting the need of a non-linear sinc correction [3] when the error term becomes dominant. We noted that the error term is characterized by a phase dispersion, which in analogy to random walk theory [8] can be described as follows: $< \varphi_n(TE, r)^2 > = N \cdot (\Delta\varphi_{n,TE1}(TE1, r)^2) = N \cdot (\gamma \cdot r \cdot Gr(r)_n \cdot TE1)^2$ [eq.2]. For small gradient fields Gr(r), the phase error term becomes negligible and the linear approximation is sufficient. On the other hand, when the error term becomes significant, the accuracy of any correction will critically dependent on a proper estimation of the phase error term that is defined by the intravoxel Gr field gradient. Another limitation of existing approaches [1-2,7] is that they rely on the central difference approximation by considering only in-plane gradients. The $Gr(r)_n = \frac{B0_{n+1} - B0_{n-1}}{2\Delta r}$ where is the field map at the nth voxel and Δr is the spatial resolution. Including the through plane gradients results in a more accurate estimate that, however, is usually not applied due to significantly increased computational burden. To speed up the through plane gradient computation, instead of computing the gradients in the through ortho-normal direction $e\overrightarrow{xy}$, $e\overrightarrow{xz}$, $e\overrightarrow{yz}$ with additional loops and conditions within the computation, we compute their nearest neighbor projections on the main orthonormal vector $\overrightarrow{ex}$, $\overrightarrow{ey}$ and $\overrightarrow{ez}$. This allows computing the additional through plane gradient without any additional computation time compared to recently proposed solutions [1-2].We assessed the performance of our method (improved 3D gradient map approximation and non-linear model for phase evolution) by comparing with the conventional approach (in-plane field map based on central finite difference) in vivo (14 healthy subjects) and on a phantom containing 5 spheres of $MnCI_2$.All scans were performed at 3T (Magnetom Trio, Siemens AG, Healthcare Sector, Erlangen, Germany) using a 3D-GRE sequence (TR/TE/ESP=47/1.23/1.23 ms, 1.6 mm isotropic). For phantom an in vivo scans.17 and 32 echoes were acquired, respectively. A weighted field map was computed from the phase images, and the nonlinear phase correction was performed [3] offline using customized Matlab scripts (Mathworks, USA).

Results and discussion

Inclusion of the through plane terms when approximating the gradient field leads to a strong reduction of artifacts near the edges and a decrease of the amplitude of the field estimation around the air bubbles in the phantom [red arrows Fig.1 A-B]. Similarly, in vivo we observe reduced field gradient estimations near the para-nasal sinus, around the cingulate region (arrow) and temporal lobe [fig.1 C-D]. In general, inclusion of through plane terms reduces the computed intravoxel field gradient in regions of strong Gr. This means that gradient field based corrections that rely on the conventional in-plane intravoxel gradient approximation is resulting in e.g. inaccurate R2* estimations in particular in regions near the sinus and brain interfaces [Fig.1 (E-F)].

Conclusion

The proposed method to compute the intravoxel gradient as combination of in plane and through plane gradients, based on the through plane projection into the in plane direction provides a more accurate gradient approximation with greater robustness to edge artifacts. The computed gradient map can be used directly to correct the effect of macroscopic field inhomogeneities on the computation of quantitative R2* maps without any thresholding [3] or additional iterative estimation [4-5] or extra computing time.

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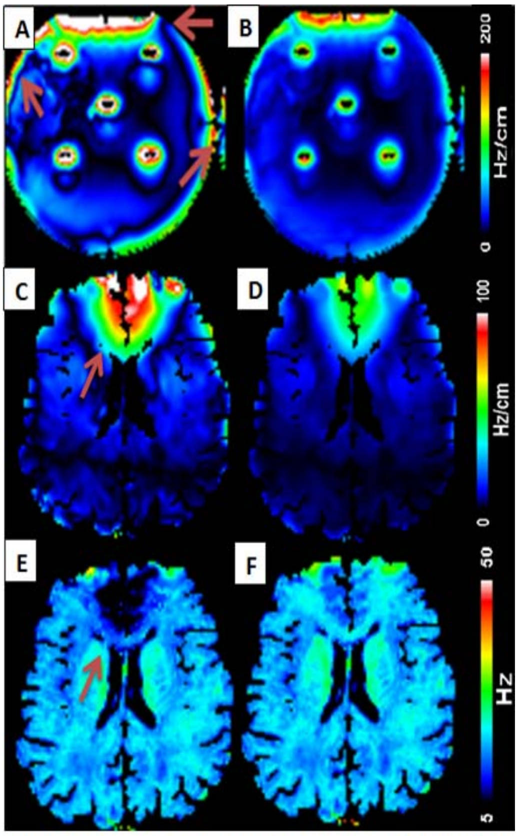

Fig.1: (A&B) (C&D) Conventional and through plane gradient maps for phantom and in-vivo DATA. (E&F)R2* maps corrected with(C&D) respectively

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