

Efficient Estimation of Thermal Physiological Parameters Using a Weibull Model and Response Surface Methodology

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Abstract

In animal experiments involving local electromagnetic field (EMF) exposure, the accuracy of biological temperature rise strongly depends on the cooling effects due to blood flow, which are commonly modeled by the blood perfusion rate (B) in the Pennes bioheat transfer equation. However, applying literature-reported values[1] of B under high-intensity exposure conditions leads to discrepancies with measurement data, while exhaustive searches for accurate parameters is computationally prohibitive. Therefore, this study proposes a novel method to efficiently perform inverse estimation of thermal parameters that satisfy both physical and physiological plausibility using a Weibull model and response surface methodology. Specifically, time-series temperature data are first fitted using the following Weibull model to achieve dimensionality reduction.

$$T(t) = \Delta T_{\max} \left\{ 1 - \exp \left[- \left(\frac{t}{\tau} \right)^{\gamma} \right] \right\} \quad (1)$$

Next, the dominant factor ΔT_{\max} is approximated as a quadratic response surface as a function of the skin and muscle blood perfusion rates ($B_{\text{skin}}, B_{\text{muscle}}$), as shown in Fig. 1(a). When the target maximum temperature rise is set to $\Delta T_{\max} = 7.00 \text{ }^{\circ}\text{C}$, the corresponding solution set forms the constraint curve illustrated in Fig. 1(b). Along this constraint line, the physiologically plausible solution domain is defined as the region bounded by the intersection with the resting-state perfusion ratio (baseline, Point D) and the limit at which muscle blood perfusion remains at its literature value (Point C). The analysis identified a feasible range extending from the baseline intersection, Point D (approx. 1.77 times the resting-state), to the maximum skin vasodilation point (Point C). Within this range, the estimated blood perfusion rates are estimated to be approximately $2.06 \times 10^4 \sim 2.83 \times 10^4 \text{ (W/(m}^3 \cdot \text{ }^{\circ}\text{C))}$ for B_{skin} and $2.88 \times 10^3 \sim 5.1 \times 10^3 \text{ (W/(m}^3 \cdot \text{ }^{\circ}\text{C))}$ for B_{muscle} . This method enables efficient estimation of thermal parameters that are consistent with both physical and physiological constraints, without requiring excessive computational costs.

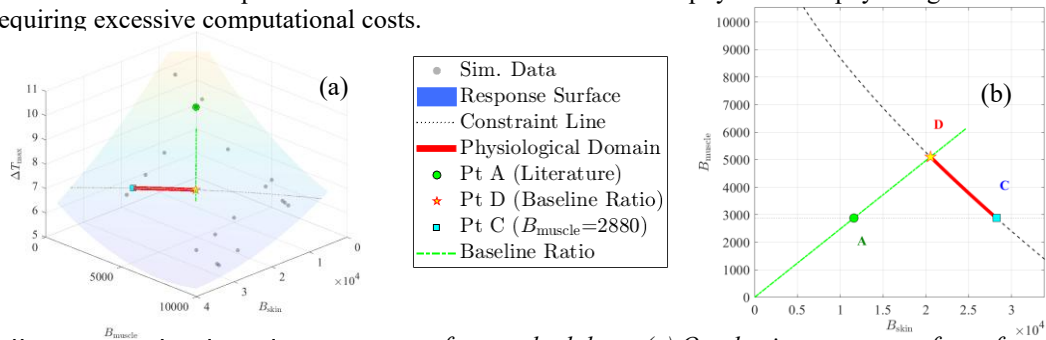


Figure 1: Parameter estimation using response surface methodology. (a) Quadratic response surface of maximum temperature rise ΔT_{\max} relative to blood perfusion rates. (b) Physiologically plausible solution domain (Point D to Point C) on the constraint curve derived from the intersection.

References

[1] S. Kodera *et al.*, “Multiphysics and Thermal Response Models to Improve Accuracy of Local Temperature Estimation in Rat Cortex under Microwave Exposure,” *Int. J. Environ. Res. Public Health*, 2017.