Fast, Thermal Dose-based Exposure Safety Supervision

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Introduction

Safety considerations of local tissue heating in MR transmit-coils is insufficiently addressed by limiting the whole-body specific absorption rate (wbSAR) [1]. However, limits on peak local SAR can be overly restrictive and do not consider exposure duration, tissue sensitivity and the local heating history (transient temperature). Instead, an approach based on the CEM43 (cumulative equivalent minutes at 43°C) thermal dose concept has been suggested [2] also in safety standard committees. Here, a method is presented to rapidly assess the exposure safety of a specific scan, overcoming the mentioned limitations. The model is capable of predicting the CEM43 dose for patients with and without thermoregulation and can be related to tissue specific damage thresholds [3].

Theory

The CEM43 dose can be calculated from the transient temperature $T(t)$ according to Eqn. 1 (R=2 above 43°C, R=4 below). The fast estimation is based on a proportionality relationship (peak local) SAR to steady-state temperature increase in the presence of temperature-independent perfusion. The impact of thermoregulation can then be considered through an analytically derived and experimentally validated square-root-based relationship which includes a parameter related to a patients thermoregulatory abilities. It is assumed that temperature approximates the steady-state exponentially with a decay constant τ that depends on the perfusion model and exposure strength only, and for which an analytical relationship as well as a simulation-based model have been derived. Using these assumptions the dose contribution of the next scan sequence can be estimated to assess safety.

$$\int_0^{t_{duration}} R^{T(t)-43} dt \quad (1)$$

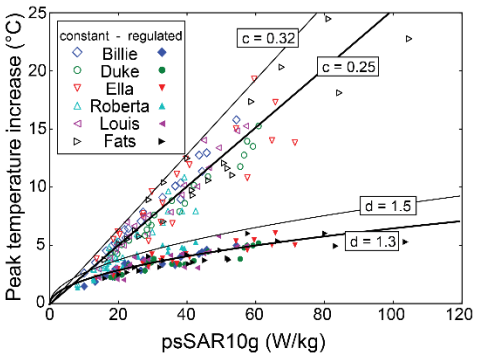

Figure 1: Relationship between peak temperature and peak 10g SAR in the presence and absence of thermo-regulation as obtained in simulations involving different anatomical models and scan positions.

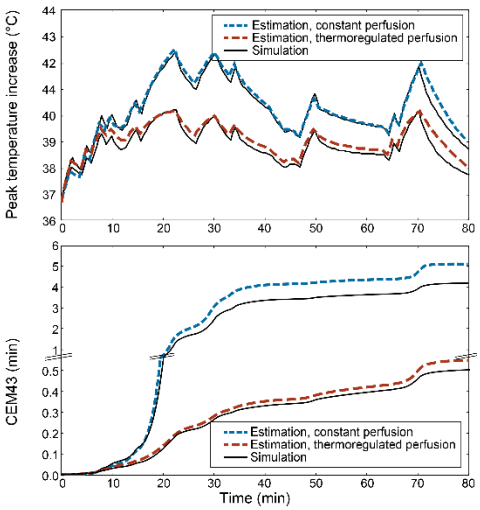

Figure 2: Simulated vs. model predicted peak temperature (top) and CEM43 dose accumulation (bottom) with and without thermoregulation.

Methods

FDTD EM and thermal simulations involving six detailed anatomical models (Virtual Population [4]) inserted each at ten positions inside a generic 1.5T coil model (16 rungs, tuning elements in the end rings, shielding, quadrature driven feeding) have been performed. The simulations were used to derive thermoregulation and exposure dependent exponential decay rates of the transient temperature development for comparison with the analytical model, and to estimate the relationships between SAR and peak temperature. The simulations were furthermore used to verify the various underlying assumptions (exponential development of temperature, relationship between thermoregulated and non-thermoregulated temperature increase, location and extent of hot-spots). Additional simulations involving different anatomical models and realistic scan sequences were used to compare predicted dose with computed dose. Comprehensive uncertainty assessment has been performed.

Results

The validity of the model and universality of underlying constant and relationships could be demonstrated over a wide range of exposure scenarios. The model is also in agreement with existing experimental data. In a complex example case involving a real scan sequence with time-varying intensities, the predicted thermal dose agreed well and within the expected uncertainties with the calculated dose (Fig.2).

Conclusions

The proposed approach allows rapid safety evaluation during a scan sequence to enable thermal dose-based online safety supervision thus considering in a natural way tissue sensitivity, scan duration, and the transient nature of heating. It can be extended to parallel transmit technology. The impact of non-linear thermoregulation can be considered. In a next step, investigation how safety margins can be included to obtain conservative estimations without overly restrictive predictions.

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