Review Article

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Super-Pulsed Diode Lasers in Oral Applications: A Comprehensive Review of Clinical Evidence and Mechanisms

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Abstract

Super-pulsed diode laser systems, characterized by peak power output of 100-300 W delivered in pulse durations of microseconds to nanoseconds with duty cycles <5%, have demonstrated superior clinical outcomes compared with Continuous-Wave (CW) and conventional Pulsed Wave (PW) modes in oral surgery and Photobiomodulation (PBM). By maintaining low average power output while delivering high instantaneous energy densities, super-pulsed operation minimizes peripheral thermal damage, reduces postoperative morbidity and expands the clinically achievable depth of photon delivery for therapeutic applications. This review synthesizes evidence from histological, thermal and clinical studies and clarifies the mechanisms by which pulse structure influences tissue penetration and thermal safety.

Keywords: Diode Laser; Super-Pulsed; Photobiomodulation; Thermal Damage; Tissue Penetration; Oral Surgery; Soft-Tissue Management

Introduction

Near-Infrared (NIR) diode lasers operating at 810-980 nm wavelengths have become established tools in contemporary dental practice for soft-tissue surgical procedures, hemostasis and therapeutic biostimulation [1,2]. Conventional diode platforms operated in Continuous-Wave (CW) or basic Pulsed (PW) modes present a fundamental thermal challenge: achievement of efficient ablation or high-dose photon delivery necessitates energy deposition rates that generate substantial collateral heat, thereby widening zones of tissue damage that compromise histological specimen quality and patient postoperative outcomes [3,4].

The emergence of super-pulsed diode technology addresses this thermal constraint through refinement of pulse-generation electronics. These systems deliver peak power outputs of 100-300 W in extremely brief pulse durations (nanoseconds to low microseconds) while maintaining average power outputs of 1-5 W through very low duty cycle operation (typically <5%) [5,6]. When pulse duration is substantially shorter than the thermal relaxation time of target chromophores and tissue water, energy deposition remains confined to microscopic volumes, allowing rapid heat dissipation during inter-pulse intervals [5-7]. This operational approach enables precise soft-tissue excision with histological margins comparable to mechanical instruments, concurrent with high-dose photobiomodulation for deep anatomical targets without nociceptor activation or epidermal injury [8-10]. The operational characteristics of super-pulsed systems enhance the clinical understanding of tissue penetration depth, demonstrating that therapeutic photon delivery to deep targets can be substantially enhanced through optimization of thermal tissue dynamics without alteration of fundamental wavelength-dependent optical properties [11-13]. This review synthesizes current evidence regarding super-pulsed diode laser technology, compares thermal and histological outcomes with CW and PW modes, clarifies mechanisms of enhanced penetration depth in therapeutic applications and provides evidence-based guidance for clinical implementation [14,15].

Physical Principles: Thermal Characteristics of CW, Pulsed and Super-Pulsed Operation

Continuous-Wave (CW) Operation

In CW mode, uninterrupted photon emission results in linear and cumulative heat accumulation at the tissue interface [3-5]. The rate of thermal energy generation typically exceeds the rate of dissipation through tissue-to-ambient conduction and blood flow-mediated cooling, resulting in progressive temperature elevation during laser exposure [3,4]. Thermal diffusion extends the zone of coagulation and carbonization 0.5-3 mm beyond the primary incision margin, with extent dependent on wavelength, power output, exposure duration and tissue vascular perfusion [4,5,17]. While CW operation offers rapid cutting and effective hemostasis, the expanded thermal injury zone compromises histopathological margin assessment and increases postoperative pain, edema and inflammatory response [3,5].

Conventional Pulsed (PW) Operation

Standard pulsed diode platforms employ pulse durations ranging from milliseconds to hundreds of microseconds (typically 10-500 ms or 50-200 μs), with peak power outputs only 1.5-3 times the average power and duty cycles of 20-50% [3,5,18]. Although this temporal structure permits partial thermal relaxation between successive pulses, relaxation remains incomplete; successive pulses deposit energy into overlapping tissue volumes that have not returned to baseline temperature, resulting in net cumulative thermal loading [3,5]. The dominant interaction mechanism remains photothermal, driven by fusion, vaporization and coagulation processes [5,18]. Peripheral thermal damage zones typically measure 0.3-1.5 mm [3,5].

Super-Pulsed Operation

Super-pulsed systems generate extremely brief pulse durations-typically 10-500 nanoseconds or single-digit microseconds-at peak power outputs of 100-300 W, maintained within the range of 1-5 W average power through duty cycles of 0.1-5% [5,6,19]. Critically, pulse duration is substantially shorter than the thermal relaxation time of water and target chromophores (approximately 10-100 microseconds), enabling energy deposition confined to microscopic volumes [5,6]. Heat dissipates during inter-pulse intervals before significant additional energy arrival, resulting in minimal cumulative thermal loading [5,6,20].

This thermal characteristic produces several practical consequences: surface temperature rise of <2-3°C despite cumulative fluence values of 10-12 J/cm²; reduction of peripheral thermal injury zones to 0.1-0.3 mm; minimal carbonization and collagen denaturation; and tissue ablation via combined photomechanical mechanisms (water expansion, thermomechanical disruption) alongside direct vaporization [5,6,19,20].

Tissue Penetration Depth: Enhancement of Therapeutic Delivery

Optical Penetration and Thermal Barriers

Classical understanding of laser penetration depth in biological tissue defines this parameter as the reciprocal of the effective attenuation coefficient-a composite function of wavelength-dependent absorption and scattering coefficients [21-23]. For NIR diodes (810-980 nm) in oral soft tissues, theoretical optical penetration depth values approximate 2-5 mm, determined by water absorption (elevated at 980 nm) and hemoglobin/melanin absorption (elevated at 810 nm) [21-23].

In clinical practice, however, CW and conventional PW operation at moderate-to-high irradiance (>200-500 mW/cm²) produces substantial superficial heating within seconds, triggering vasodilation, tissue edema, increased blood perfusion and elevation of tissue water content [24-26]. These changes induce progressive refractive index mismatches at tissue layer interfaces, substantially amplifying light scattering and attenuating photon transmission to deeper structures [24-26]. Additionally, even brief elevation of cutaneous temperature above 42-45°C activates C-fiber nociceptors, producing pain and forcing clinician reduction of irradiance or exposure duration, which further limits total fluence delivery to deep targets [27,28].

Super-Pulsed Advantages for Depth

Super-pulsed systems circumvent the thermal barrier by restricting heat generation to microscopic nanosecond-duration events, each separated by microsecond-to-millisecond intervals permitting nearly complete thermal relaxation [5,29,30]. Even at peak power densities of 100-300 W, surface temperature elevation remains minimal (<1-2°C) because average power output is low and inter-pulse cooling dominates [5,29,30].

Thermographic and spectroscopic studies have documented that super-pulsed operation at 810 nm achieves transmission of 20-50% greater optical power through 1-3 cm of muscle and subcutaneous tissue compared with CW delivery at equivalent total energy, attributed to preservation of low surface temperature, minimal scattering augmentation and maintained optical transparency [12,29,30,31]. This expansion of the thermal safety window directly enhances clinical depth capacity: targets located 1-3 cm below the surface now receive therapeutic fluence within clinically practical timeframes and minimal surface discomfort [5,12,29,30].

This enhancement of therapeutic delivery capacity is particularly significant for deep-target photobiomodulation. Temporomandibular joint disorders, neuropathic pain conditions and deep muscular dysfunction now benefit from super-pulsed NIR delivery permitting safe achievement of therapeutic fluence-a clinical capability that was marginal or impossible with conventional CW/PW platforms without dangerous parameter escalation [13,32,33].

Histological Evidence of Reduced Thermal Damage
Comparative Analysis
Multiple *ex-vivo* studies have systematically quantified peri-incisional thermal injury across laser modalities using standardized tissue models, most commonly porcine oral mucosa and skin. Thermal damage zone assessment typically employs histomorphometric analysis of biopsy specimens excised perpendicular to incisions, measuring epithelial necrosis width, collagen denaturation, charring and depth of thermal alteration at standardized distances from cut margins [5,34,35].

A 2022 comparative analysis directly evaluated micro-pulsed (μPW, ~100 microsecond pulses) versus super-pulsed (SPW, nanosecond pulses) diode laser operation on porcine tissue. Under conditions producing equivalent excision times, super-pulsed operation demonstrated significantly narrower thermal injury zones (mean 0.2-0.4 mm lateral thermal damage) compared with micro-pulsed settings (0.8-1.5 mm lateral damage) [2]. Cut quality and depth were preserved in super-pulsed operation and hemostatic effectiveness was equivalent between modalities [2]. Carbonization and charring extent were substantially reduced with super-pulsed operation [2].

Comparable findings have been reported across multiple wavelengths and tissue models. Histological *ex-vivo* evaluation of 808 nm, 980 nm and 976 nm diode laser operation demonstrates that reduction of pulse duration and increasing peak power (while maintaining low duty cycle) progressively narrows thermal damage band width, with super-pulsed protocols achieving margin quality comparable to mechanical cold-steel instrumentation when appropriate average power and exposure duration parameters are maintained [35-37].

Pathology Significance
From diagnostic pathology perspective, excessive peri-incisional thermal artifact significantly impacts specimen interpretability and diagnostic reliability. Thermal hyalinization and charring obscure epithelial architectural features critical for dysplasia grading in potentially malignant lesions. Preservation of histoarchitectural details and reduced thermal artifact with super-pulsed diode operation have direct clinical consequences for lesion surveillance accuracy and treatment planning decisions [2,5].

Clinical Applications and Outcomes
Diagnostic Biopsy and Soft-Tissue Procedures
Quality of excisional margins directly influences pathologist confidence in dysplasia assessment and adequacy of lesion evaluation [35,36]. Super-pulsed diodes facilitate clean, interpretable specimen margins with decreased re-biopsy risk [2,9]. The reduced collateral inflammation correlates with decreased postoperative edema and accelerated healing kinetics [2,9]. Recent clinical documentation has reported shorter healing timeframes and improved patient-reported comfort with super-pulsed diode biopsies compared with traditional electrosurgical approaches or CW diode operation [2,38].

In frenulum removal, gingival recontouring and peri-implant soft-tissue management procedures, clinical objectives extend beyond tissue removal to achievement of minimal postoperative pain and edema, rapid healing and precise functional and aesthetic contours [9,38]. Multiple clinical reports document that super-pulsed diode techniques achieve faster healing, reduced postoperative pain and more predictable gingival form compared with traditional approaches [9,39].

A clinical study directly comparing 810 nm and 980 nm diode operation during implant surgery documented significantly greater temperature elevation with 980 nm operation, accompanied by increased patient-reported discomfort [40]. The authors concluded that 810 nm wavelength combined with super-pulsed temporal delivery provided superior thermal control and patient tolerance [40].

Photobiomodulation Applications: Efficacy and Thermal Integration

Mechanisms and Evidence Foundation

Photobiomodulation-non-thermal application of light to stimulate cellular and tissue responses-typically employs wavelengths in visible-red (600-700 nm) and near-infrared (700-1100 nm) ranges to activate mitochondrial cytochrome c oxidase and additional chromophores, increasing ATP production, reducing oxidative stress and modulating inflammatory signaling pathways [41-43]. Systematic reviews and meta-analyses across multiple medical specialties support clinical efficacy of photobiomodulation for pain reduction, tissue healing and regenerative outcomes when appropriate parameters are employed [41-43].

In dental practice, photobiomodulation indications include temporomandibular disorders, oral mucositis, periodontal regeneration, implant osseointegration, post-endodontic pain management and neuropathic pain conditions [41-45]. Photobiomodulation efficacy demonstrates dose-dependence, with most clinical protocols targeting 2-30 J/cm² depending on target depth and tissue type [41,43]. However, efficacy is highly sensitive to thermal side-effects: temperature elevation exceeding 3-5°C negates antalgic and anti-inflammatory benefits through nociceptor sensitization and inflammatory cascade activation [41,43,46].

Super-Pulsed Advantage

This thermal constraint resolution represents a decisive advantage of super-pulsed technology. Superficial targets can be adequately treated with conventional CW/PW diodes at low power output. However, deep targets-temporomandibular joint capsule, pterygoid and deep masseter musculature, inferior alveolar nerve trunk-present clinical challenges with standard CW operation requiring either impractically long exposure times or moderate power with substantial risk of superficial thermal damage [5,27,28,33].

Super-pulsed systems maintain low surface thermal signatures even at cumulative fluence of 10-15 J/cm², enabling delivery of therapeutic doses in clinically practical timeframes (typically 1-3 minutes per anatomical region) while maintaining surface temperature elevation <1-2°C [5,27,28,33].

Preclinical animal model studies utilizing thermographic and spectroscopic analysis have demonstrated that 810 nm super-pulsed diode operation achieves superior penetration and deeper target stimulation compared with CW NIR delivery at equivalent total energy [31,33]. Clinical reports documenting temporomandibular dysfunction and pain management support application of super-pulsed NIR photobiomodulation protocols for symptom reduction and functional improvement [32,33].

Expanded Safety and Efficacy Window

A critical insight is that super-pulsed photobiomodulation expands the therapeutic window-the range of irradiance and fluence parameters that can be safely applied-by enlarging the thermal safety margin. This expansion permits delivery of higher cumulative doses, extended treatment duration per anatomical region, and/or larger treatment areas without thermal penalty, thereby enabling clinically meaningful photobiomodulation effects in deeper anatomical structures [5,12,29,33].

Safety Framework and Evidence Limitations

Thermal Safety Principles

Despite the thermal advantages of super-pulsed operation, inappropriate parameter combinations-elevated average power, reduced spot size, stationary beam delivery, elevated duty cycle-retain capacity to produce excessive thermal loading and tissue damage [3,5,47,48]. Histological and thermographic investigations consistently demonstrate that, for equivalent fluence targets, energy concentration into very brief dwell times or extremely small spots produces peak tissue temperatures negating benefits of brief pulse delivery [47-49].

Essential safety principles for super-pulsed diode application include: prioritizing J/cm² and W/cm² dosimetry over nominal peak power; maintaining continuous dynamic scanning for photobiomodulation applications; preferring 810 nm wavelength for deep-target applications; implementing conservative parameter escalation; systematic documentation of all parameters; monitoring patient-reported thermal sensation; and implementing parameter reduction (20-30%) for tissues with elevated melanin content [47,48,50].

Evidence Base Limitations

While super-pulsed diode laser evidence is accumulating, several limitations warrant acknowledgment. The majority of *ex-vivo* thermal and histological studies employ animal tissue models; direct validation on human tissue remains limited [2,48]. Randomized controlled clinical trials directly comparing well-optimized CW/PW protocols with super-pulsed regimens at equivalent fluence across multiple oral indications remain sparse [2,48]. Long-term clinical outcomes documentation (>12 months follow-up) following super-pulsed photobiomodulation in large patient cohorts has not been systematically published [41]. Optimal pulse parameter specifications for different tissue types and specific clinical indications require further characterization [2,5]. Comparative cost-effectiveness analysis of super-pulsed versus conventional diode platforms in routine practice settings remains absent from the literature.

Further well-designed prospective clinical trials with standardized dosimetry protocols, objective outcome assessment and sustained follow-up periods are needed to establish comprehensive evidence-based clinical practice guidelines specific to super-pulsed diode laser applications in dental medicine [2,5,41].

Conclusion

Super-pulsed diode laser systems represent a meaningful technical and clinical advance in laser-assisted dental practice by achieving harmonization of high-power optical energy delivery with excellent thermal safety profiles. Through temporal decoupling of peak power from average power via ultra-short pulse generation and very low duty cycle operation, these systems accomplish three major clinical objectives:

- Precision soft-tissue surgery: Rapid soft-tissue excision with minimal peripheral thermal damage, excellent histopathological margin preservation and reduced postoperative pain and edema-clear advantages over CW and conventional PW operation in biopsy procedures and soft-tissue management
- Deep-target photobiomodulation: Delivery of therapeutic photon fluence to deep anatomical structures (nerve, joint capsule, muscle) without nociceptor activation or epidermal injury-expanding clinically achievable therapeutic depth substantially beyond constraints imposed by thermal limitations in CW/PW systems
- Integrated surgical-therapeutic approach: Single chairside platform combining efficient hemostasis with evidence-based regenerative photobiomodulation, supporting comprehensive, modern laser-assisted dental practice

Enhancement of therapeutic photon delivery to deep tissues through super-pulsed operation reflects removal of thermal safety barriers that previously prevented full utilization of wavelength penetration capacity. This distinction clarifies why super-pulsed operation is particularly effective for deep-target photobiomodulation: it expands the practical depth to which therapeutic fluences can be delivered safely within clinically reasonable treatment timeframes. For clinicians implementing super-pulsed diode technology, rigorous adherence to evidence-based thermal management principles is essential. When deployed within this systematic framework, super-pulsed diode systems represent a well-supported option for contemporary, integrated laser-assisted dental practice.

Conflict of Interest Statement

All authors declare that there are no conflicts of interest.

Informed Consent Statement

Informed consent was taken for this study.

Authors' Contributions

All authors contributed equally to this paper.

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