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An Insight into Thermoregulatory Strategies of Thalattosuchia Crocodylomorphs: Finite Element Modeling and Simulation of Heat Transfer

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1. Introduction

This study employs finite element modeling to explore thermoregulatory challenges in Thalattosuchia, the extinct marine crocodylomorphs that transitioned from terrestrial to aquatic environments. Unlike their modern poikilothermic relatives that thermoregulate through basking, these ancient marine predators faced substantially greater thermal stresses due to water's 24-fold higher thermal conductivity compared to air. To understand how they maintained thermal balance, we developed an innovative 3D computational framework combining anatomical CAD reconstructions with inferred physiological parameters from extant marine mammals. Our approach advances beyond seminal work of Natarajan seal thermoregulation 2D model [1] using a 3D finite element model (FEM) that accurately represents complex morphology and heat transfer processes.

This reveals several key insights into Thalattosuchian thermal strategies: vascular adaptation appears crucial for maintaining core temperature during prolonged dives, while behavioral changes likely complemented physiological mechanisms. Particularly sensitive to body mass distribution and diving duration, our results suggest that these marine reptiles developed specialized blood flow patterns distinct from both modern crocodilians and marine mammals. These findings provide quantitative evidence for evolutionary adaptations to marine life, addressing long-standing questions about secondary aquatic transitions in reptiles.

Beyond specific paleobiological implications, our methodology establishes a new paradigm for investigating extinct species physiology.

Computational modeling can overcome the limitations of fossil evidence alone, especially for species without living counterparts. This framework offers testable predictions about metabolic rates in marine reptiles and creates opportunities to re-examine other mesozoic species thermal adaptation. This interdisciplinary approach bridges the gap between paleontology and thermal engineering, opening new avenues for understanding prehistoric life through advanced computational analysis.

2. Methods

2.1 Geometric Modelling and animal physical characteristics

The numerical model of the animal was obtained from fossils to generate a 3D-reconstructed Thalattosuchia as visible in Fig. 1, which includes the distribution of the different anatomical layers.

As done for other species [2-4], the animal was then subdivided into five anatomical compartments: the head, the forelimbs, the hindlimbs, the torso and the tail. Thanks to the body symmetry, only half of the body was involved for the simulations. Each body compartment was then divided into four tissue layers: skin, fat, muscle, and core (bone or viscera). Thermal properties (tissue conductivity k_i, heat capacity Cp_i) and

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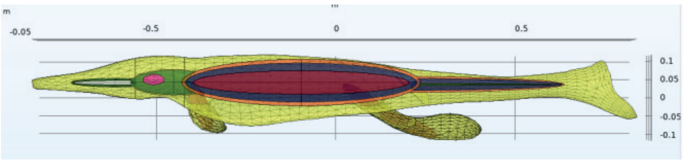

Figure 1. 3D-Reconstructed and meshed geometry of a Thalattosuchia (yellow: skin and interstitial tissues; orange: periabdominal fat; dark blue: muscles; purple: vicera; green: skull; pink: brain; grey: oral cavity).

Table 1. Tissues properties

Parameters	Thermal conductivity k ($W/m.K$)	Tissue Density (kg/m^3)	Thermal Capacity C_p ($J/kg.K$)
Blood	–	1000	4184
Skin	0.41868	1000	3474
Fat	0.29075	980	3474
Muscle	0.41868	1000	3474
Bone+Core	0.41868	1000	3474

physiological parameters (tissue density ρ_i, anatomical morphologies and sizes) for each anatomical sites i were assigned based on comparable marine reptiles (see Tab. 1, adapted from [5]).

2.2 Governing Equation

For each part of the animal body, the steady-state heat equation was solved including metabolic heat specific sources Q obtained from paleobiochemical analysis for each layer [6]. The metabolic specific heat generation is split into the basal metabolic rate (distributed across all anatomic parts, ~1/2 W/kg) and exercise-induced heat source (generated in muscles and calculated from minimal mechanical energy to counteract swimming drag, ~2/3 W/kg). Moreover, inter-anatomical-compartments convective exchanges due to blood interstitial flows at a given temperature are also taken into account. Finally, the boundary conditions correspond to a Newton law depicting the convective heat flux exchanged by the animal with its surrounding water environment characterized by the convection coefficient h which depend on the Reynolds number and thus on the swimming velocity.

2.3 Numerical Implementation

This approach combines anatomical reconstruction with a thermophysiological model, enabling a 3D finite element analysis of heat transfer in this extinct marine reptile. This simulation was performed for various parameters datasets using Comsol Multiphysics with a mesh of 131k tetrahedral elements.

3. Results and discussion

Our simulations yielded core body temperatures ranging from 22°C at the skin (depending on water temperature) to 34.5°C in active muscle tissue, aligning with the 26–38°C range inferred from geochemical studies [6]. Temperature distributions show regional variation. The tail was 2–3°C cooler than the torso due to metabolic heat distribution. In limb extremities (22–33°C) the temperature distribution followed expected convective patterns, with coldest regions at the skin-water interface.

Varying water temperatures (22–26°C) produced core temperatures 3–11% higher than literature values [6]. Approximately 90% of body volume maintained temperatures above 26°C, with only superficial skin layers (≤14% volume) falling below viability thresholds. Our results support that even with moderate metabolic rates in thalattosuchian animals, blood flow-induced thermal adaptation may suffice to slow down heat loss.

4. Conclusions

This study applied FEM to analyze heat transfer in Thalattosuchia, revealing viable thermoregulatory strategies despite aquatic challenges. Despite our various metabolic heat distribution assumptions, results align with geochemical studies (26–38°C core range). Our findings are in line with the results [7-9] of general hypertrophy of cephalic vasculature indicating increased blood flow volume and velocity. Enlarged blood vessel pathways suggest enhanced advective heat transport capacity. This framework enables future studies to refine crocodylomorph-specific parameters and explore their marine adaptations.

Conflict of Interest Statement

None.

Contributor Roles

SBL: Writing original draft, Computing, Results Analysis; RP: Model's Data acquisition, Results Analysis; JC & VS: Methodology, Conceptualization, Supervision, Validation; TL: Methodology, Conceptualization, Supervision, Writing & editing.

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