FDTD Calculations of Induced E-field in a Cylindrical Z-gradient Coil

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Abstract
To study the E-field induced by the rapid time change of magnetic gradient fields, we present the use of Finite Difference Time Domain (FDTD) method for numerically calculating the E-field inside a cylindrical shielded z-gradient coil. We show that the calculated Bz-field agrees well with that from the static analysis. The results from a cylindrical body model are consistent with the results in quasi-static limit analysis. Initial results indicate that the FDTD method can be used with complex human body models to illustrate relative [E] field characteristics.

Introduction
It is known that rapidly switched magnetic MRI gradient fields can cause nerve stimulation in the body. This nerve stimulation is the act of an induced electric field inside of body tissues associated with a time-varying magnetic field. Direct calculation of the induced E-field is complicated by the complex interactions between the body tissues and fields. The finite element method has been implemented to make such calculations for simple coil and body geometries [1]. Recently, Bowtell, et. al. gave an analytical expression to allow direct calculation of E-field for a conducting cylindrical phantom in a quasi-static limit [2]. Here we demonstrate the use of FDTD method to estimate gradient coil B and E fields inside a human body model. Previously the FDTD method has been used in calculating Bz and SAR for RF coils [3].

Methods
A short shielded z-gradient coil was modeled using a XFDTD software package (Remcom, Inc., State College, PA) with 5mm isotropic resolution. The z-gradient has 60 turns of primary coil, and 40 turns of secondary coil, with the inner diameter of 0.702m, outer diameter of 0.850m, and shield length of 1.217m. All turns were driven individually for the simplicity of the simulation. User defined linearly increased current sources (I(t) = tZ,) were applied to ramp up the gradient field with the slew rate of 64T/m/sec and d/τ = 0.887A/msec. Transient solutions were run up to the time t' (t' < t). Bz was then re-scaled to the field at t' = 400A, corresponding to a gradient strength of 28.9mT/m. Since E is proportional to time rate of change of B, E approach constant after some running time and there is no need to re-scale it.

Results
Fig. 1 shows the comparison of the calculated Bz in r = 0.0m and 0.285m between the FDTD method and the static analytical method. For z < 0.3m close to the center of the z-gradient coil, the two results are almost the same. For z > 0.3m, there are small deviations. This error is due to rounding of coil z positions to 5mm to fit one cell and the small number of empty boundary cells. The overall error is below 5%, indicating good agreement. Fig. 2 shows the magnitude of the E-field in the x = 0 plane for a cylindrical body phantom (σ = 0.2 S/m, εr = 78, r = 0.2m, and L = 1.22m), and a human body model with 23 distinct tissue types (σ and εr values are set at f = 2.3kHz [4]). For the cylindrical phantom, in the x = 0 plane, E3 is anti-symmetric about both y-axis and z-axis, Er and Eb are at least two-orders smaller than Es close to zero. This is consistent with the quasi-static analytical results in Ref [2]. The peak |E| is at position r = 0.2m and z = 0.37m, with the value of 2.0 V/m. For the human body model, the chest is in the middle of the z-gradient. For this position of the model patient there are relatively larger |E|-field distributed in the region above the stomach, in the lower part of spine, and some part of the hips. The values of |E| will change with different tissue σ and εr. The artifact of discrete gaps in the human body model affects the results to some degree. Fig. 3 shows the transverse plane at z = 0.4m (hip region). It can be seen that the body model's hands touch the abdominal region. This causes a relatively large |E| in the gap between hands and torso. An artificial gap in the bottom also causes a relatively large local |E|. However, since the tangential component of E-field is dominant, averaging E around the peripheral region of the torso in the transverse plane gives |E| = 1.2 V/m.

Discussion
We have shown that FDTD method can be used to calculate the induced E-field inside gradient coils, regardless of the complex structure of the loadings. There are some errors in the calculation compared to the static analysis. This can be seen in the leakage of |E| at both edges of z-gradient coils (Fig. 2). Increasing the mesh resolution and introducing additional empty boundary cells at the expense of CPU running time can reduce this error. Here we presented the results for a z-gradient coil. The same method can be applied for x-gradient, or y-gradient, or their combination. The FDTD method can also be used in transient eddy current analysis. One limitation of this approach is that dispersive media effects are not taken into account. Also, there are artifacts from the discretization effects of the model, particularly where gaps are created. However, it may prove useful in a relative vs. absolute sense in comparing different gradient designs.

References