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Infrared Laser Applications in Ophthalmology - Thermal Considerations

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Abstract

This study presents an analysis of the thermal dynamics of transparent ocular tissues subjected to infrared laser radiation. From a thermodynamic perspective, the results support the clinical viability of utilizing infrared lasers for both vitrectomy and thermos-keratoplasty. Specifically, in the context of vitrectomy, thermal elevations resulting from vitreous vaporization via an intraocular laser probe remain substantially below the threshold for retinal damage at distances exceeding 2mm from the beam axis. Regarding thermos-keratoplasty, the findings demonstrate that peak thermal intensity can be spatially modulated, shifting the focus from the corneal epithelium to the stroma to facilitate targeted collagen contraction. Furthermore, this research outlines additional therapeutic applications for infrared lasers and underscores the critical importance of accurately characterizing the infrared optical properties of ocular media.

Keywords: Thermos-Keratoplasty, Infrared Lasers; Thermal Intensity.

Introduction

Lasers functioning within the visible spectrum constitute a cornerstone of therapeutic intervention in clinical ophthalmology. The inherent optical transparency of preretinal ocular media facilitates the unhindered transmission of focused, high-intensity radiation to specific intraocular targets. Upon exposure, the absorption of photon energy by pigmented structures or by adjacent pigmented tissues generates thermal elevations sufficient to induce photocoagulation. Clinically, this photo coagulative process is primarily utilized to facilitate the fusion of adjacent tissue layers, occlude pathological vasculature, or fenestrate pigmented anatomical structures [1-3].

While visible light lasers dominate ophthalmology, surgical specialties such as otolaryngology and gynecology predominantly utilize Carbon Dioxide CO_2 lasers, which emit radiation within the infrared spectrum at a wavelength of 10.6 m to 10.600 nm. This contrasts sharply with the visible spectrum 400-700nm [4]. Due to the high opacity of water to radiation at 10.6 m, the absorption kinetics of CO_2 laser energy by hydrated soft tissues are functionally analogous to the absorption of visible light by the retinal pigment epithelium. Clinically, the utility of the CO_2 laser relies on the transmission of energy through an air medium facilitated by endoscopic instruments such as laryngoscopes or colposcopes to target anatomical structures that are otherwise difficult to access. This modality enables precise incision and photocoagulation characterized by superior hemostasis and minimal collateral thermal injury to the surrounding parenchyma [5-9].

Historically, ophthalmic investigation into infrared lasers has been negligible, with the exception of preliminary assessments regarding corneal safety thresholds. The adoption of this technology was previously hindered by prohibitive costs and the efficacy of conventional surgical modalities for anterior segment intervention. However, the increasing ubiquity of Carbon Dioxide CO_2 lasers across diverse surgical disciplines has enhanced their accessibility, prompting a re-evaluation of the clinical utility of thermally modulating optically transparent ocular media [10]. Consequently, this report quantitatively analyzes the thermodynamic behavior of clear ocular media relative to the radial distance from the beam axis of a 1mm diameter intraocular CO_2 laser probe. The study examines four distinct exposure durations, standardized to induce a peak central temperature elevation of 65°C. To achieve this thermal endpoint, power outputs of 1.43, 0.42, 0.31, and 0.22 watts were necessitated for exposure intervals of 0.1, 0.5, 1, and 5 seconds, respectively [11]. Additionally, the inset delineates the spatiotemporal thermal distribution specifically the temperature rise versus radial distance at four temporal checkpoints during a constant 0.31watt irradiation. Infrared radiation and to discuss possible applications of infrared lasers in vitrectomy and thermos-keratoplasty [12-15].

Main objective of this investigation is the escalating prevalence of laser-based ophthalmic interventions, the complex interactions between laser radiation and diverse ocular tissues remain incompletely elucidated. This gap in knowledge is primarily attributed to anatomical constraints that preclude the invasive placement of measurement instrumentation without risking iatrogenic injury [16]. To mitigate these limitations, in silico computational modeling and high-fidelity surgical simulations have emerged as critical tools. These methodologies facilitate the non-invasive interrogation of intra-tissue thermodynamic behavior, thereby enabling the prediction of therapeutic efficacy and the refinement of clinical protocols. specifically, Sub-Threshold Micro-Pulse Laser (SMLP) therapy aims to elicit therapeutic outcomes by targeting the Retinal Pigment Epithelium (RPE) while preserving the neural retina from visible photocoagulative damage [17–19]. This modality triggers a cascade of biochemical responses, including the modulation of inflammatory pathways, tissue repair

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mechanisms, and the upregulation of RPE-mediated heat-shock proteins [20-22]. While simulations offer a unique capability to evaluate surgical strategies and predict thermal shock phenomena inaccessible to empirical measurement, their predictive validity is intrinsically contingent upon the accuracy of the underlying physical and optical tissue parameters [23].

Consequently, this study presents a comprehensive literature review of existing computational models to delineate the transient thermal effects within the eye. The primary objective is to identify the most robust values for critical parameters specifically density, specific heat, thermal conductivity, refractive index, and absorption coefficient as these variables govern thermal and optical propagation. Particular emphasis is placed on optical properties relevant to the 577 nm wavelength employed in contemporary photocoagulation modalities.

Patient and methods

Design of the Study

Infrared (IR) thermography is defined as the acquisition of surface temperature distributions via emitted radiation to generate a visual representation known as a thermogram. This technique provides a two-dimensional thermal map, distinguishing it from IR thermometry, which yields only a single-point temperature value. Furthermore, IR thermography is distinct from IR photography; the former detects emitted thermal radiation, whereas the latter captures infrared radiation reflected from an external source.

Setting of the study

The study was carried out over a period of approximately ten weeks. During this time, all patients who were clinically suspected of having acute appendicitis and who met the inclusion criteria were enrolled in the study.

The study instruments and sampling

Infrared (IR) thermography has been widely utilized in ophthalmology to investigate ocular physiology, pathology, and surgical outcomes. This modality facilitates the non-invasive assessment of ocular surface temperature (OST), revealing significant correlations between thermal profiles and various physiological or pathological ocular alterations. However, it is imperative to acknowledge that OST is influenced not only by intrinsic ocular changes but also by extrinsic environmental factors [24-25].

Vitrectomy is a cornerstone intervention in the management of vitreoretinal pathologies; however, conventional mechanical instrumentation carries the inherent risk of exerting tractional forces on adjacent structures during vitreous shearing. To mitigate this, the intraocular carbon dioxide (CO_2) laser has been proposed as a method to vaporize vitreous tissue without inducing traction. Due to the high absorption of 10.6 mu, radiation by water, safety profiles are favorable; it is estimated that less than 10^{-4} of emitted radiation penetrates beyond 0.1 mm from the laser tip, effectively sparing the adjacent retina. Thermal modeling of a 2 mm diameter spot size indicates that a temperature elevation of 65°C requires power inputs of 11.4 W, 2.32 W, 1.29 W, and 0.58 W for exposure durations of 0.1, 0.5, 1 and 5 seconds, respectively. Furthermore, radial heat distribution analysis confirms that thermal spread remains highly localized during these exposures.

Ethical Considerations

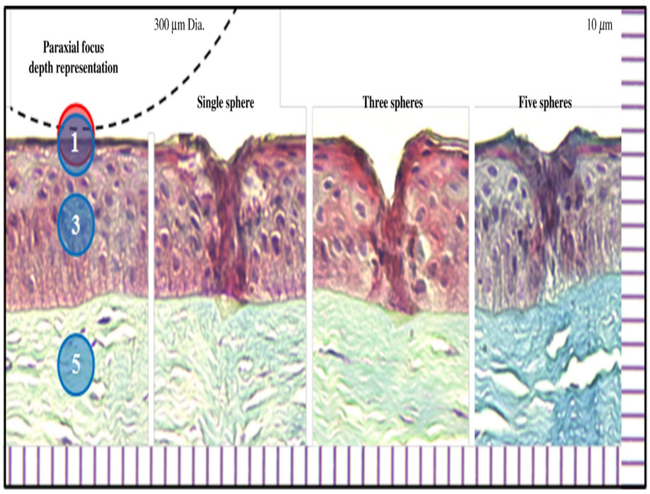
The study was conducted in compliance with ethical standards. Permission to access patient data and perform diagnostic evaluations was obtained from the respective hospitals. All patient data were anonymized to maintain confidentiality. If required by the institutional review boards, verbal or written consent was obtained prior to inclusion.

Results

Single pulse ablation craters were generated on hydrated corneal tissue utilizing a consistent pulse energy of sim 0.2 mJ. Energy delivery was quantified at the distal probe tip using a pyroelectric detector (ED-100A, Gentec, Saint-Foy, Canada). To account for variable attenuation across the different optical assemblies, laser output was modulated to normalize the incident energy to sim 0.2 mJ at the tissue interface for all tested geometries (one, three, and five sphere chains). This energy level was selected to exceed the ablation threshold of the single sphere configuration (sim 1 J/cm^2) by one order of magnitude, ensuring a standardized baseline for comparative analysis.

While initial transmission losses are dominated by Fresnel reflections approximated at 25% per configuration increment (representing four sapphire/air interfaces) losses diminish significantly with propagation length. In extended sphere chains, attenuation reaches negligible values of sim 0.1 dB/sphere. As detailed in prior studies [26], this efficiency is attributed to the progressive filtering of Periodically Focused Modes (PFMs), which intersect spherical interfaces at the Brewster angle, thereby minimizing reflection losses. Thermal injury was identified by hyper-pigmented regions within the samples. It is noted that stromal tearing and folding observed in the one and five-sphere micrographs were classified as histological processing artifacts extending into native tissue, distinct from laser induced damage. However, subtle stromal alterations (yellow staining) observed in the one- and three-sphere groups were indicative of deeper thermal penetration compared to the five-sphere configuration.

Figure 1: *Trichrome histology of ablation craters created in the epithelium layer of porcine cornea using a detachable microsphere scalpel with integrated illumination. The dashed line illustrates the physical scalpel tip with 300-µm diameter for size comparison.*



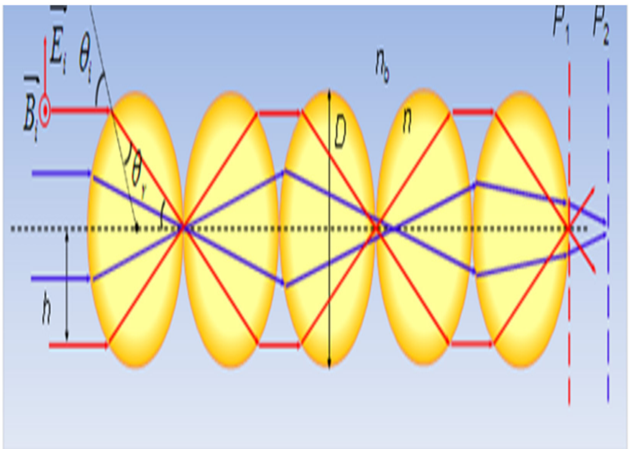
Given the inherent optical transparency of corneal tissue, histological evaluation was requisite to quantify the dimensions of ablation craters and the extent of collateral thermal injury. Immediately following the laser intervention, globe specimens were fixed in formalin. To isolate the region of interest, the eyes underwent latitudinal sectioning oriented to the pupillary axis (pole), with peripheral tissue excised to preserve only the polar corneal button. These specimens were subsequently trimmed to longitudinal sections of approximately ~1 mm, thickness and processed using Masson's Trichrome staining. Morphometric analysis was conducted utilizing an optical microscope interfaced with a CCD digital imaging system. (Figure 1), presents representative micrographs for each sphere configuration, including a native control sample to visualize the focal characteristics of the Periodically Focused Modes (PFM) versus paraxial foci for the ~300mu sphere assemblies.

Discussion

Short ablation depths with small thermal damage regions have been achieved with Er:YAG laser probes in the previous studies [3–17,32]. However, our contact mode mid-IR microsphere scalpel can create spatially small ablation craters below the limit of current intraocular fiber delivery systems, while using a less powerful laser source. Sapphire microspheres with a refractive index of 1.71, used as lenses, focus laser light at the sphere's surface creating a robust contact laser device where the transmission medium will not affect the device's performance. By building these sphere chains inside an air filled HWG's tip and sealing it to the end sphere, all internal focusing surfaces maintain their relative refractive indices even when submerged in the vitreous.

Ablation crater depths on corneal tissue were measured between 10 and 25 µm. Previous studies [26,27] were performed with a less optimal larger end sphere and at a pulse energy of ∼0.1 mJ. In contrast, this study used identical diameter spheres and a pulse energy of ∼ 0.2 mJ. The much smaller depth of ablation craters and more compact thermal damage zone observed for the five-sphere chain is due to the mechanism of self-limiting depth of surgery discussed in Sec. 2 and schematically illustrated in (Figure 2). Although retinal tissue has different optical and mechanical properties than cornea, by using the Er:YAG laser which has such a strong water absorption peak, future retinal tissue ablation results may be comparable. Removal of small deposits with thicknesses between 20 and 50 µm on top of the retina, while minimizing damage to the retina which has a thickness ranging between 150 and 300 µm, is the primary goal of this scalpel design.

Figure 2: *Different depth of focuses for different modes based on spherical aberrations in odd-numbered sphere chains.*



The purpose of the left section is to better illustrate the scale of the sphere to the corneal layer tested as well as overlay the approximate focal points of the paraxial rays. The one sphere case shows that the PFM and paraxial focus are near the sphere's surface which combine to form a spatially larger, and not self-limiting ablation depth causing deeper thermal damage beyond the crater and reaching the stroma. However, the crater is shallow corresponding to a drop-off in energy density as seen in (Figure 2). For the three sphere case, the energy density does not drop off significantly immediately because the PFM combined with the paraxial modes form a thinner but longer region for ablation up to a ∼ 40 µm depth, which is achievable with the erbium:YAG laser due to cavitation bubble effects. However, for the five-sphere case, the paraxial modes are focused too deep into the tissue to have any significant effect on energy density at the surface, and since the five-sphere chain's intensity drops off significantly at ∼10µm depth, the crater and thermal damage are shallower.

Although not observed or characterized in this preliminary study with corneal tissues, it is possible that exploding and imploding vapor bubbles at the treatment site may result in mechanical damage to other more delicate ophthalmic tissues of interest such as the retina, which do not have the same robust mechanical properties as the cornea. We believe that these bubbles are highly localized and shallow, and therefore will not cause significant mechanical tissue damage due to the low pulse energy, small spot diameter, and contact mode application of our probe. In our theoretical model, we assumed that these cavitation bubbles, which are formed almost immediately at the beginning of each pulse, act as a low absorption conduit to allow the Er:YAG laser energy to travel deeper into the tissue. The Er:YAG laser only has an optical penetration depth of ∼10 µm in water at high temperatures; however, the longer pulse duration could be responsible for the depths of thermal heating measured in the histology. Due to the bubbles' small size and rapid dispersion, they should not obscure the surgeon's vision. However, further detailed studies utilizing a high-speed camera to directly image the cavitation bubble dynamics during mid-IR ablation of both corneal and retinal tissues will be necessary in future work to confirm these claims.

Regarding the use of such ultraprecise laser scalpels in the intraocular surgery, it should be noted that it might be suitable for cutting and delaminating of the membranes rather than for their areal ablation. The speed of cutting can be significantly increased by using diode-pumped erbium:YAG lasers with the higher pulse repetition rates on the order of 1000 Hz. Use of the proposed device in combination with the mechanical tissue holders and picks may be helpful for reducing the surgical time and achieving the best surgical outcomes. More studies are required to develop the actual surgical procedures; however, it is apparent that the safety and high speed of tissue cutting may be potential advantages for such ultraprecise laser scalpels.

By integrating multiple functions like illumination into a single ophthalmic handpiece, the singular surgeon also gains more surgical freedom for simultaneous use of other devices in the otherwise occupied hand. We have improved upon the previous single function microsphere probe by integrating enhanced illumination into the otherwise wasted space of the HWG. Also, by making the microsphere scalpel detachable and disposable between procedures, the expensive germanium oxide trunk fiber is preserved representing significant cost savings. Other instruments commonly used in intraocular surgery could also be integrated with the microsphere scalpel. The most obvious is the vitrector or the suction device used to remove debris from the vitreous. By placing a vitrector tip directly adjacent to the microsphere scalpel, any debris created from the ablated tissue or small sections of tissue cut free by the scalpel is instantly removed from the surgical site. However, the current microsphere scalpel is considered a 20 gauge (∼900 µm OD) instrument, which is on the large side of current instruments which are 25+ gauge (∼500 µ m OD).33,34 It may be possible to replace the large HWG and miniaturize the microsphere scalpel, since the key optical components are the 200-µm-OD germanium oxide fiber and a chain of five 250 µm microspheres; however, preliminary studies have shown larger contact-mode spatial beam diameters when putting the fiber in direct contact with the microsphere chain.

Conclusion

The foregoing analysis has examined thermal elevations induced by the absorption of infrared laser radiation within transparent ocular tissues. The resulting thermal models elucidate the correlation between temperature profiles and optical absorption coefficients, thereby substantiating the thermodynamic viability of infrared laser vitrectomy and TKP. While distinct from clinical practicability and acknowledging the merits of alternative physical modalities, these findings hold substantial clinical relevance for the refinement of vitrectomy instrumentation and the advancement of safe, non-invasive techniques for modifying corneal curvature. Furthermore, this fundamental thermal analysis is applicable to other ocular media and highlights the critical need for precise quantification of their infrared optical properties. Ultimately, the data suggest a broad spectrum of therapeutic applications for infrared lasers, ranging from the management of pathological myopia and thermal inactivation of resistant corneal viral pathogens to novel approaches for extracapsular cataract extraction and the treatment of orbital neoplasia.

Recommendations and Future Research

Based on the thermal analysis and clinical potential discussed in the text, here are five academic recommendations and future research directions for Infrared Laser Applications in Ophthalmology. High-resolution quantification of optical properties, prioritize the development of a comprehensive database of infrared optical properties (absorption coefficient, scattering coefficient, and anisotropy) for specific ocular tissues (cornea, aqueous humor, lens, vitreous) across a continuous spectrum of infrared wavelengths rather than discrete points. Conduct spectroscopic mapping of age-dependent changes in ocular media transparency. Research should quantify how the water content variations in the aging vitreous or sclerotic lens affect thermal relaxation times and laser energy absorption thresholds.

Integration of real-time thermal feedback mechanisms, while thermodynamic feasibility is established, clinical safety relies on preventing collateral thermal damage (e.g., endothelial damage during corneal reshaping) Develop "closed-loop" laser delivery systems that utilize non-contact real-time temperature monitoring. This would allow the system to dynamically adjust power density or pulse duration if the tissue temperature approaches the threshold for denaturation or necrosis. Investigate the integration of infrared thermography or optical coherence tomography (OCT)-based thermometry directly into surgical microscopes to provide surgeons with a heat-map overlay during procedures like Laser Thermal Keratoplasty (LTK).

Biomechanical Stability in Corneal Remodeling, the text mentions "altering corneal curvature" for myopia, but historically, thermal reshaping (like TKP) suffers from regression (the cornea returning to its original shape). Research must move beyond immediate thermal effects to long-term biomechanical stability. Recommendations should include combining thermal laser treatments with chemical stiffening agents to "lock in" the refractive change. Evaluate the efficacy of combined protocols using Infrared Laser remodeling followed by Corneal Collagen Cross-linking (CXL). Longitudinal studies are needed to determine if this hybrid approach prevents the regression of corneal curvature changes over 1–5 years periods.

Optimization of Pulse Structure for Pathogen Inactivation, the potential to treat "resistant viral infections" suggests a narrow therapeutic window where the virus is inactivated without harming the host corneal stroma. Move away from Continuous Wave (CW) lasers toward ultra-short pulsed laser systems for this application. The goal is to maximize the peak temperature of the target (pathogen) while keeping the total energy delivered low enough to protect the surrounding transparent media (thermal confinement). Define the Arrhenius damage integrals specifically for resistant viral strains (e.g., Herpes Simplex, Adenovirus) versus corneal keratocytes. Establish a safety ratio that defines the exact laser parameters required to achieve viral inactivation while maintaining stromal transparency.

Advanced Modeling for Intraocular Applications, develop complex 3D finite-element models (FEM) that account for fluid dynamics (convection) in the eye. Simple static models may overestimate heating because they ignore the natural cooling effect of aqueous humor circulation and choroidal blood flow. Simulate the thermodynamic impact of convection currents induced by laser heating in the vitreous cavity. Research should determine if laser-induced convection aids in the procedure (by moving debris) or poses a risk to the retinal pigment epithelium (RPE).

Conflict of Interest

The authors declare no conflict of interest

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