Safe MR scan times based on CEM43 tissue damage thresholds, using electromagnetic and thermal simulations with anatomically correct human models and considering local thermoregulation

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Introduction: The use of magnetic resonance imaging (MRI) is rapidly increasing due to its excellent soft-tissue contrast, improving diagnostic capabilities, and the absence of ionizing radiation. However, adverse health effects resulting from whole-body and local tissue heating by the absorbed radiofrequency (RF) energy must be carefully managed. This study investigates the maximum thermal load in local temperature hotspots for various anatomical models and positions. The simulation results for different blood perfusion models are compared to experimental temperature measurements in humans. Based on CEM43 (cumulative equivalent minutes at 43°C) tissue damage thresholds, thermally safe scan times and scenarios are investigated.

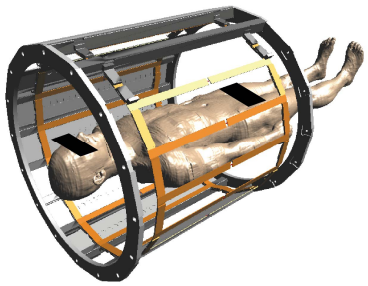

Fig. 1: Anatomical human model (Duke) within a generic 1.5 T birdcage

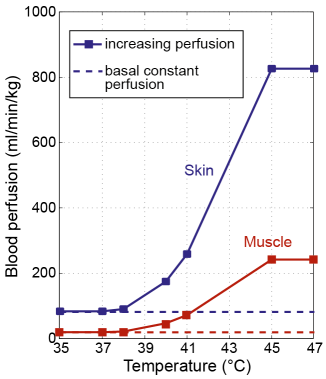

Fig. 2: Temperature dependent local blood perfusion in muscle and skin, according to [5]

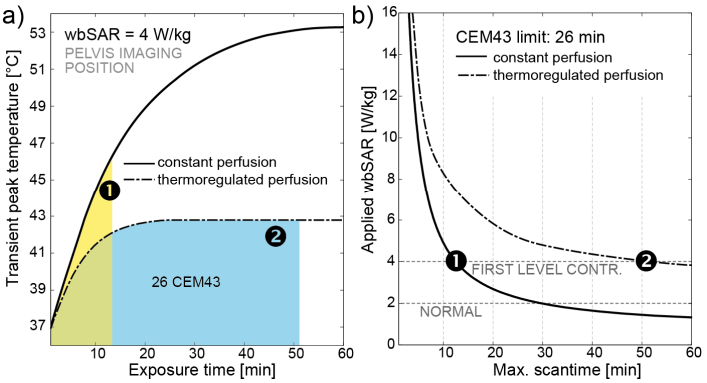

Fig. 3: (a) Transient peak temperature increase in muscle during MR exposure (pelvis imaging position), and (b) corresponding scan times to reach 26 CEM43 in the context of applied wbSAR exposure levels.

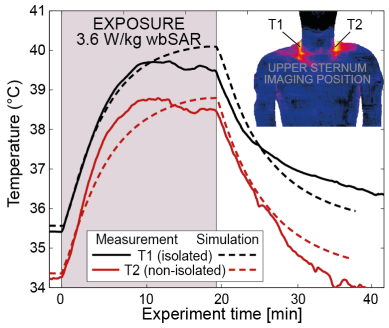

Fig. 4: Skin surface validation measurement at the predicted temperature hotspot on the shoulder (skin thermally isolated / non-isolated), and simulation of the same scenario

Methods: Three anatomical human models were used for numerical evaluations (Billie, Duke, Ella [1]), in ten different Z-axis positions (head to calves) within a generic 1.5 T body coil at 64 MHz. The human models are based on image data with a resolution better than 0.9 x 0.9 x 2 mm^3 and consist of more than 69 different organs and tissues, which have been reconstructed as triangular surface meshes allowing for flexible discretization. A typical simulation scenario is depicted in Figure 1.

The dielectric and basal thermal tissue properties have been assigned according to the comprehensive literature review of [2]. All digestive lumina are modeled as filled with air. The simulated SAR distributions [3] were used as input for the thermal simulations.

The impact of temperature dependent local blood perfusion was assessed by comparing simulations with a basal perfusion to simulations with locally thermoregulated perfusion values (Fig. 2). Skin and muscle perfusion changes are most relevant as they physiologically show high temperature dependencies and the highest SAR values mainly occur in peripheral areas (peripheral muscles, skin, fat/SAT). Experimental temperature measurements were performed close to numerically predicted hotspot regions (skin above the peripheral muscle tissues in the shoulder; upper sternum imaging position).

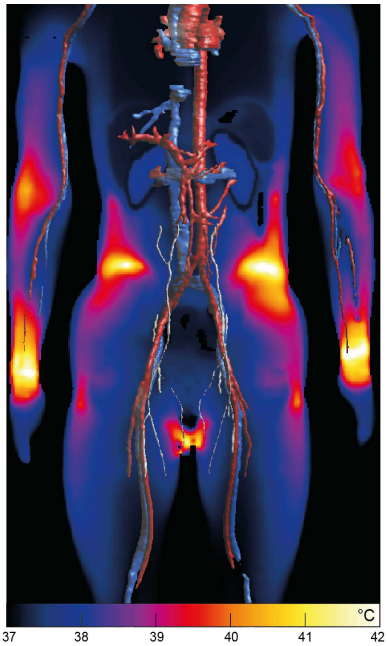

Fig. 5: Temperature distribution for Duke in the pelvis imaging position for thermoregulated perfusion at steady state

The transient temperature increase distribution can be translated to CEM43 (cumulative equivalent minutes at 43°C), assessing the effective thermal dose. Application of tissue specific CEM43 threshold values [4] allows an estimation of safe MR scan times and exposure level combinations. While some tissues already experience effects at 2 CEM43 (e.g. blood-brain barrier), in MR heated tissues (esp. muscle, skin, fat) the threshold is in the range of 20-30 CEM43.

Results: In the FIRST LEVEL CONTROLLED OPERATING MODE (4 W/kg whole-body averaged specific absorption rate, wbSAR), peak local temperatures of up to 42.8°C were computed for a temperature dependent perfusion model, and 53°C when neglecting thermoregulation (Fig. 3a) in the pelvis imaging position (Fig. 5), where the highest temperature increase was found. The tissue damage threshold for muscle is proposed around 26 CEM43. For this specific simulation scenario, and for continuous exposure with a wbSAR of 4 W/kg (2 W/kg), this would allow scan times of > 50 min (>> 240 min) for the assumed thermoregulated model, but only 13 min (30 min) for patients with completely impaired thermoregulation (Fig. 3b). Validation measurements with different exposure levels show good agreement with simulations (Fig. 4), providing the assumption of high temperature induced perfusion changes (factor > 4 in muscle).

Conclusions: Local thermoregulation can have a strong impact on SAR induced heating. Safety concerns arise especially for patients with disabled or partially dysfunctional perfusion abilities (e.g. the elderly, diabetics). The high estimated and measured temperature rise indicates the necessity of considering thermal dose models such as CEM43, which take into account exposure time and temperature.

References: [1] Christ et al. 2010, PMB 55, [2] Hasgall et al. 2011, www.itis.ethz.ch/database, [3] Murbach et al. 2011, Prog Biophys Mol Bio 107(3), [4] Yarmolenko et al. 2011, Int J Hyperthermia 27(4), [5] Song et al. 1984, IEEE transactions on bio-medical engineering 31(1).