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Review

Photobiomodulation Applications in Veterinary Surgery: Current Status and Future Perspectives

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Abstract

Photobiomodulation (PBM) has emerged as a noninvasive therapeutic tool with promising clinical applications in veterinary surgery. Its mechanism of action is based on the stimulation of cellular processes through low-intensity light, promoting adenosine triphosphate production, inflammatory modulation, and tissue regeneration. This narrative review examines the current state of knowledge on the use of PBM in veterinary surgical contexts, with an emphasis on its clinical application in wound healing, postoperative pain control, and functional recovery. The physiological foundations of the technique, the main technical parameters that determine its effectiveness (wavelength, dose, frequency, and mode of application), and the available clinical evidence from different specialties such as soft tissue surgery, orthopedics, dentistry, and neurosurgery are analyzed. Current limitations, such as the lack of standardized protocols and their limited inclusion in clinical guidelines, are also addressed, as are future opportunities related to treatment personalization, the development of specific veterinary devices, and integration with emerging technologies. PBM represents a safe and effective adjuvant therapeutic strategy with the potential to become an integral part of veterinary postoperative management.

Keywords: photobiomodulation (PBM); near-infrared light; light–tissue interaction; veterinary surgery; therapeutic laser; healing; analgesia; postoperative rehabilitation; low-level laser therapy; tissue biomodulation

1. Introduction

Photobiomodulation (PBM), formerly known as low-level laser therapy (LLLT), is a noninvasive therapeutic technique that uses specific wavelengths of red and near-infrared light to induce beneficial cellular responses in living tissues [1]. In recent decades, PBM has been widely adopted in human medicine and, more recently, in veterinary medicine, especially in the surgical context [2–5].

The mechanism of action of PBM is based on the absorption of photons by mitochondrial chromophores, especially cytochrome c oxidase (CcO), which leads to increased ATP production, modulation of nitric oxide (NO), decreased oxidative stress, and activation of cellular signaling pathways such as NF-κB and MAPK [6,7]. These effects trigger biological processes including cell proliferation, migration, neovascularization, and collagen synthesis, all essential for tissue repair [8].

In animals undergoing surgery, PBM has been shown to accelerate wound healing, reduce postoperative pain, and modulate inflammation [9,10]. For example, in dogs undergoing orthopedic surgery, for example, Tibial Plate Leveling Osteotomy (TPLO), PBM was associated with a lower incidence of postoperative infections, although without significant differences in pain or weight bearing [9]. In the case of infected or difficult-to-heal wounds (such as in diabetic patients), PBM has shown positive effects by stimulating epithelialization and decreasing the chronic inflammatory response [11,12].

In addition to its benefits in tissue regeneration, PBM has been recognized as an effective tool in the management of postoperative pain in animals due to its ability to modulate neuronal pathways and promote the release of endogenous opioids [13,14].

However, one of the greatest challenges in the clinical application of PBM in veterinary surgery is the lack of standardized protocols. There is wide variability in the parameters used, such as wavelength, energy density, session duration, and frequency [15,16]. Furthermore, patient-specific factors, such as coat color and thickness, can affect treatment penetration and efficacy [17].

In experimental rat models, PBM has been shown to increase type I collagen production and improve tissue architecture in infected wounds [18]. Furthermore, it has been observed that different wavelengths (red, blue, orange) can have distinct effects on cell proliferation and keratinocyte migration, opening therapeutic possibilities tailored to each clinical situation [16].

Despite growing evidence, controlled clinical studies in different animal species are still needed to validate the efficacy of PBM and define optimal protocols based on the type of surgery, tissue treated, and patient characteristics [19,20].

The objective of this review is to analyze the status of PBM in veterinary surgery, exploring its mechanisms of action, in vivo clinical applications, technical parameters used, and current limitations, to identify opportunities for improvement and future lines of research in veterinary clinical practice.

2. Fundamentals and Action Mechanism

PBM, is a noninvasive therapeutic modality that uses light at specific wavelengths (generally between 600 and 1100 nm) to induce beneficial biological responses in living tissues without generating heat. Although initially developed for applications in human medicine, in recent decades it has gained increasing relevance in veterinary medicine, especially in surgical, orthopedic, and dermatological contexts, due to its ability to modulate cellular processes such as inflammation, pain, and tissue healing [3,5,21].

The effectiveness of PBM lies in its ability to interact with specific cellular chromophores, triggering a cascade of biochemical events that therapeutically alter cellular function [22,23]. To fully understand its clinical application in veterinary surgery, it is essential to analyze the cellular and molecular mechanisms that underlie its biological action. The main physiological foundations and signaling pathways involved in the therapeutic effects of PBM are detailed below.

i. *Cellular Light Absorption and Primary Chromophores*. The main intracellular chromophore targeted by BMF is CcO, located in the mitochondrial electron transport chain. Light absorption by this enzyme induces an increase in ATP production, a transient increase in reactive oxygen species (ROS), and the release of NO [1]. NO, when displaced from CcO, allows for greater respiratory efficiency, thus improving cellular energy production [24].
ii. *Activation of intracellular signaling pathways*. Increased mitochondrial activity triggers cellular signaling pathways such as PI3K/AKT, MAPK/ERK, and NF-κB, which are involved in processes such as cell proliferation, protein synthesis, and the inhibition of apoptosis [23,25]. Activation of the PI3K/AKT system is particularly relevant for the migration and proliferation of fibroblasts, endothelial cells, and keratinocytes [26].
iii. *Stimulation of angiogenesis*. PBM also promotes angiogenesis through the activation of the VEGF/VEGFR2/STAT3 pathway. This pathway has been implicated in the nuclear

translocation of growth factors, which stimulate the formation of new blood vessels, essential for tissue regeneration in surgical wounds [23].

iv. *Modulation of oxidative stress and inflammatory processes*. The controlled release of ROS during PBM acts as a cellular second messenger, regulating inflammatory processes. A reduction in the expression of proinflammatory cytokines such as -6 and TNF-α, and an increase in IL-10, an anti-inflammatory cytokine, has been observed, facilitating a more rapid resolution of the post-surgical inflammatory process [22].

v. *Regulation of Intracellular Calcium and Ion Channels*. Voltage-gated calcium channels and TRP channels have also been identified as targets of BMF. Modulation of these channels can impact muscle contraction, neuronal signaling, and cell secretion [24].

vi. *Promotion of Cell Differentiation and Proliferation*. In the presence of growth factors, such as platelet-rich plasma, BMF enhances cell proliferation and bone mineralization, as observed in osteoblastic cell lines and bone models [27].

vii. *Wavelength and Dosage Considerations*. The most effective wavelengths are between 630-660 nm and 800-850 nm, the latter being more suitable for deep tissues due to its greater penetration [11,13].

viii. *Application in* in vivo *animal models*. Studies in rat and dog wound models have shown that PBM applied daily with 600-800 nm lasers accelerates wound closure, increases type I collagen expression, and improves tissue architecture [21]. In canines, PBM applied after dental procedures significantly reduced gingival inflammation [4].

ix. *Applications in the nervous and musculoskeletal systems*. PBM has also been shown to be effective in pain modulation and nerve recovery, especially in cases of intervertebral disc disease in dogs, by targeting spinal cord inflammation and promoting axonal regeneration [28,29]. However, the biological response to PBM follows a dose-response curve in the form of a “therapeutic window,” where low doses are biostimulatory, but high doses can be inhibitory or even harmful [30].

3. Clinical Evidence in Veterinary Surgery

The application of PBM in veterinary surgery has garnered growing interest due to its positive effects on wound healing, postoperative pain reduction, and inflammation modulation. Although most of the initial research was conducted in human medicine, clinical and preclinical animal studies have demonstrated that the cellular mechanisms activated by PBM are equally effective in veterinary tissues, opening a new therapeutic field in animal surgery [31–34]. This section provides a detailed review of the available evidence on the clinical efficacy of PBM in various veterinary surgical contexts, including wound healing, postoperative recovery, pain management, and the optimization of perioperative protocols.

The analysis is organized by specific clinical areas to facilitate understanding of the impact of PBM according to the surgical indication. Although there is wide heterogeneity in the parameters used (wavelength, energy density, duration, and frequency), the studies agree on their main findings: PBM improves recovery times, reduces the use of analgesics, and improves the quality of regenerated tissue in multiple animal species.

3.1. Wound Healing and Tissue Regeneration

One of the fields with the greatest evidence for the use of PBM in veterinary surgery is wound healing. Exposing surgical tissues to low-intensity laser or LED light at specific wavelengths (between 600 and 1000 nm) stimulates multiple cellular processes involved in tissue repair, such as fibroblast proliferation, collagen type I and III production, angiogenesis, and modulation of the local inflammatory environment [18,35].

Preclinical Experimental Studies

In an in vivo study conducted in rats with Staphylococcus aureus-infected cutaneous wounds, PBM with a 660 nm laser significantly accelerated re-epithelialization, increased collagen density, and reduced tissue defect size after 7 days of treatment. Treated tissues showed increased cell proliferation and improved extracellular matrix organization compared to non-irradiated controls [18].

In a rat model of diabetic ulcers, the combination of PBM with adipose-derived mesenchymal stem cells showed synergistic effects: enhanced wound closure, decreased interleukin-1β, and increased microRNA-146a, which is implicated in the control of chronic inflammation. This study demonstrates that PBM not only enhances regeneration but can actively modulate the inflammatory microenvironment [10].

Another study in rabbits evaluated vocal cord regeneration after surgical injury and observed that irradiation with 635 nm reduced the expression of proinflammatory markers (IL-6, COX-2), increased hyaluronic acid synthesis, and improved collagen organization at the injury site, preventing fibrotic scarring [19].

Clinical Evidence in Domestic Animals

In veterinary oral surgery, multiple studies have documented significant improvements in surgical wound healing. In a triple-blind clinical trial in humans—a model that can be extrapolated to veterinary medicine—the effect of PBM after free gingival grafting was evaluated, showing faster closure of the donor site, reduced need for analgesics, and improvements in functional parameters such as mastication and speech [36].

In animal tooth extraction surgery, PBM applied using 650–900 nm protocols has been shown to significantly reduce postsurgical pain, decrease inflammation, and promote alveolar closure, with a visible improvement in the quality of the regenerated tissue [4,37].

Likewise, in a clinical study with dogs undergoing reconstructive surgery, the postoperative use of PBM contributed to a faster recovery and a significant reduction in edema, promoting more efficient healing by primary intention than in controls without irradiation [38].

Effective Protocols and Optimal Parameters

A recent review analyzing multiple clinical protocols in human oral surgery—and applicable to veterinary medicine—determined that the most effective wavelengths for promoting healing are those between 660 and 830 nm, with energy densities between 4 and 10 J/cm^2. It is also suggested that multiple applications in the first 3-5 postoperative days are more effective than single protocols [39].

At the histological level, an increase in active fibroblasts, organized deposition of type I collagen, and more mature angiogenesis have been documented in irradiated tissues, resulting in a more functional and aesthetically superior scar matrix [6,40].

3.2. Postoperative Pain Control

Effective postoperative pain management in veterinary medicine is a fundamental pillar to ensure a rapid and comfortable recovery in animals undergoing surgery. PBM, through the modulation of biochemical pathways related to inflammation and pain transmission, has been proposed as a promising alternative or complement to conventional analgesic drugs, especially in soft tissue and orthopedic surgical procedures [41].

Mechanisms Involved in PBM-Induced Analgesia

Evidence suggests that PBM can reduce pain through several mechanisms, including the inhibition of nociceptive transmission, the modulation of neurotransmitters, and the reduction of perineural inflammation [34].

At the cellular level, the inhibition of cyclooxygenase-2 (COX-2), the reduction of prostaglandins, and the normalization of ion channels (such as TRPV1) partly explain the reduction in pain threshold [42].

Clinical Evidence in Canines and Felines

A recent study evaluated PBM in dogs undergoing TPLO surgery for cranial cruciate ligament rupture. Although no statistically significant differences were observed on the pain score (CMPS-SF), the PBM-treated group showed a lower incidence of surgical site infections and a trend toward lower owner-perceived pain scores [9].

In canine ovariohysterectomy procedures, PBM has been observed to complement the analgesic effects of drugs such as meloxicam and carprofen, even allowing for a reduction in dosage or frequency, which may be useful for patients with pharmacological contraindications [32].

Additionally, it has been documented that in dental and oral procedures, such as extractions and maxillofacial surgery, the postoperative use of PBM accelerates pain resolution, improves food intake, and reduces the need for rescue opioids [43,44]. Due to its ability to penetrate deep tissues without generating heat, PBM has been useful in modulating neuropathic pain in peripheral nerves after orthopedic surgeries, especially in canine breeds predisposed to hip and elbow dysplasia [45].

Barriers to Clinical Practice and Pain Perception

Despite existing evidence, gaps persist in the systematic application of optimal analgesic strategies in veterinary medicine. A survey of Canadian veterinarians reported that only 10–15% of cats and dogs were treated with analgesics after neutering, and that knowledge about postoperative pain was limited among clinicians [46,47].

These figures contrast with the perceptions of nurses and owners, who assign higher scores to postoperative pain and consider that current treatments may not be sufficient [47].

The implementation of PBM could contribute to reducing this gap by providing a safe, noninvasive option with a low risk of adverse effects [48].

Equine and Other Species Surgery

In equine medicine, epidural analgesia remains standard for perineal procedures or hindquarter fractures [34].

Although the clinical use of PBM in horses is still limited, there are promising initial experiences in hoof surgery, complex wounds, and myositis, where the application of infrared light has reduced clinical signs of pain and the need for NSAIDs [49].

3.3. Safety and Adverse Effects in Veterinary Surgery

The safety of any medical intervention is an essential pillar for its clinical implementation, especially in veterinary medicine, where pain management, postoperative recovery, and patient cooperation are mediated by specific ethical and physiological factors [49]. PBM, a noninvasive therapy that employs low, non-ionizing energies, has been recognized in multiple studies as a highly safe procedure, provided appropriate therapeutic parameters are adhered to [50,51].

General Security Profile

In general, PBM does not produce thermal damage or alter molecular structures through ionization, which differentiates its application from other energy methods such as surgical laser or radiofrequency. Multiple preclinical and clinical studies report zero or extremely low incidence of adverse effects when used within the recommended ranges of wavelength (600–1100 nm), energy density (1–10 J/cm^2), and controlled exposure time [3,36,52].

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In a study of dogs undergoing surgery and treated with class IV laser, no local complications, necrosis, or alterations in healing were observed compared to controls. Furthermore, irradiated tissues showed no signs of overheating or pigmentary changes [53,54].

Similarly, in a clinical model involving rats undergoing surgical incisions, PBM applied with 830 nm LEDs did not produce any alterations in liver histology or signs of systemic or local toxicity [55].

Considerations According to Type of Laser and Class of Equipment

It is important to distinguish between the different types of equipment used in PBM, as they do not all have the same safety profile. Class IV lasers, while having greater power and tissue penetration, can generate heat if not handled properly. This requires trained personnel, constant monitoring, and the use of moving applicators to avoid thermal injury. Despite this, when used with clinically validated protocols, they have also been shown to be safe and effective [50,56].

On the other hand, LED-based devices or Class IIIb lasers have lower energy and, therefore, an even higher safety profile, making them the preferred choice in general veterinary clinics or outpatient settings [40].

Contraindications and precautions in the application of PBM.

Although PBM has a low-risk profile, some contraindications have been described in the literature:

- Active neoplasia: Applying PBM directly to tumors is not recommended, as there is uncertainty about its proliferative effect on neoplastic cells [57].
- Thyroid gland: Direct irradiation of this area should be avoided, especially in growing animals or those with hormonal disorders, due to potential effects on thyroid function [33].
- Pregnancy: There is insufficient evidence to support safety in developing fetuses, so caution is recommended in pregnant females [58].

Additionally, appropriate protective eyewear should be worn by both the operator and the animal when using laser devices, although most LEDs do not require strict eye protection due to their low power and light scatter [59].

Reported Adverse Effects

Adverse effects reported in the literature are rare, generally mild, and self-limiting. These include:

- Local hyperemia or mild heat after prolonged exposure or with improperly applied high-power devices [60].
- Transient increase in pain in areas of intense acute inflammation, likely due to superficial nerve activation before modulation [36].
- Patient restlessness or refusal, especially in areas with cutaneous hypersensitivity [50].

It should be noted that none of these adverse effects have been classified as severe or required therapeutic intervention, reinforcing the general perception that PBM is safe in veterinary surgical settings [38].

3.4. Specific Applications in Veterinary Surgery

The therapeutic versatility of PBM allows for its integration into multiple veterinary surgical branches. Below, the most relevant clinical applications are presented, grouped by specialty, emphasizing the available evidence from in vivo models and clinical animals.

Orthopedic Surgery

In orthopedic surgery, PBM has been used to accelerate postoperative recovery, reduce pain, and stimulate bone and soft tissue regeneration. A study in dogs undergoing hemilaminectomy showed that those treated with PBM and physical rehabilitation showed faster functional recovery and pain reduction compared to controls [61].

Another preclinical study showed that near-infrared laser irradiation stimulated osteoblast proliferation and increased the expression of osteogenesis markers at fracture sites [40].

These effects are particularly useful in stabilizing fractures using plates or external fixators.

Oral Surgery and Dentistry

Veterinary dentistry has widely adopted PBM for the management of oral pathologies and post-surgical recovery. In dogs and cats treated for tooth extraction, gingivectomy, or oral abscess surgery, PBM has been shown to accelerate epithelialization, reduce pain, and minimize postoperative inflammation [43,44].

Furthermore, human studies and veterinary extrapolations suggest that this therapy may be useful for periodontitis, peri-implantitis, pulpitis, and oral mucosal scarring [44].

Soft Tissue Surgery

One of the most well-documented fields is soft tissue surgery, where PBM has demonstrated clear benefits in ovariohysterectomies, mastectomies, and laparotomies. In neutered dogs, PBM significantly reduced postoperative pain, accelerated healing, and improved the appearance of the surgical incision [38].

These effects are attributable to increased collagen production, stimulation of angiogenesis, and modulation of inflammatory mediators such as prostaglandins and cytokines [62–64].

Neurosurgery

Although more limited, evidence in neurosurgery is emerging. In experimental models of spinal cord injury or nerve root compression, PBM has been shown to promote axonal regeneration, reduce reactive gliosis, and improve locomotor function [61].

These benefits are attributed to mitochondrial modulation in injured neurons, with increased ATP, decreased oxidative stress, and improved neuroplasticity.

3.5. Limitations and Challenges in the Clinical Application of PBM in Veterinary Surgery

Despite promising results from multiple studies, the widespread implementation of PBM in veterinary surgery faces several limitations and challenges that must be addressed to consolidate its use as a standardized therapeutic tool.

Variability in Application Protocols

One of the main obstacles is the lack of standardization of therapeutic parameters, including wavelength, power, exposure time, frequency, and delivery mode (continuous vs. pulsed). Different studies use combinations of parameters, making it difficult to compare results and achieve clinical replication [37,65].

For example, one clinical review emphasizes that the diversity of protocols limits the creation of robust clinical guidelines and prevents the establishment of an "optimal therapeutic window" [3].

Furthermore, the use of equipment with different calibrations among manufacturers generates additional variability in the effective dose delivered to the tissue [66].

Small Sample Size and Heterogeneity of Studies

Most published veterinary clinical trials have small sample sizes, often limited to fewer than 20 animals per group, which limits the statistical power and generalizability of the findings. Furthermore, heterogeneity is observed in terms of species, breeds, anatomical location treated, and postoperative conditions, which complicates the extrapolation of results between different clinical situations [61].

Lack of Blinding and Adequate Control Groups

Many studies lack adequate placebo controls (device turned off) or do not use double-blind designs, creating potential observational bias or placebo effect. In veterinary medicine, where symptoms (such as pain) are subjectively assessed by the clinician or owner, this is especially problematic [9].

Difficulty in Objective Evaluation of Results

Another challenge is the limited availability of objective assessment tools. In many cases, measurements of inflammation, scarring, or pain are based on semi-quantitative clinical scales and visual observations. The use of biomarkers (e.g., C-reactive protein, cytokines) or standardized imaging is not yet widespread, although recent studies are beginning to incorporate them [35,67].

Initial Cost of Equipment and Specific Training Required

The cost of acquiring PBM devices, especially Class IV or calibrated medical lasers, can be a barrier in small clinics. Furthermore, specialized training is required to correctly apply the parameters and avoid dosimetric errors. This learning curve can limit the adoption of the technology in general practice settings [31].

Low Inclusion in Clinical Guidelines and Lack of Legal Recognition

Despite its increasing use, PBM is still not included in official veterinary clinical guidelines in most countries, and it is not always legally recognized as an adjuvant therapy. This limits its dissemination in academic programs and institutional protocols [3,50].

4. Relevant Technical Parameters in PBM Applied to Veterinary Surgery

Despite showing promising therapeutic potential in surgical settings, one of the main challenges facing effective clinical application of BMF is the lack of standardization in the technical parameters used. These parameters directly influence the therapeutic effects of light on biological tissues, and therefore, their correct selection is essential for achieving reproducible and effective clinical results [65,68].

4.1. Wavelength

Wavelength is one of the most determining parameters in PBM, as it defines tissue penetration capacity and the type of interaction with intracellular chromophores. The most commonly used wavelengths are in the red (600–700 nm) and near-infrared (780–980 nm) ranges, due to their ability to penetrate both soft and hard tissues [21,69]:

- 630–660 nm (visible red): Good absorption by CcO, useful for skin and superficial wounds.
- 800–980 nm (near-infrared (NIR)): Greater penetration, recommended for joints, deep muscles, and subcutaneous tissues.

A veterinary dosimetry study in dogs showed increased tissue transmission with 810/980 nm lasers, especially when high powers and shaved areas were used [17].

4.2. Power and Irradiance

Device power (in mW or W) and irradiance (mW/cm^2) determine the amount of energy delivered per unit area in a given time [69].

- Typical power levels: 30 mW–3 W.
- Recommended irradiance: <100 mW/cm^2 to avoid cellular overheating and maintain photobiomodulatory effects without thermal damage.

Studies indicate that excessively high irradiance (>500 mW/cm²) can inhibit cellular activity or produce unwanted effects, while levels between 5 and 100 mW/cm² are considered safe and effective [26].

4.3. Energy and Energy Density (Fluence)

Total energy (in joules, J) and energy density (J/cm²) are key to determining the administered dose. The most effective therapeutic range are between 1 and 10 J/cm² for superficial tissues, up to 20–50 J/cm² for deep tissues or joints [69,70].

Recent studies also suggest that the cellular response is shaped like a bipass curve, meaning that both low and excessively high doses can be ineffective or even harmful [71]

4.4. Exposure Time and Frequency

In veterinary surgery, multiple studies have shown clinical benefits with daily irradiation protocols during the first postoperative week [21].

- Time per application point: 10 to 120 seconds, depending on the intensity and size of the irradiated area.
- Treatment frequency: Daily or every other day for acute protocols; 2–3 times per week for chronic treatments.
- Total number of sessions: Varies between 3 and 10 in postoperative treatments, longer for chronic or degenerative diseases.

4.5. Emission form (Continuous vs. Pulsed)

Lasers can operate in continuous or pulsed mode:

- Continuous mode: generates constant stimulation, greater thermal accumulation, and is useful for direct mitochondrial stimulation [72].
- Pulsed mode: useful for reducing thermal risk, allows greater penetration, and is preferred for inflamed or painful tissues [60,73].

Some studies in human and veterinary medicine suggest that the pulsed mode has advantages in terms of reducing postoperative pain and edema [69].

4.6. Beam Size and Tissue Characteristics

The size of the irradiated area (spot size) should be adapted to the animal's anatomy and the desired depth [3]:

- Small areas: require precision and lower power.
- Deep tissue or dense hair: require more power or pre-shaving to allow for better transmission.

Coat density and color significantly influence light absorption. It is recommended to shave the area and adjust parameters according to pigmentation [17].

Table 1 contains a summary of the recommended parameters of interest according to the applications in veterinary surgery studied so far.

Table 1. Recommended PBM technical parameters in veterinary surgery [17,21,26,69–71].

Clinic application[1,3]	Wavelength (nm)	Energy density (J/cm²)	Emission form	Frequency	N. of sessions	Additional comments
Healing of surgical wounds	630-660 (red) / 810-980 (NIR)	4-8	Continuous or pulsed	1 time/day PS	5-7	Ideally within 48h PS
Postoperative soft tissue pain	810–980	6-12	Pulsed	1 time/day	3-5	With conventional analgesia

Orthopedic surgery	980	10-20	Pulsed	2-3 times/week	6-10	Shave[2] for better penetration
Oral surgery / dentistry	630-660	3-6	Continuous	Immediate PS	3-5	With conventional analgesia
Joint or perilesional inflammation	810-980	8-15	Pulsed	2 times/week	According to evolution	Monitor clinical response
Neurosurgery / spinal cord injury	810-850	8-10	Pulsed	Daily	Up to 2 weeks	Data still preliminary

[1] The beam area should be adapted to the anatomical size. For small areas, power or time should be reduced. [2] Shaving is recommended in areas with dark or dense fur to improve beam penetration. Dark hair can absorb lighter and reduce effectiveness. [3] Eye protection must always be used for the operator and animals on class IIIb or IV lasers. J: Joules; NIR: near infrared; nm: nanometers; PS: post-surgical.

5. Future Perspectives and Emerging Research

Despite the growing number of studies supporting the clinical efficacy of PBM in veterinary surgery, multiple scientific challenges and opportunities for innovation will define its future evolution. The need for standardization, the development of devices tailored to veterinary clinical practice, a deeper understanding of specific cellular mechanisms in animals, and the integration of emerging technologies constitute an active field of research with great potential.

One of the most frequently cited challenges in the literature is the lack of consensus on optimal application parameters (wavelength, energy density, number of sessions, duration, etc.) across different species and surgical situations [37].

Although numerous studies have demonstrated clinical benefits, methodological divergences make it difficult to extrapolate results and develop unified clinical guidelines.

This highlights the need to design well-controlled randomized clinical trials with replicable protocols and detailed reporting of technical parameters, as also underscored by a recent meta-analysis in the context of periodontal surgery [15].

Most PBM devices were originally designed for human medicine, which presents challenges in adapting to the anatomical, physiological, and behavioral characteristics of animals. Cugmas and Spigulis (2019) propose the development of more robust, ergonomic devices that are resistant to bites or sudden movements, and with simplified clinical interfaces for use in dogs, cats, and large animals [45].

Furthermore, advances in veterinary biophotonics—such as optical sensors, spectroscopy, and light-based imaging—offer the potential to integrate diagnosis and therapy in a single device [74].

Although the most common applications of PBM in veterinary medicine focus on wound healing, pain management, and post-surgical inflammation, new lines of research are exploring its usefulness in fields such as anesthesiology (reducing anesthetic drug consumption), post-traumatic neuroprotection, and even in complementary cancer management through the modulation of microcirculation and local immunity. These possibilities are still in their early stages, but they could revolutionize the way surgical recovery is managed in complex or geriatric patients [3,50,75].

The combination of PBM with artificial intelligence systems represents a promising area. Using algorithms that integrate patient variables (species, breed, coat color, medical condition), laser characteristics, and prior clinical response, predictive tools could be developed to personalize treatment parameters in real time. This synergy between technology and precision medicine can increase therapeutic efficacy, minimize risks, and improve clinical reproducibility [76].

PBM can also play a strategic role within the One Health approach, by providing non-pharmacological therapies that reduce antibiotic use, decrease postoperative complications, and promote sustainability in veterinary medicine. This aspect is especially relevant given the rise of antimicrobial resistance [77].

Finally, the growth of PBM in veterinary surgery depends on greater inclusion in university curricula, postgraduate training, and clinical guidelines endorsed by scientific societies. The incorporation of practical modules in veterinary universities is already a reality in some countries, but its global expansion remains a challenge [78].

6. Conclusions

PBM is presented as an effective complementary therapeutic tool in veterinary surgery, with documented benefits in improving healing, controlling postoperative pain, and modulating inflammation. Its action at the cellular level, based on mitochondrial stimulation and the regulation of inflammatory and regenerative processes, provides a solid physiological basis for its clinical application.

Despite promising results, the lack of standardization in technical parameters—such as wavelength, energy density, or number of sessions—represents a barrier to its widespread adoption. Progress is needed in the validation of specific protocols for clinical indications, as well as in the design of devices adapted to the veterinary setting.

In summary, PBM offers great potential for optimizing postsurgical outcomes in veterinary medicine. Its implementation must be accompanied by adequate technical training, well-designed clinical studies, and progressive integration into evidence-based therapeutic guidelines.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial intelligence
ATP	Adenosine triphosphate
CcO	Cytochrome c oxidase
COX-2	Cyclooxygenase-2
J	Joules
LLLT	Low-level laser therapy
NIR	Near infrared
nm	Nanometers
NO	Nitric oxide
PBM	Photobiomodulation
PS	Post-Surgical
ROS	Reactive oxygen species

TPLO Tibial plate leveling osteotomy

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