An approach to Temperature-based Virtual Observation Points for Safety Assurance and Pulse Design

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Target audience: anyone interested in RF safety, temperature calculation and pulse design.

Introduction: Radiofrequency (RF) energy can induce heat in body tissues during MRI, and currently 10gSAR is the quantity most used to ensure patient safety. Although temperature increase induced by SAR absorption is much more related to health risk, it is not typically used for general safety assessment mainly due to the perceived complexity and computation time. Hence, fast temperature methods have been recently proposed to allow real-time temperature computation[1,2]. SAR-based safety evaluation of multichannel transmit systems has been accelerated using Virtual Observation Points (VOPs)[3] with a predefined overestimation of 10gSAR. This enables rapid RF safety monitoring and RF pulse design based on 10gSAR. In this work, we propose a method to identify temperature based VOPs using fast temperature calculation methods for a specific heating time. Calculated temperature based VOPs enable fast parallel transmit RF pulse design with iterative or non-iterative methods based on strict temperature constraints.

Method: Suppose we have a series of M RF pulses or pulse segments in one interval TR (Fig. 1), and for each of these pulses there is a combination of amplitudes and phases of the N channels of a transmit array. This combination associated to the m[th] pulse is stored in the complex vector $\boldsymbol{v_m}$. For each RF pulse and for each voxel of the subject it is possible to associate a matrix[4,5] S, where σ is the electrical conducitivity of the subject and E_n is the electric field generated by the n^{th} channel when driven with unit voltage

$$S(r) = \begin{bmatrix} \sigma(r)E_1(r)E_1^*(r) & \cdots & \sigma(r)E_1(r)E_N^*(r) \\ \vdots & \ddots & \vdots \\ \sigma(r)E_N(r)E_1^*(r) & \cdots & \sigma(r)E_N(r)E_N^*(r) \end{bmatrix} \quad [1]$$

which allows the computation of the SAR in each location r by multiplying

$$SAR_m(r) = \boldsymbol{v_m}'S(r)\boldsymbol{v_m} = v_{1,m}^*S_{11}(r)v_{1,m} + v_{1,m}^*S_{12}(r)v_{2,m} + \cdots + v_{N,m}^*S_{NN}(r)v_{N,m} \quad [2]$$

The temperature induced by SAR absorption can be computed with the Pennes' bioheat equation

$$\rho(r)c(r)\frac{\partial T(r)}{\partial t} = \nabla\cdot\left(k\nabla T(r)\right) - W(r)\rho_{bl}c_{bl}(T(r)-T_{bl}) + Q(r) + \rho(r)SAR(r) \quad [3]$$

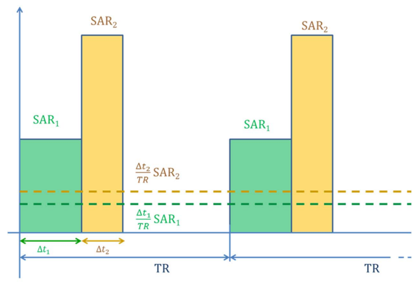

Figure 1: Schematic of two different SAR pulses in the time interval TR(solid bars), and the levels averaged over TR (dashed lines),

where c is the heat capacity, W the blood perfusion rate, k the thermal conductivity, ρ the material density, the subscript bl indicates values for blood, and Q the heat generated by metabolism. For short TR, the temperature increase depends on the average value of SAR over the time interval TR[6]. If we indicate the SAR associated with the m[th] pulse with $SAR_m(r)$

$$\rho(r)c(r)\frac{\partial T(r)}{\partial t} = \nabla\cdot\left(k\nabla T(r)\right) - W(r)\rho_{bl}c_{bl}(T(r)-T_{bl}) + Q(r) + \rho(r)\frac{\Delta t_1}{TR}SAR_1(r) + \rho(r)\frac{\Delta t_2}{TR}SAR_2(r) + \cdots + \rho(r)\frac{\Delta t_M}{TR}SAR_M(r) \quad [4]$$

Using the linearity of eq. [4], we can focus on the contribution from each single generic pulse separately within short TR. Total temperature can be calculated by summing all the temperatures generated by individual pulses. Defining $T = T_0 + \sum_{m=1}^{M} T_{SARm}$ where T_0 corresponds to the equilibrium temperature, and T_{SARm} to the temperature increase due to RF power absorption of the m[th] pulse, using the linearity of eq. [3], we can write

$$\rho(r)c(r)\frac{\partial T_0(r)}{\partial t} = \nabla\cdot\left(k\nabla T_0(r)\right) - W(r)\rho_{bl}c_{bl}(T_0(r)-T_{bl}) + Q(r) \quad [5]$$

$$\rho(r)c(r)\frac{\partial T_{SARm}(r)}{\partial t} = \nabla\cdot\left(k\nabla T_{SARm}(r)\right) - W(r)\rho_{bl}c_{bl}T_{SARm}(r) + \rho(r)\frac{\Delta t_m}{TR}SAR_m(r) \quad [6]$$

Substituting eq. [2] in eq. [6]

$$\rho(r)c(r)\frac{\partial T_{SARm}(r)}{\partial t} = \nabla\cdot\left(k\nabla T_{SARm}(r)\right) - W(r)\rho_{bl}c_{bl}T_{SARm}(r) + \rho(r)v_{1,m}^*\frac{\Delta t_m}{TR}S_{11}(r)v_{1,m} + \rho(r)v_{1,m}^*\frac{\Delta t_m}{TR}S_{12}(r)v_{2,m} + \cdots \quad [7]$$

For a given heating time t_h, for the superposition of the effects in eq. [3] we write

$$T_{SARm}(r) = v_{1,m}^*\frac{\Delta t_m}{TR}T_{11}(r)v_{1,m} + v_{1,m}^*\frac{\Delta t_m}{TR}T_{12}(r)v_{2,m} + \cdots + v_{N,m}^*\frac{\Delta t_m}{TR}T_{NN}(r)v_{N,m} = \frac{\Delta t_m}{TR}\boldsymbol{v_m}'T_{increase}(r)\boldsymbol{v_m} \quad [8]$$

where each value $T_{ij}(r)$ of the matrix $T_{increase}$ is a solution of the equation

$$\rho(r)c(r)\frac{\partial T_{ij}(r)}{\partial t} = \nabla\cdot\left(k\nabla T_{ij}(r)\right) - W(r)\rho_{bl}c_{bl}T_{ij}(r) + \rho(r)S_{ij}(r) \quad [9]$$

calculated numerically from $t = 0$ to $t = t_h$. Once all the values T_{ij} are computed with eq.[9], the number of locations where the matrix $T_{increase}$ is evaluated can be reduced with the use of the VOP compression (3). In fact eq.[2] and eq.[8] reveal that $T_{increase}$ has the same structure of the S matrix, in that they are both positive definite and Hermitian. The temperature increase T_{inc} can be finally computed with the sum $T_{inc}(r) = \sum_{m=1}^{M}\frac{\Delta t_m}{TR}\boldsymbol{v}'_{\boldsymbol{m}}T_{increase}(r)\,\boldsymbol{v_m}$ [10], such that the absolute temperature becomes $T(r) = T_0 + \sum_{m=1}^{M}\frac{\Delta t_m}{TR}\boldsymbol{v}'_{\boldsymbol{m}}T_{increase}(r)\,\boldsymbol{v_m}$ [11] where T_0 is pre-computed as the steady-state solution to [5]. This matrix formalism allows very fast computation for pulse design or other purposes.

Discussion: The properties of $T_{increase}$ allow design of RF pulses with constraints on temperature using convex optimization methods[7], as well as iterative methods[8]. In addition, by applying the VOP compression to the temperature matrix $T_{increase}$ and reducing the number of matrices involved in the design it is possible to accelerate the optimization. The linearity of the process does not allow inclusion of some thermoregulatory effects, such as local changes in perfusion. The method has been tested on a RF pulse optimization constrained by temperature increase, with the fields generated by an 8 channels stripline array positioned around the head, with the operating frequency of 300 MHz: more details are provided in Ref. 9.

References: 1. Shrivastava D, Vaughan JT. 2009, J Biomech Eng., Jul;131. 2. Carluccio G *et al.*, IEEE TBME, 60:6:1735-1741, 2013. 3. Eichfelder G et al. (2011) MRM 66:1468–1476. 4. Zhu et al., (2012) MRM 67:1367–1378. 5. Graesslin et al., (2012), MRM 68:1664–1674. 6. Wang Z, Collins CM. Concepts in MR 2010;37B:215-9 7. Golub GH, et al. (1996) JHU Press: Matrix Computations. 8. Boulant N et al. (2013) MRM 72: 679-88. 9. Deniz CM et al, (2015) ISMRM submitted.