# Towards Direct B1 Based Local SAR Estimation

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**Introduction:** Safety regulations specified by the International Electrotechnical Commission [1] require the local specific absorption rate (SAR) in the human head to remain under 10W/Kg averaged over 10g of volume for more than 10 min. The distributions of electrical conductivities, of volumetric mass densities and of electric field amplitudes are essential for the local SAR estimation. Numerical simulations [2] such as the Finite Difference Time Domain (FDTD) must be employed to estimate local SAR distributions. However, it may take up to several days to estimate the electric fields in complex loads such as in anatomically accurate human heads/bodies. Furthermore, a patient-specific head/body model maybe required for estimation of local SAR in multichannel parallel transmission MRI [3,4]. Conversely, we propose to estimate the local SAR by means of closed forms derived directly from the Maxwell's equation and without requiring any human head/body model. In previous work [5], local conductivity ($\sigma$ $Sm^{-1}$) and permittivity ($\varepsilon = \varepsilon_r$ 8.85 $10^{-12}$ $CN^{-1}m^{-2}$) were computed using iterative simulations on RF-excitation ($B_1$) images based on the Method of Moments (CONCEPT II, technical university of Hamburg-Harburg). Instead of using such cumbersome iterative solution, we propose to estimate the local dielectric properties ($\sigma$, $\varepsilon_r$) in a single step by applying differential operators directly on the $B_1$ images. Furthermore, we present a closed form of the axial electric field ($|E_z|$) also calculated directly from the $B_1$ images, that will allow us to estimate the local SAR based on the assumption that in various geometries [6] the axial-component of the electric field is dominant. The proposed real-time local SAR estimation will be valuable for a patient-specific solution needed in advanced MRI systems such as the parallel transmit.

**Theory:** From Maxwell `s equations in combination with Ohms law the following relation (eq. 1) can be found using harmonic analysis ($i = \sqrt{-1}$).
Using reciprocity theory the analogue of eq. 1 is found (eq. 2) for the excitation ($B_1^+$) and receive ($B_1^-$) field [7].

1) $$-\nabla^2 H = \mu\varepsilon\omega^2 H + i\mu\sigma\omega H$$

2) $$-\nabla^2 B_1^\pm = \mu\varepsilon\omega^2 B_1^\pm \pm i\mu\sigma\omega B_1^\pm$$

For human tissues the permeability $\mu$ is approximately equal to the permeability of free space ($\mu_0 = 4\pi\ 10^{-7} N\ A^{-2}$), allowing eq. 2 to be solved in terms of $B_1^\pm$ for $\varepsilon_r$ (eq. 3), and $\sigma$ (eq. 4). Where $\Re(z)$, and $\Im(z)$ denote the real and imaginary part of z, respectively. The $|E_z|$ component of the electric field can be obtained directly from eq. 5 by substituting the found solutions for $\sigma$ and $\varepsilon_r$.

3) $$\varepsilon_r = -\Re\left(\frac{c^2\nabla^2 B_1^\pm}{\omega^2 B_1^\pm}\right)$$

5) $$|E_z| = \left|\frac{\partial_x(iB_1^{-*} - iB_1^+) - \partial_y(B_1^{-*} + B_1^+)}{\mu\sigma - i\mu\varepsilon\omega}\right|$$

4) $$\sigma = \left|\Im\left(\frac{\nabla^2 B_1^\pm}{\mu\omega B_1^\pm}\right)\right|$$

6) $$SAR = \frac{1}{2\rho}\left|\Im\left(\frac{\nabla^2 B_1^\pm}{\mu B_1^\pm}\right)\right|\left|B_1^- \frac{\partial_x(iB_1^{-*} - iB_1^+) - \partial_y(B_1^{-*} + B_1^+)}{i\nabla^2 B_1^-}\right| + \delta$$

Using the found expression for $|E_z|$ the local SAR can be estimated (eq. 6) under the assumption that $|E_z|$ dominates the electric field.

**Methods:** Simulated $B_1$ images of the human head were obtained using FDTD (XFDTD software, Remcom Inc, State Collage, PA, USA). For this purpose a 49 anatomical structures 1 $mm^3$ resolution MRI based head model [8] was used. Simulations were preformed at 300Mhz ($\omega = 2\pi\ 3\ 10^5\ s^{-1}$) using an idealized 16-element quadrature-birdcage head coil where each element was independently fed by a 1A 50Ω terminated source. [7]. Derivatives were obtained numerically using the central difference method. Errors introduced by discontinuities in the derivative were replaced by means of nearest neighbor substitution and smoothened using a Gaussian filter. All tissues were assumed to have a constant density ($\rho$) 1kg/L density.

**Results:** Based on the simulated $B_1^+$ (fig. a) the local SAR (fig. b) was calculated using eq. 6 assuming $\delta = 0$. Results were subsequently compared to the simulated $E_z$ approximation (fig. c), and the exact solution (fig. d). Difference between simulated and calculated local SAR based on the $B_1^+$ image shows a Gaussian distribution, Mean±SD, -20±19% and -30±21% (fig. e), for the $|E_z|$ approximation and $|\mathbf{E}|$ solution, respectively.

**Discussion:** We showed how local SAR information can be derived directly form $B_1$ images using a closed form solution based on the Maxwell's equations. In addition to provide patient specific head/body models with complete dielectric constants, this method has other potential applications such as in the detection of tumors [9] and other deceases based on the measured dielectric properties. This fast and straightforward closed form solution allows patient-specific local SAR calculations to be made in real-time. Further work is necessary to extend the proposed method to regions where the dominant $E_z$ approximation does not hold.

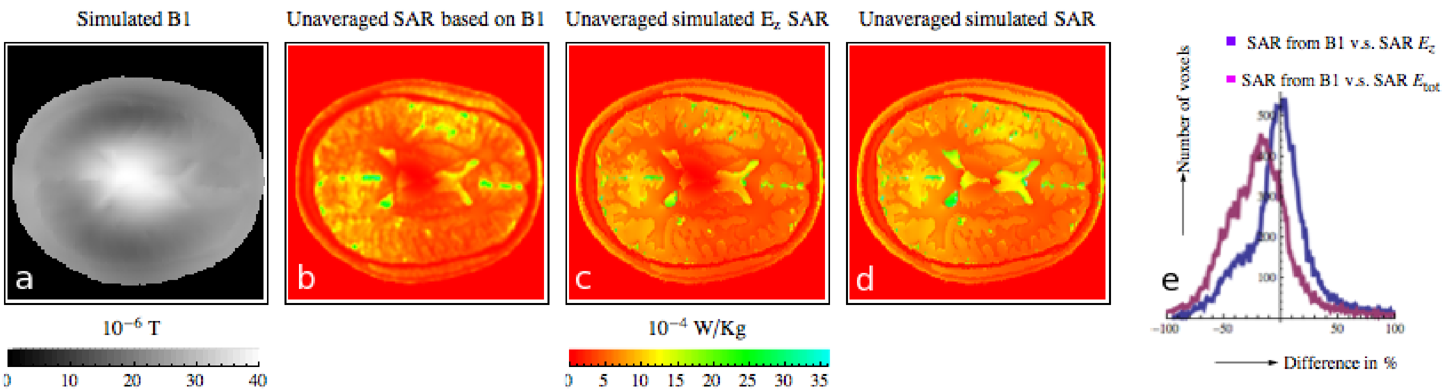


**Figure:** $B_1^+$ image and direct SAR estimation. **a)** Transverse slice of the $B_1^+$ field in the human head model. **b)** The unaveraged SAR calculated from the simulated $B_1^+$ image. **c)** The unaveraged SAR based on the dielectric properties from the head model and $|E_z|$ calculated from the simulated $B_1^+$ image. **d)** The actual unaveraged SAR as provided by the simulation. **e)** The difference between the unaveriged SAR calculated from the B1 relative to the simulated SAR based on $|E_z|$and $|\mathbf{E}|$

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**References:** [1] IEC Standard 60601-2-33, [2] Gandhi, Radio Science, Vol 30, No. 1; 161-177 (1995), [3] Sodicksonet al., Acad Radiol. Vol. 12, No.5; 626-35 (2005), [4] Zelinski et al. JMRI Vol 28, No. 4; 1005-1018 (2008), [5] Katscher et al. Proc. Intl. Soc. Mag. Reson. Med., Vol. 14, (2006), [6] Van den Bergen et al. Phys. Med. Biol., Vol. 52; 5429–5441 (2007) [7] Hoult. Concepts in Magn. Reson, Vol. 12, No. 4; 173–187 (2000), [8] Makris et al. Med. Biol. Eng. Comput., in print (2008)., [9] Joines et al. Med. Phys. Vol 21, No 4; 547-550 (1994)