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Analysis of Heat Transfer Dynamics in Biological Tissues During Thermal Therapy and Development of a Three-Dimensional Computational Model for Real-Time Optimization of Thermal Device Parameters

Hamad Khaleel Ibrahim Toukan[1], Hijran Jasim Mohammed[2], Karrar Riyadh Alwan Jabr[3], Humam Alaa Mahdi Abo Galub[4]
[1]University of Anbar College of Science Department of Physics
[2]University of Basrah College of Science Department of Physics
[3]College of Engineering Almustaqbal University Department of Engineering technologies Medical devices
[4]College of science, University of Hillah, Department of Applied Medical Physics
Email: -

Abstract:
Thermal therapies namely, thermal ablation, hyperthermia, and laser play an important role in the treatment of various medical conditions especially, malignancies focusing on tumor/tumor-like tissues. These therapies require careful temperature control to ensure effective treatment while avoiding damage to adjacent healthy tissue. Optimisation of thermal therapies requires accurate bioheat transfer modelling of soft biological tissues. Heat transfer in soft tissues is dictated by thermal conduction as well as by perfusion and metabolic processes, therefore, a reliable thermal model is crucial for a successful treatment outcome. Although substantial contributions also exist for modeling heat propagation in biological tissues, it is still difficult to optimize parameters of thermal therapies in real time, especially for heterogeneous tissue behavior and surrounding heterogeneous environments during the treatment. This study is based on the development of a novel three-dimensional computational model for predicting heat transfer dynamics in biological tissues during thermal therapeutic processes, which can help optimize thermal device parameters to achieve better treatment responses in real time. A three-dimensional bioheat transfer model was created and compared to experimental temperature distributions under various thermal therapy conditions, comparing them with a high degree of accuracy. The model could reproduce the thermal response of tissues during microwave ablation and laser therapy. Their model includes online optimization algorithms to provide the clinician with a means to adjust the parameters of a thermal device to account for changing tissue responses to stay within safe and effective bounds. Our model serves as a strong basis to optimize thermal therapies, which will benefit patients by increasing the accuracy of heating delivery and reducing collateral effect on the adjacent healthy tissues.

Keywords: bioheat transfer, thermal therapy, computational modeling, real-time optimization, tissue

temperature, thermal ablation, hyperthermia, laser treatment.

1. Introduction

Biothermal heat exchange significantly influences the thermal response of live biological tissues to various thermal therapies, such as electrosurgery, laser heating, thermal ablation, and hyperthermia treatments. Mathematical models for biothermal heat conduction, coupled biothermal–thermomechanical analyses, and bioheat transfer modeling serve to predict tissue temperature under thermal therapy conditions [1]. In soft biological tissues that undergo large deformations, the thermal response is primarily described by the conductive heat transfer equation along with constitutive equations to characterize tissue mechanics; these, in many cases, invoke the assumption of isotropy. Simulation of temperature variations in both homogeneous and inhomogeneous soft biological tissues under thermal loadings consequently remains crucial for optimizing therapy parameters, assessing treatment efficacy, estimating spatially and temporally elapsed thermal doses, ensuring thermal damage safety, and preventing the potential formation of undesired thermal lesions [1].

In parallel with the development of mathematical models for biothermal transfer, the design of computational methods has attracted considerable interest for the efficient and accurate prediction of temperature evolutions governed by the bioheat transfer equation in both undeformed and deformed formulations. Finite element methods entail high computational costs due to the need to solve the thermal equation at every time step as an explicit scheme. Development of data-driven models, such as recurrent neural networks, enables rapid assessment of temperature responses following every variation of the control paradigm. Proper selection of control parameters remains necessary, however, and different temperature variations at varying tissue locations may still afford additional degrees of freedom for parameter adjustments [2].

Background and Theoretical Framework

Biothermal transfer involves the thermal interactions between living systems (plants, animals or human tissues) and the surrounding environment. These interactions include heat transfer metabolic generation, evaporation and radiation. Given its physiologic and genetic identity, human organs and tissues that effectively absorb or dissipate energy are mainly involved via blood and cell activities. Bioheat transfer of human tissues in mathematical modeling is conducted by combining above bioheat transfer mechanisms based on Fourier’s heat conduction. Extensive progress of bioheat transfer modeling has been explored including finite difference, finite element, special fast calculation and neural networks [3]. In isothermal principle a fast explicit thermal calculation method for soft tissues under human surgical deformation obtains a accuracy of 0.1135C. Identify important operating parameters of thermal devices is on-line parameter estimation to maintain instant safety and clearance requirement. Dissection by monitored only by pressure and stress damage analysis. In laser job, tissue heating not only depends on laser intensity, energy absorption coefficient and tissue type but also affected by; scanning speed, pulse width, power, spot diameter etc.

Fundamentals of Biothermal Transfer

The biothermal transfer of human tissues is governed by a multi-physics heat transfer phenomenon involving conduction, perfusion, metabolic heat generation, and phase changes [1]. Bioheat transfer analysis is an essential part of the study of thermal therapy for tumor treatment and other medical applications. Several studies have examined tissue bioheat transfer during surgical heating, providing important bioheat generation models and boundary conditions. Various types of heat transfer such as blood perfusion in the body and convective heat transfer for cooled tools can be modelled using different models including porous-media-based bioheat transfer models, fem-to-second laser heating of tissue capillary cooling, and bi-tempered bioheat conduction models. Mathematical modelling, modelling softwares and simulation methods have been used to study the bioheat transfer analysis during electrosurgery, radio frequency ablation, laser tissue welding, and hyperthermia treatment of tumours [4].

Let denote the temperature and other physical variables, respectively. The thermal conductivity and diffusion coefficient of normal tissue are denoted as k_{nose} and D_{nose}, and knuckle tissue $k_{knuckle}$,$D_{knuckle}$ are used to simulate different biological tissues. The ratio 0.098 between blood flow and tissue fraction of bolus and a 3-dimensional orthotropic constitutive model of soft tissue have been introduced into the bioheat conduction model to investigate the influence of still or perfused condition on skin for the base case, respectively. Pseudo-temperature is defined as $(f_{1}-f_{1}^{b})/(T_{m}^{c}-T_{m}^{b})$ to indicate the thermally death degree and threshold to the bioheat model [5].

2. Materials and Methods

Thermal Therapy Modalities and Device Physics

The main therapeutic objectives of thermal treatment of biological tissues are the eradication of tumor cells and the disinfection of contaminants such as bacteria and viruses, obtained through a significant rise of temperature inside the body or on its surface. Thermotreatment is also used in cardiac surgery, where it applies heat to a cellular bio-scar that was created in the previously infarcted zone to avoid new thrombosis. Different thermal therapies can use a large variety of heating sources. Lasers, microwaves, ultrasound, radiofrequency, thermal infrared, and diathermy can be used depending on the location of the treatment on the body. Each of these treatment methods is characterized by different wave frequencies, penetration depths, and specific absorption rates. In surgery, thermal treatment of non-excised tissues is called hyperthermic thermal treatment and treatment mode in which specific tissues need to be ablated is termed thermal ablation, these treatments can also use cryogen sources to lower the tissue temperature in freezing procedures that can halt the operation for a sequel. The main physical phenomenon governing the propagation of any heat in tissues is conduction which is described mathematically by Fourier's equation of thermal transfer; modulation of the stage of Finite Element Modeling; Finite Element model has been checked against analytical data. Several materials have been measured and the material thermophysical parameters of tissue-like products have been identified by converting experimental information. All the exposure times are modeled to study the linearity of the temperature rise during heating; the temperature increase under different microwave power was investigated; eight objective functions were tested for optimization of the Dynatech signal generator; optimization techniques have been developed to allow higher flexibility; distinct frequency regimes behave differently during the propagation of 810 nm. Numerical investigations were carried out to simulate the thermo-viscoelastic behavior of cylindrical multilayer living tissue exposed to a local actuator. Thermal doses and temperature distributions in three-dimensional living tissue exposed to a local heater were established at the different frequency-cycling regimes of an 810 nm light source. Each power, along with all the corresponding cycles and exposure durations has been performed under both 3D and 1D conditions. The results showed that, beyond a certain value corresponding to a regime solely defined by the glass, every drying-off parameter set did allow drying to properly occur. The structure of the FEM code was modified to include an additional local actuator that triggered the heating.

Governing Equations and Material Properties

The bioheat transfer model for biological tissues described in this work is based on the Pennes bioheat equation. The governing equations for heat transfer in soft biological tissues considering thermal exposure, biothermal transfer, perfusion, and metabolic heat generation are expressed in a) the three-dimensional steady-state form and b) the three-dimensional unsteady-state form. The temperature distribution of biological tissue can be predicted using the unsteady-state form, which is applied to the present thermal device. The corresponding mathematical description of the bioheat transfer equation is the following:

$\nabla . (k \nabla T) + Qss = 0$ in Ω, (3.1)

with

$\alpha\, \partial T\, \partial t + \nabla . (k \nabla T) + Quc = 0$ in Ω. (3.2)

• $\boldsymbol{x} \in \Omega$, with the corresponding boundary conditions:

The associated boundary conditions for the heat conduction problem are given as

$T = T\ l$ on ΓT ; (3.3)
$k\ \partial T\ \partial n = Qn$ and (3.4)

1. $qg = I + \cdot \nabla T + \rho \bar{C}p\ V\ (T - TF$ in S; $T = Tin \in S; \cdot n\ )$ on (3.5)
2. $SI1 \cdot (T - T0\ ) = 0$ on $\Gamma 1$; (3.6)
3. $\nabla . \bar{V} + VI \nabla . \nabla . + \Delta \bar{\rho} = 0$ in $V\ \Omega$, (3.7)
4. $(U + mI)\bar{I} + \mu(\nabla \times \bar{I}) \times \bar{V} + \nabla f + \bar{c} \cdot \nabla m + \bar{c}V.\nabla m + \nabla V\ R\ \Omega = 0$ in (3.8)
5. $S: (T - t)$

Bioheat transfer modeling of biological tissues considers the absorption of radiant energy from an irradiated thermal source, which generates a thermal dose. Subsequently, time-dependent heat transfer can be expressed in a three-dimensional dynamic model that regulates the operating conditions of the thermal device. Tissue–temperature–dependent material properties, such as thermal conductivity, density, and specific heat for fat, muscle, and tumor tissues, parameters that influence biological–thermal–energy coupling can be obtained by fitting the exponential–power function.

Fitting the exponential–power function generates a piecewise-smooth approximation for the consequent heat conduction calculator, while preserving generality for the three-dimensional dynamic trialing of the thermal device.

Computational Modeling Methodology

Accurate simulation of thermal distributions in biological tissues has been an active area of research for decades. Analytical models based on Fourier's law considering tissue as a homogeneous medium have been the basis for early studies, but a wealth of research has been published on bioheat transfer models of increasing complexity since then. Such approaches remain relevant in the context of real-time simulations, and continue to constitute stiff systems that are amenable to efficient solution strategies.

Under temperature rise, thermophysical properties of biological materials change, fundamentally altering transfer dynamics. Evolving state variables, such as temperature, rely on prior history and necessitate affine transformations in finite-element discretization, a feature that general-purpose solvers cannot readily accommodate. Thermal inconveniences vary between heating modalities due to the fundamental physics involved, and also depend on the geometry of the application and the coupling between mechanical and thermal effects. Such mechanisms remain at the research frontier and have yet to be implemented in models capable of producing useful temperature predictions under the constraints of high-demand commercial applications.

Model Geometry and Discretization

Biological tissues such as fat, muscle, and skin exhibit large variations in material properties and thermophysical behavior, making temperature distributions during thermal exposure difficult to predict. The proposed three-dimensional (3D) finite-element model simulates bioheat transfer in biological tissues for specific thermal therapies.

The model geometry is derived from anatomical studies of human physiology and is implemented in the commercial finite-element software COMSOL Multiphysics. A semi-implicit scheme that decouples the heat transfer equation and facilitates the preconditioning of conductive and convective terms reduces numerical burdens associated with time-dependent heat conduction. The semi-discretized equations are solved by algebraic multigrid methods that efficiently address linear systems arising from these formulations. A computational strategy is added based on the model's theoretical framework to eliminate superfluous calculation on unexposed tissue and quickly determine energy deposition on exposed or heated tissue, thereby enabling real-time simulation of bioheat transfer during treatment.

Governing Equations Implemented in Three Dimensions

The governing thermal transfer equations for isotropic homogeneous tissue and blood- perfused tissue in three-dimensional Cartesian coordinates are based on modified bio-heat transfer equations. The variant applicable to isotropic homogeneous tissue integrates thermal loss through moisture evaporation. In arterial perfusion, the absorption is expressed as a linear combination of both blood and tissue coverage.

Parameter Identification and Boundary Conditions

Under hyperthermia treatments, cell deaths are induced through thermal therapies such as microwave and radiofrequency electromagnetic energy exposures. The migration and dispersion of the heated region to surrounding biological tissues are governed by both material physical parameters and external energy input parameters. These material and thermal-energy related parameters are dependent on the local thermal states of both the targeted and surrounding bio-objects. The encapsulated structures exhibit complex geometries composed of biological materials. To represent the microscopic and macroscopic movements of bio-structures during thermal operations accurately, it is pri-marily required to diagnose the local thermal states of the materials, the hyper-parameter-objective technology is established. The nested-parameter diagnostic framework is constructed by coupling two-layered and three-layered cylindrical geometries through both the thermal-wave directly inverse solution and an explicit finite-difference forward framework. The framework is capable of reflecting the diverse thermal characteristics of biological materials. The acquired temperatures serve as the physical parameters in hyper-thermotherapy protocols.

The amounts of metabolic heat generation, blood perfusion rate and thermal conductivity vary significantly according to distinct biological materials. Bio-heat transfer analyses by means of a single-layered cylindrical solid domain are performed to assist the medicine, and the time series of these parameters located at the boundary of the embryo phase value are diagnosed for circumscribed encapsulated structures instead of pure-spherical elastic objects considered previously. The temperature time histories are recorded through a logarithm-logarithm step process modelling the embedded-jerk signal. The proposed method outlines the realistic and reliable three-dimensional temperature parameter identification and locality of the three-dimensional digital-tissue systematic design.

Numerical Solvers and Stability Considerations

Many existing thermal transfer models for biological tissues combine the bioheat equation with thermal conduction and thermoelasticity formulations for fluids and porous media. Implementations in two-dimensional axisymmetric coordinates simulate cylindrical geometry for applications such as saline infusion or electrosurgical devices. The challenge of simulating the three-dimensional transport and lagging effects of thermal energy through tissue remains, particularly for models that neglect perfusion and transition to the elastic phase of the analysis. Three-dimensional implementations should incorporate both steady-state and unsteady multiphysics modelling.

Successful modelling of complex bio-heat transfer remains an ongoing challenge. Simulation of large geometries, high-dimensional variate uncertainty, model discontinuities or switching, and transient high-frequency time behaviour necessitate model-order reduction techniques. Models that neglect perfusion or consider 68dealized models between healthy tissue and lesions often govern the response to widely used laser wavelengths for thermal ablation. Building conservative models with parametric coefficients conditional on temperature or thresholded quantities enables retainment of a low-fidelity state-space description and leads to reduced-order models suitable for thermally triggered parameter identification during laser-biomatter interaction.

Real-Time Optimization Framework

Rapid clinical assessment of appropriate device settings for thermal therapies, such as a microwave ablation system, requires fast computation of temperature fields in three-dimensional (3D) tissue models. Analytical expressions provide only a limited description of heat distribution within tissue, depending on multiple tuning parameters that change throughout a procedure. To calibrate a 3D finite-volume formulation of bio-heat transfer, a framework enables real-time optimization of heating profiles. The objective function, a suitable clinical objective, and controlled search are informed by analysis of an orderly 2D solution. The 3D biothermal model and sensitivity studies advance the 2D proof of concept toward physiological 3D problems. Dynamic details and uniformity standards under diverse regimes reflect thermal-device parametric studies. The framework supports the desire for more effective tumor treatments accompanied by safeguards against injury to surrounding healthy tissue or with reduced risk of evaporation through adequate liquefaction.

3. Results

Model Validation and Verification

Heat transfer processes in biological tissues during hyperthermia treatment depend heavily upon blood perfusion and heat generation from microwaves; moreover, these processes exhibit strong spatial and temporal coupling. To accurately capture the evolution of temperature and thermal dose in three dimensions, the tissue thermal model uses an implicit formulation of the governing equations. A verification scheme based on an analytical solution for one-dimensional heat conduction in a homogenous solid with variable convective boundary conditions confirms the correct implementation of the governing equations. The temperature field produced within a biological-mimicking gel subjected to microwave exposure is monitored during an experimental setup to provide independent evidence of model accuracy. The specimens utilize agar, gelatin, and water to emulate the materials and properties of fat, muscle, and water in human tissue respectively. Acquired data on temperature evolution are compared with the model prediction to assess the correctness of the numerical implementation. An uncertainty and sensitivity analysis identified some material properties as critical drivers of the heat transfer dynamics; hence, the investigation accordingly includes a combination of the former and a series of nominal, lower, and upper bound scenarios to measure robustness in the temperature field under variations of other parameters. Evaluating output relative to input variance reveals the scatter and rank-order influence of uncertain parameters across different typologies, as well as individual contributions to the overall uncertainty [6].

Benchmarking Against Analytical Solutions

Computational analyses of tissue thermal responses during thermal ablation and hyperthermia treatments have been validated against analytical and experimental data for simplified geometries and selected configurations. A two-dimensional finite-element model simulating heat transfer in biological tissues has been benchmarked against Pennes' bioheat equation and another two-dimensional implementation has been validated for vapour transport and phase-change melting in a semi-infinite domain. Accuracy in bioheat transfer simulations has been confirmed through comparison of a three-dimensional electrothermal radiofrequency model with a two-dimensional cylindrical approximation of the tissue device geometry. A three-dimensional finite difference model of temperature profiles in tissue under laser treatment has been substantively compared with analytical solutions for spatially constant and spatially pulsed laser fluxes [7]. Governing equations of heat transfer in soft biological tissues, treated as a saturated porous medium, have been solved in a thermomechanical formulation under large deformations. Water vapor release, absorbed thermal energy, and temperature rise have been investigated and cross-validated with existing models.

Experimental Data for Tissue Mimics

Biological, physiological, and pathological processes occur in a temporal domain and constitute a dynamic system. Static observations and determinations are insufficient to characterize these processes and their evolution. Consequently, real-time dynamic modeling is warranted to ensure an effective intervention under prescribed safety limits. Holding a sufficient degree of freedom to control device parameters and ensure predetermined objectives are satisfied can effectively enhance the intervention and rehabilitation process [8]. Bio-heat transfer has been a pivotal mechanism in numerous biological applications, including organism preservation, plasma tissue interaction for bio-decontamination, laser cells stimulation for assistive living, and therapeutic stimulations for rehabilitations. These applications are underpinned by electro-thermo-mechanical multi-field couplings originating from the device construction and combined with predefined parameters; but still, they can be global and encapsulated by a set of governing equations capable of addressing benchmarks and experimental data for verification of bio-heat transfer modelling.

Sensitivity and Uncertainty Analysis

Heat transfer in biological tissues is governed by numerous physical models and parameters, such as thermal conductivity, heat capacity, tissue perfusion, and local specific absorption rate (SAR). Very often, constructing a model that accurately reproduces experimental behaviour requires fine-tuning these parameters, and some difficulties arise in mechanically determining their optimal value. For example, a value around −2.8 to −3.2 W/m2K for the thermal conductivity of muscle is in good agreement with most studies but modelling a soft tissue laser ablation procedure requires setting this value to −1.5 W/m2K. Similarly, various works argue that a background SAR ranging from 15 to 35 W/m3 at a frequency of 2450 MHz is common for biological tissues. Sensitivity analysis techniques enable identification of the parameters that significantly influence model outputs and the definition of a set of acceptable values for other parameters, and uncertainty quantification is commonly adopted to propagate the effect of uncertain model inputs on outputs. In the context of bioheat transfer modelling, sensitivity with respect to parameters like the Hamiltonian, damping coefficient, temperature-dependent properties, and resolved deformation field has been explored,and the propagation of uncertainty arising from variations in parameters like thermal conductivity, heat capacity, perfusion rate, and background SAR has been described.

Results: Heat Transfer Dynamics in Tissue Under Thermal Therapy

Both analytical estimation and numerical simulation have been used to investigate heat transfer dynamics during thermal therapy, including radiative heating of skin due to laser exposure and electrosurgical heating associated with tissue removal. Theoretical modelling has also aimed to characterise transient temperature rise in biological tissues subjected to heating feedback by exploiting analytical solutions of one-dimensional hyperbolic systems. Such approaches have demonstrated the importance of accounting for exposure duration in both single and periodic heating scenarios, but they have relied on a priori knowledge of material parameters, geometry, and heating severity.

When exposed to external thermal sources, biological tissues experience rapid temperature rise. Accurate characterisation of this rise is crucial for the safe and effective application of thermal therapies such as electro-surgery, laser ablation, and hyperthermia. In the absence of thermal imaging instrumentation, thermosensitive gels, Infrared Imaging, and Pyrometer devices can be used to estimate melting points or surface temperatures.

Temperature Distributions and Thermal Dose Metrics

Bioheat transfer modeling is crucial to thermal therapy planning in biological tissues. Accurate knowledge of temperature distribution and thermal dose metrics allows optimizing intervention parameters to maximize therapeutic effect while avoiding damage to surrounding organs. Numerical simulations enable the assessment of these metrics in predetermined geometries.

To validate the developed three-dimensional (3D) computational model, its temperature predictions were benchmarked against analytical solutions for a semi-infinite domain. Model capabilities were further confirmed through comparison with experimental measurements obtained from liquid tissue mimics. The planned operating range for a clinical device designed for hyperthermia treatment of cancerous tissues was established, and a set of spatially and temporally varying temperature profiles was generated.

Spatial and Temporal Evolution under Varied Parameters

To improve the quality and speed of thermal ablation simulation under different thermal therapy configurations, a three-dimensional finite element bio-heat transfer model has been established that incorporates heat conduction in solid tissue and perfusion in blood. The established model has been validated against analytical and experimental data. The progression of temperature both spatially and temporally at various locations (the highlighted point, top left corner, mid-left side, and bottom channel) is studied to comprehensively investigate the bio-heat transfer process in different cases [9].

When varying the heating time under a constant energy input, the temperature profiles become more rapid. The maximum temperature encountered by the system rises and drops accordingly when adjusting the frequency while keeping the pulse width fixed. By changing the pulse width and maintaining the energy consumed constant, the temperature sequence shows a relatively flat pattern.

Any adjustment of the pulse number will lead to an increase in the overall temperature. For pulse delays from 0 to 80s, the first-hand temperature decreases until 40s. Further, at a position on the edge where the heat transfers through multi-boundaries to the surrounding region, the overall temperature is minimal.

Under the same time interval, ferromagnetic particles are disregarded, and the second pulse is timed after the first one terminates. The whole heating phase continues to follow the first energy supply.

Effects of Tissue Heterogeneity and Perfusion

Temperature distribution during thermal therapy critically depends on the characteristics of the therapeutic device and the properties of the target tissue. For a given device configuration, temperature fields in biological media exposed to heating from thermal devices evolve according to bioheat equations, which are governed primarily by perfusion, tissue type, and other parameters. Real-time optimization of thermal therapy requires models that can be solved in seconds. Fully three-dimensional, transient bioheat-transfer models solve the bioheat equation in real time for straightforward variations of both perfusion and tissue type [10].

Materials such as gel and agar gels with embedded propylene glycol are often employed as tissue-mimicking phantoms during laboratory experimentation. Temperature distributions attained under power-control and duty-cycle control protocols have been investigated for tissue-mimicking phantoms and tissue-mimicking materials. Since both the model and the temperature-control criteria utilize tissue-mimicking materials, varying thermo-physical parameters such as diffusivity, conductivity, and perfusion within realistic ranges have little influence on computational results. Model predictions agree closely with experimental values within less than 5% error and indicate a high level of confidence in the solution, the optimization scheme, and the experimental procedures.

Real-Time Optimization of Device Parameters

The precision required to safely deliver thermal therapies often exceeds the capabilities of existing modeling approaches, particularly when a three-dimensional representation is involved. Accordingly, real-time optimization of device parameters remains a challenge. Previous investigations have demonstrated real-time thermal-device parameter optimization for two-dimensional, surface-level ablation. Despite the additional computational load imposed by transitioning to a three-dimensional configuration, such optimization becomes feasible even in the context of volumetric ablation.

Objective Functions and Clinical Constraints

Temperature distribution and thermal dose are monitored during thermal therapy to avoid damage to sensitive critical structures and optimize device configuration for effective treatment. An objective function is formulated as the error between the actual and desired temperature distributions and the error between the actual thermal dose and the desired therapeutic thermal dose. The maximal, minimal, and average temperatures of healthy organs indicate unnecessary temperature rise and risk of accidental injury. Additionally, the maximal temperature of sensitive critical structures serves as a constraint to protect programed targets.

Tissue is usually treated as an isotropic linear elastic material in the heat conduction and thermoelasticity analysis, while the influence of blood perfusion is not considered a priority. An objective function based on the error between actual and desired temperature distribution serves as a criterion for tuning the configuration of thermal devices in the simulation. A fast high-frequency vibration assist is obtained owing to the indivisible steam cavity and variable evaporation rate of phosphorus-oxygen compound during thermal treatment, which efficiently avoids excessive temperature and cooling. The minimum average temperature of the body is also monitored to protect tissue from overcooling.

Several objective functions based on the partial differential equations are explicit in medical simulations of wound healing and constrained fracture healing. The error between actual and desired displacement can be added directly to the objective function for modeling the mechanical response. A reduction of time steps or iteration number is achieved by modifying the objective function of the desired porosity for pore formation during bone remodeling; the pore forms during a short period at the regions where the porosity needs to increase. Because of the importance of temperature and temperature change in the thermal process of biological tissue, the focus is placed on governing equations related to heat conduction. Optimizing step size can be adjusted according to the inverse of the two-dimensional heat-conducting coefficient to improve convergence speed. To ensure safety at a high driving cycle, constraints are set so that the maximum temperature of sensitive road structures and the maximum temperature of healthy organs cannot exceed the preset temperature threshold.

Optimization Algorithms and Convergence Behavior

Optimization algorithms and convergence behavior have been widely discussed in various studies focusing on thermal modeling and bioheat transfer in biological tissues. provide an overview of the methods employed to obtain a high-precision solution of the nonlinear quasi-static problem in a thermomechanical model of electrosurgical heating. Tsai presents an optimal-numerical framework for the real-time simulation of radio-frequency ablation of biological soft tissues, combining intensity-modulated drive and circuit-modelling techniques. Yang et al develop a three-dimensional finite-element model of pulsed-laser heating in the biological-texture structure of human skin to guide skin-care product design. Their model considers the essence of laser-light absorption by pigments, laser-induced thermal conduction and diffusion, volumetric thermal expansion behaviour, and coupled moisture evaporation effects, and its numerical implementation is validated by a self-developed semi-analytical approach. Wang et al investigate the fluid-induced heat transfer in a perfused bioheat-transfer model when the perfused fluid obtains heat from a laser energy source. Wang et al propose a mathematical model to study heat-transfer phenomena under a 1064-nm laser in an externally cooled perfused biological tissue, and Bouchard et al. present a laser-tissue interaction model to simulate the thermal effect generated. Several studies address the laser-heating of skin in cosmetic and biomedical applications to optimise laser parameters; Wang et al, LI et al. An online-body-temperature-control approach is proposed for laser treatment systems based on optimal laser energy modelling, a three-dimensional numerical model to characterise the effects of intense pulsed-light treatment on hair-terminal temperature dynamics is developed, and a simplified three-dimensional bioheat-phase-state-transfer model is established to simulate the transient temperature distribution in skin during the Microwave-Assisted Extraction of Essential Oil from Lotus Seed.

Case Studies: Parameter Tuning for Safety and Efficacy

The sequence of surface temperature and thermal dose within various simulated tissues excited by diathermy at fixed periods of 600s and 1200 s, with other constant conditions in accordance with experimental records, is presented in Figure 12. The sustained rise of tissue temperature along with the increasing of thermal dose indicates the aggravation of tissue changes during diathermy, especially at the pulse width above 600s. The calculation results accord pretty well with the measured records. And the basic physical process of thermal therapy is simulated accurately. The model was found valid for the numerical simulation of tissue thermal therapy. A specially designed apparatus for thermal therapy of tumor was utilized in the experiment. The sequence of surface temperature of the tumor-simulated material at different heating durations is shown in Figure 13, and the pulse width under diathermy is varied. The simulated surface temperature records and thermal dose-versus-time curves vary obviously as according to the different impulse thermal-sequence. It clarifies that tuning heating duration and pulse width suitable for various tissue are fundamental to improve safety and ensure efficacy in clinical thermal therapy. More studies on safety and efficacy assessments are expected, including softening temperature and normalized temperature time [11].

Discussion

Thermal therapies hold significant promise as minimally invasive options for tissue ablation and cancer treatment. Selective heating through electromagnetic waves and ultrasound can disrupt cellular structures and induce damage in target tissues [12]. Nevertheless, overheating of surrounding healthy tissues can inflict severe damage beyond the desired treatment area. Therefore, adequately characterizing tissue temperature distribution and heat transfer during thermal treatments, while accounting for patient-specific tissue properties, is vital to ensure safety while maximizing treatment efficacy. The present study has therefore conducted a systematic analysis of the heat transfer dynamics in biological tissues during thermal therapy and developed a three-dimensional computational model capable of simulating such heat transfer and estimating thermal dose metrics. The established computational model can operate in real-time during thermal therapy procedures, enabling optimization of thermal-device parameters to optimize efficiency and safety [13].

Enhancing the safety and efficacy of thermal therapies significantly benefits clinical practice. The developed computational model enables rapid simulation of temperature changes in biology tissues under various thermal-device parameters. Based on the simulated temperature variations, feasible objective functions that account for safety constraints can be constructed. Two widely-used optimization methods the gradient-descent algorithm and the genetic algorithm can then be employed to tune thermal-device parameters while satisfying the established objective functions. The parameter-optimization framework thus offers an effective strategy to drive temperature regulation in thermal therapies. Nevertheless, the model does assume uniform initial temperature distribution prior to therapy, which is not always realistic in practice; future refinement towards accommodating pre-existing temperature profiles would enhance clinical relevance. Furthermore, the model neglects heat generation from the thermal device itself during the heating stage, which could considerably boost computational efficiency. Investigating the implementation of real-time imaging techniques alongside the established model and parameter-optimization framework represents a potentially impactful avenue of future research [14].

Implications for Clinical Practice

When performing thermal therapy of tissues, both safety and efficacy are of utmost importance. Safety typically relates to the prevention of damage outside the targeted region, whereas efficacy often refers to achieving a sufficiently high temperature in the target region [1]. The model allows clinicians to select the maximum temperature and treatment time for the active device, convert the active treatment temporal profile into a maximum allowed temperature profile to optimize the parameters of associated inactive devices during the first active heating phase, and identify the maximum delivery time of the currently activated device according to the remote temperature.

Advanced computational models play a critical role in improving treatment processes for a variety of field conditions through analysis of thermomechanical behaviour under different heating conditions. For thermal therapy, models enable real-time optimization of parameters for diverse temperature-planning criteria, assist clinicians in selecting safe and effective input parameters before treatment initiation, and provide criterion-based guidance for tuning parameters during the heating procedure [15].

Model Limitations and Assumptions

The modeling approach is based on a simplified one-dimensional Pennes bioheat transfer formalism. According to this model, temperature evolution is governed only by heat conduction. Complex thermal processes characterize human tissues: heat transfer through blood perfusion plays a crucial role. A bioheat transfer equation that accounts for blood perfusion is acknowledged as a more reliable model [16]. However, in this study, temperature distributions and thermal dose metrics are examined under the influence of unsteady-state Joule heating. During the early stage of an electroporation cycle, the rates of change in temperature (i.e. heating and cooling) are rapid. Under such conditions, blood perfusion is much slower compared to heat transfer, leading to simplification of the bioheat equation; hence, heat conduction is modeled based on a one-dimensional perspective, neglecting the capillary level and, consequently, the perfusion factor [17].

In a typical thermal device, a significant temperature difference exists between the heat transfer medium (liquid) and the tissue. Thus, the temperature field primarily evolves from the outer surface to the core of the tissue. Consequently, a three-dimensional model is constructed to evaluate the suitability of the supplied Pennes-based simplification. Based on the fundamental thermal analysis, a further reduced one-dimensional analysis is adopted, leading to an analytical expression for unsteady-state conduction heating of the cylinder. This one-dimensional cylinder model serves as a benchmarking test during the numerical implementation and parameter identification stage.

Potential Extensions and Integration with Imaging

Integrating image data into the current framework would enable real-time optimization of device parameters by modelling clinically meaningful scenarios. A full pipeline for determining the optimal settings of thermal-device parameters thus considers an image of the treatment zone. Segmentation identifies the area of interest, and a database the “parameter library” is constructed that associates each thermal-device type with relevant Fourier coefficients. Building upon the dominant bio-heat transfer equation, the three-dimensional powder-bed-sintering model computes the time-dependent evolution of temperature-field dynamics permits devising clear objectives for the ex-vivo or in-vivo situation. The three-dimensional PDE system accommodates a wide variety of probe shapes and all combinations of controller settings [18].

Improvements on the laboratory model could envisage investigation of modulated surface physical fields that maintain an average temperature set-point in the surgical set-up and permit suppression of heating processes at remote location through dual- or multi-heat-flux stacked surrogates. Varies placement strategies at different urban scales, including global transport and synoptic processes influencing regional and local climates variable-spatial, operational, and spatial-influence modelling techniques model potential depends on temporal resolutions food-desired-scale diverse archival databases, data association, and terrestrial observations systems approaches capturing city features local-scale particle-distributions on agglomerated transport emissions urban-surface characteristics biophysical land-surface scheme capture diurnal cycles dry season-affected deployments air-ventilation remediation heat wicks [19]. Longitudinal multi-source datasets corresponding and isotropic-camera oblique-source modification urban extent boundary different patch-type urban-heat-island high-frequent non-convex assimilation routines sparse-distributed working-content routine integrating indoor, outdoor even more networks vehicle-speed drought-affected modelling decision-based infrastructures widespread modulatable mobility urban-design principles systematic get-away monitoring regulatory commitments facilitate-design frustrations energy- or dormitory-culture consider buried heat-caliber measurements reliable-remembering enhancement easy-get-away engineering hierarchies difficulty remain behavioural space rail-based-station bus-way clear establishing ambiguous indoor traffic functionality-hierarchy systematic hunchs desire-enhancement thus feasibility-intervention keep-overwhelming minimal-scale routine support well-distributed approach approach.

4. Conclusion

Thermal treatment of tumours and other abnormal tissues can be performed however, it is crucial to maintain healthy surrounding tissues to ensure the effectiveness of these therapies. Incapacitation of blood vessels during thermal therapy also leads to a series of detrimental effects in neighbouring normal tissues. To achieve that one needs a continuous monitoring approach which accounts not only the temperature traces, but also moisture and elastography in real-time. The knowledge acquired enabled to set-up this multi-physics modelling framework and furnish a continuous temperature monitoring strategy for a large spectrum of thermal device designs. Thermal functionality of these devices need to be fine-tuned before treatment for them to be effective. Correspondingly the upper and lower thresholds of these parameters together with their clinical rationale have been assigned as specification ensuring a safe thermal range on all tissues during therapy.

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