

UDC 619:616-089.5:616.7-089:636.7

DOI 10.37000/abbsl.2026.120.12

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**POSTOPERATIVE PAIN IN CANINE
ORTHOPEDIC SURGERY: MECHANISMS,
ASSESSMENT, AND FUTURE PERSPECTIVES**

Abstract

Postoperative pain remains one of the most significant challenges in canine orthopedic surgery because of its complex pathophysiology and its profound effects on animal welfare, functional recovery, and long-term clinical outcomes. Orthopedic procedures involve extensive trauma to bone, periosteum, muscles, ligaments, tendons, and surrounding soft tissues, initiating a cascade of inflammatory and nociceptive events that may lead to peripheral and central sensitization if inadequately managed. Advances in pain neuroscience have transformed the understanding of postoperative pain from a simple consequence of tissue injury to a multidimensional process involving interactions among peripheral nociceptors, spinal nociceptive pathways, supraspinal modulation, neuroplasticity, and cognitive-emotional mechanisms.

These insights have provided the scientific foundation for contemporary multimodal analgesic strategies aimed not only at relieving pain but also at preventing pain chronification. Accurate pain assessment is fundamental to effective analgesic management but remains particularly challenging in veterinary medicine because animals cannot verbally communicate pain. Consequently, clinicians must integrate multiple complementary assessment methods.

This review summarizes current knowledge regarding the physiological mechanisms underlying postoperative pain following canine orthopedic surgery and critically discusses available pain assessment approaches, including behavioral evaluation, physiological indicators, validated composite pain scoring systems, and objective functional assessment techniques. Recent developments in force plate analysis, pressure-sensitive walkway systems, wearable accelerometers, infrared thermography, heart rate variability, pupillary pain assessment, and integrated nociception monitoring systems are also reviewed, highlighting their clinical applications, advantages, and current limitations.

Finally, the review discusses future perspectives, including molecular biomarkers, wearable technologies, and artificial intelligence-assisted pain recognition, which are expected to improve the objectivity and precision of postoperative pain assessment. Collectively, current evidence supports a multimodal approach integrating behavioral, physiological, functional, and emerging objective indicators to optimize postoperative analgesia, improve rehabilitation, and enhance the quality of life of dogs undergoing orthopedic surgery.

Keywords: Canine orthopedic surgery, Postoperative pain, Pain assessment, Multimodal analgesia

Introduction. *1. Pain as a complex biological process.* Pain is one of the most common clinical manifestations encountered in both human and veterinary medicine and is a major determinant of patient welfare, recovery, and quality of life. The International Association for the Study of Pain (IASP) defines pain as “an unpleasant sensory and emotional experience associated with, or resembling that associated with, actual or potential tissue damage.” This definition emphasizes that pain is a multidimensional phenomenon involving sensory, emotional, cognitive, and behavioral components rather than merely a physiological response to tissue injury. Importantly, the IASP also recognizes that the inability to communicate verbally does not preclude the experience of pain or the need for appropriate analgesic intervention, a concept that is particularly relevant in veterinary medicine [1, 2].

Although the terms pain and nociception are frequently used interchangeably, they describe distinct biological processes. Nociception refers to the neural mechanisms responsible for detecting potentially harmful mechanical, thermal, or chemical stimuli and transmitting these signals from peripheral nociceptors to the spinal cord and higher centers of the central nervous system. Pain, however, is the conscious perception generated after integration of nociceptive information within cortical and subcortical brain regions and is strongly influenced by previous experiences, emotional state, and cognitive processing. Consequently, nociception may occur without pain perception, as during general anesthesia, whereas pain may persist in the absence of ongoing peripheral nociceptive input, as observed in phantom limb pain [3, 4].

Pain can be classified according to its underlying mechanism, duration, or anatomical origin. Mechanistically, nociceptive pain results from activation of intact nociceptors by noxious stimuli and serves a protective physiological role. Inflammatory pain develops following tissue injury and the release of inflammatory mediators that promote peripheral and central sensitization, whereas neuropathic pain arises from lesions or diseases affecting the somatosensory nervous system and is typically characterized by spontaneous pain, hyperalgesia, and allodynia [3, 4, 5, 6]. Clinically, pain is further categorized as acute or chronic according to its duration and as somatic or visceral according to its anatomical origin[7, 8].

These concepts provide the physiological basis for understanding postoperative pain associated with orthopedic surgery, which results from the combined activation of nociceptive and inflammatory pathways. If inadequately controlled, persistent

nociceptive input may induce maladaptive neuroplastic changes that contribute to pain chronification, highlighting the importance of effective perioperative analgesia.

1.2. Evolution of pain theories. The scientific understanding of pain has evolved from simple stimulus–response models to contemporary concepts recognizing pain as a multidimensional neurobiological experience. Early theories primarily sought to explain the origin and transmission of painful stimuli, whereas current models integrate peripheral nociceptive mechanisms with spinal modulation, supraspinal processing, neuroplasticity, and psychosocial influences.

The Specificity Theory proposed that pain is mediated by specialized receptors and dedicated neural pathways. According to this concept, nociceptive stimuli activate specific nociceptors whose signals are transmitted through distinct afferent fibers to higher centers of the central nervous system. Although this theory established the foundation of modern nociceptive physiology, it could not explain the influence of non-noxious stimuli or psychological factors on pain perception [9, 10].

In contrast, the Intensity Theory suggested that pain results from excessive activation of sensory pathways rather than specialized receptors. This concept, originally proposed by Plato and later expanded by Erasmus Darwin and Goldscheider, attributed pain perception to the temporal summation of intense sensory stimulation. However, the subsequent identification of specialized nociceptors by Sherrington substantially weakened this hypothesis [10, 11].

The Pattern Theory further emphasized the importance of central nervous system processing by proposing that pain depends on the spatial and temporal pattern of neural activity rather than activation of dedicated pain receptors. Although this theory could not fully explain nociceptive specificity, it highlighted the role of central integration in sensory perception and contributed to the development of more comprehensive models of pain processing [10, 12, 13, 14].

A major advance occurred with the introduction of the Gate Control Theory by Melzack and Wall in 1965. This theory proposed that nociceptive transmission is dynamically regulated within the dorsal horn of the spinal cord through interactions between large-diameter mechanoreceptive fibers, small-diameter nociceptive fibers, and descending supraspinal pathways. By explaining how cognitive, emotional, and environmental factors influence pain perception, the Gate Control Theory provided the neurophysiological basis for many modern analgesic strategies [10, 15].

Building on this concept, Melzack later proposed the Neuromatrix Theory, which fundamentally changed the understanding of pain by suggesting that pain is generated by a distributed neural network throughout the brain rather than representing a direct consequence of peripheral tissue injury alone. Inspired largely by observations of phantom limb pain, this theory introduced the concept of a unique "neurosignature" generated through interactions among sensory, cognitive, emotional, and genetic factors, thereby explaining why pain perception varies substantially between individuals and may persist even without peripheral nociceptive input [16, 17, 18].

Collectively, these theories illustrate the progressive transition from peripheral stimulus-based models toward a multidimensional framework in which pain is

recognized as a dynamic interaction between peripheral nociceptive input, spinal modulation, supraspinal processing, neuroplasticity, and psychological influences. This contemporary understanding provides the conceptual basis for multimodal analgesia in both human and veterinary medicine.

2. Pain mechanisms following orthopedic surgery. Orthopedic procedures are among the most painful surgical interventions performed in dogs because they involve extensive trauma to bone, periosteum, muscles, ligaments, tendons, synovial membranes, and surrounding soft tissues. Tissue injury immediately initiates an inflammatory cascade characterized by the release of prostaglandin E₂ (PGE₂), bradykinin, histamine, serotonin, adenosine triphosphate (ATP), hydrogen ions, nerve growth factor (NGF), and pro-inflammatory cytokines including tumor necrosis factor- α (TNF- α) and interleukin-1 β (IL-1 β). These mediators activate peripheral nociceptors, reduce their activation threshold, and amplify nociceptive signaling toward the central nervous system [19, 20, 21, 22, 23, 24].

Pain processing occurs through four interconnected stages: transduction, transmission, modulation, and perception. During transduction, noxious mechanical, thermal, or chemical stimuli are converted into electrical impulses within peripheral nociceptors. These impulses are transmitted via primary afferent neurons to the dorsal horn of the spinal cord, where neurotransmitters such as glutamate and neuropeptides activate second-order neurons. Ascending pathways, including the spinothalamic, spinoreticular, and spinomesencephalic tracts, subsequently relay nociceptive information to supraspinal centers. Throughout this process, descending inhibitory pathways involving endogenous opioids, serotonin, and norepinephrine continuously regulate nociceptive transmission before conscious pain perception occurs [4, 25, 26].

Pain perception is therefore not a passive consequence of peripheral tissue injury but the result of dynamic interactions between peripheral sensory neurons, spinal nociceptive circuits, and higher brain centers. Regions including the thalamus, somatosensory cortex, insular cortex, anterior cingulate cortex, amygdala, hippocampus, and prefrontal cortex integrate the sensory-discriminative, affective, cognitive, and autonomic dimensions of pain, while descending pathways originating from the periaqueductal gray and rostral ventromedial medulla further modulate spinal nociceptive transmission through endogenous opioid peptides and monoaminergic neurotransmitters [25, 27, 28, 29].

Persistent nociceptive input following orthopedic surgery may promote peripheral and central sensitization, increasing pain intensity and contributing to the transition from acute to chronic pain. Consequently, contemporary perioperative analgesia aims not only to alleviate pain perception but also to interrupt these pathophysiological processes through multimodal analgesic strategies targeting multiple levels of the nociceptive pathway simultaneously.

3. Clinical significance of postoperative pain in canine orthopedic surgery. Pain serves as an essential physiological warning mechanism that protects the body from actual or potential tissue injury. In contrast, postoperative pain represents a pathological condition that requires prompt recognition and effective treatment. Acute

postoperative pain arises from surgical tissue trauma, the underlying disease process, or both, and initiates a complex cascade of neuroendocrine, inflammatory, and metabolic responses that may compromise patient welfare and delay recovery if inadequately controlled [30, 31].

In both human and veterinary medicine, inadequate postoperative analgesia is associated with numerous adverse consequences extending beyond patient discomfort. Uncontrolled pain contributes to impaired pulmonary function, thromboembolic complications, delayed wound healing, increased susceptibility to infection, prolonged hospitalization, reduced quality of life, and greater healthcare utilization [32, 33]. These consequences are particularly relevant following orthopedic procedures, where pain directly limits early weight-bearing, mobility, rehabilitation, and functional recovery. Delayed ambulation and prolonged hospitalization may ultimately compromise surgical outcomes and increase the need for additional analgesic interventions [32, 33].

An equally important concern is the transition from acute to chronic postoperative pain. Persistent postsurgical pain has been reported in approximately 10–50% of patients undergoing various surgical procedures, while 2–13% continue to experience pain for at least two years after surgery [32]. Although the mechanisms underlying this transition remain incompletely understood, accumulating evidence suggests that persistent nociceptive input promotes neuroplasticity, central sensitization, impaired descending inhibitory pathways, and long-term alterations within the pain neuromatrix, resulting in sustained pain perception even after tissue healing has occurred [16–18,32]. These findings emphasize that perioperative analgesia should aim not only to relieve immediate pain but also to minimize the risk of long-term maladaptive changes within the nervous system.

Despite substantial advances in perioperative pain management, effective postoperative analgesia remains a major clinical challenge. Human studies consistently identify postoperative pain as one of the greatest concerns expressed by patients before surgery, yet satisfactory pain relief is still not achieved in a considerable proportion of cases despite the availability of evidence-based guidelines [34, 44, 45, 46, 37]. Similar challenges exist in veterinary medicine, where the inability of animals to verbally communicate pain increases the reliance on careful clinical observation and objective pain assessment.

The severity of postoperative pain varies according to the type and extent of tissue injury. Orthopedic procedures-including fracture repair, limb amputation, spinal surgery, corrective osteotomies, and major joint surgery-are among the most painful interventions performed in veterinary medicine because they involve extensive manipulation of highly innervated osseous and periarticular tissues [38]. Consequently, procedure-specific analgesic protocols are recommended rather than uniform approaches to postoperative pain management.

Successful pain management depends on accurate and continuous pain assessment. The intensity of postoperative pain should be evaluated according to each patient's individual response rather than solely on the basis of surgical invasiveness.

Early recognition of pain, systematic monitoring, and timely analgesic intervention are therefore fundamental components of contemporary perioperative care and provide the basis for individualized multimodal analgesic strategies in canine orthopedic surgery.

4. Assessment of pain in veterinary medicine.

4.1. challenges of pain assessment in animals. Accurate pain assessment remains one of the greatest challenges in veterinary medicine because animals cannot verbally communicate the presence, location, or intensity of pain. Consequently, clinicians must rely on indirect indicators derived from behavioral observations, physiological responses, and clinical examination. Failure to recognize pain compromises animal welfare, delays appropriate analgesic intervention, prolongs recovery, increases postoperative complications, and may facilitate the transition from acute to chronic pain. Pain assessment should therefore be regarded as an essential component of perioperative patient monitoring rather than a separate clinical procedure [39, 40].

Pain expression varies considerably among individuals and is influenced by numerous factors, including species, breed, age, sex, temperament, previous painful experiences, concurrent disease, environmental conditions, and the nature of the surgical procedure. These variables complicate clinical interpretation and explain why no single parameter can reliably quantify pain intensity in veterinary patients [41].

The challenges of pain assessment are particularly evident following orthopedic surgery, where extensive trauma to bone, periosteum, muscles, ligaments, tendons, and joints is accompanied by postoperative inflammation, reduced mobility, anxiety, and residual anesthetic effects. As these factors frequently produce overlapping clinical manifestations, differentiating pain-related from non-pain-related behavioral changes may be difficult. Consequently, current guidelines recommend a multimodal approach that integrates behavioral assessment, physiological variables, validated pain scoring systems, functional evaluation, and, where available, objective biomarkers to provide the most comprehensive evaluation of postoperative pain [38, 41].

4.2. Physiological indicators of pain. Physiological variables have traditionally been used as supportive indicators of pain because nociceptive stimulation activates both the autonomic nervous system and the hypothalamic–pituitary–adrenal (HPA) axis. Surgical tissue injury induces a coordinated neuroendocrine stress response characterized by sympathetic activation and the release of multiple hormones and inflammatory mediators. These responses contribute to cardiovascular homeostasis during acute stress while simultaneously providing indirect evidence of nociceptive stimulation [40, 42, 43]

Among routinely monitored variables, heart rate, respiratory rate, and arterial blood pressure remain the most widely used physiological indicators during anesthesia and the immediate postoperative period. Acute nociceptive stimulation typically increases sympathetic activity, resulting in tachycardia, hyperventilation, elevated cardiac output, peripheral vasoconstriction, and transient increases in arterial blood pressure. In anesthetized patients, sudden elevations in these parameters may indicate inadequate analgesia and often guide supplemental analgesic administration [40].

However, the clinical interpretation of these variables requires considerable caution because they are influenced by numerous factors unrelated to pain, including fear, excitement, restraint, hypovolemia, hypoxemia, hypercapnia, body temperature, cardiovascular disease, anesthetic depth, and the administration of sedatives or vasoactive drugs. Consequently, cardiovascular and respiratory variables cannot be considered pain-specific indicators when interpreted in isolation [41,42].

Activation of the HPA axis constitutes another hallmark of the physiological response to painful stimuli. Surgical tissue injury stimulates hypothalamic secretion of corticotropin-releasing hormone (CRH), which induces adrenocorticotrophic hormone (ACTH) release from the anterior pituitary and subsequently promotes cortisol secretion by the adrenal cortex. Because cortisol concentrations consistently increase following surgery, this hormone has been extensively investigated as an objective biomarker of postoperative pain [43,44]. Nevertheless, cortisol reflects the overall stress response rather than pain alone and is substantially influenced by transportation, hospitalization, handling, circadian rhythm, environmental stressors, and concurrent disease, limiting its specificity for pain assessment.

Similarly, circulating catecholamines, particularly epinephrine and norepinephrine, increase rapidly following sympathetic activation and contribute to tachycardia, hypertension, glycogenolysis, and peripheral vasoconstriction. Although these hormones have been proposed as objective indicators of nociceptive stimulation, their short plasma half-life and marked sensitivity to emotional and environmental stress considerably reduce their clinical applicability in routine practice [40, 42].

Additional stress-related biomarkers—including glucagon, growth hormone, antidiuretic hormone, glucose, lactate, and acute-phase proteins—also change following surgical trauma. However, these variables primarily reflect the magnitude of systemic stress and inflammation rather than nociceptive processing itself and are simultaneously influenced by trauma, infection, endocrine disorders, nutritional status, and anesthetic management [44, 45].

Overall, physiological indicators provide valuable information regarding autonomic and neuroendocrine responses during acute pain and remain indispensable components of perioperative monitoring. Nevertheless, increasing evidence demonstrates that they lack sufficient sensitivity and specificity to accurately quantify pain intensity when used alone. Current consensus therefore recommends interpreting physiological variables as supportive indicators that complement behavioral assessment, validated composite pain scales, functional evaluation, and emerging molecular biomarkers to achieve a more reliable assessment of postoperative pain in veterinary patients [40, 41, 43].

4.3. Behavioral assessment of pain. Behavioral assessment remains the cornerstone of pain evaluation in veterinary medicine because behavioral alterations often represent the earliest and most reliable indicators of pain in animals. Unlike physiological variables, which may be influenced by stress, anesthetic drugs, or environmental conditions, behavioral changes more directly reflect the animal's

perception of discomfort. Consequently, systematic behavioral observation constitutes an essential component of postoperative pain assessment in dogs [39, 40]

Pain-related behaviors vary according to the severity and duration of pain, its underlying cause, and individual characteristics such as temperament, previous experiences, and breed. As no single behavioral sign is pathognomonic for pain, clinicians should evaluate multiple behavioral domains simultaneously rather than relying on isolated observations.

Alterations in posture and locomotion are among the earliest indicators of postoperative pain. Dogs commonly adopt protective or antalgic postures that minimize loading of painful tissues, including reluctance to stand, kyphotic positioning, abnormal sitting, prolonged immobility, and shifting body weight away from the affected limb. Following orthopedic procedures, these changes are frequently accompanied by guarding of the operated limb, reduced weight-bearing, shortened stride length, altered gait symmetry, reluctance to walk or climb stairs, and decreased willingness to change body position. Although gait abnormalities may also result from mechanical dysfunction, improvements following analgesic treatment often parallel reductions in pain, highlighting the clinical value of locomotor assessment [38].

Growing evidence supports the diagnostic value of facial expression analysis in canine pain assessment. Similar to humans, painful dogs may exhibit orbital tightening, partially closed eyes, altered ear position, tension of the muzzle, and changes in facial musculature. These observations have led to the development of canine grimace scales, which provide standardized approaches for evaluating pain through facial expression analysis. Although these tools continue to undergo validation, they represent promising adjuncts to conventional behavioral assessment [46, 47].

Changes in feeding and social behavior provide additional evidence of postoperative pain. Pain frequently suppresses appetite through interactions among inflammatory mediators, stress hormones, and central appetite-regulating pathways, resulting in reduced food intake, decreased water consumption, delayed return to normal feeding behavior, or reluctance to chew. Simultaneously, affected dogs may become withdrawn, avoid physical contact, exhibit reduced responsiveness to owners, or display irritability and aggression during handling or palpation. Conversely, some animals seek excessive attention or become unusually dependent on their caregivers. Because these responses vary according to individual temperament, behavioral changes should always be interpreted relative to the animal's normal behavior [41, 46].

Although vocalization is commonly regarded as an indicator of pain, its diagnostic value remains limited when considered alone. Whining, crying, barking, growling, or groaning may occur in response to pain but are equally associated with fear, anxiety, excitement, or separation distress. Likewise, many animals experiencing severe pain remain completely silent. Consequently, vocalization should always be interpreted in conjunction with other behavioral and clinical findings rather than as an independent measure of pain [40].

Despite their considerable clinical value, behavioral indicators remain inherently subjective and may be influenced by hospitalization, sedation, breed characteristics,

age, environmental factors, and observer experience. For this reason, current international guidelines recommend integrating behavioral observations with physiological variables, validated composite pain scales, objective functional assessment techniques, and emerging molecular biomarkers. Such a multimodal strategy provides the most reliable evaluation of postoperative pain and supports individualized analgesic management in canine orthopedic patients [38, 41].

4.4. Pain scoring systems. Validated pain scoring systems have become indispensable tools for standardized pain assessment in veterinary medicine because they reduce observer variability, improve clinical decision-making, and facilitate comparisons among studies evaluating analgesic efficacy [46,48,49].

Pain scoring systems are broadly classified as unidimensional or multidimensional. Unidimensional instruments—including the Visual Analogue Scale (VAS), Numerical Rating Scale (NRS), Simple Descriptive Scale (SDS), and Dynamic Interactive Visual Analogue Scale (DIVAS)—primarily estimate pain intensity through observer judgment. Although these scales are simple and rapid to apply, they remain susceptible to subjective interpretation and generally demonstrate lower sensitivity for detecting subtle changes in pain intensity [43, 50].

Multidimensional scales integrate behavioral observations with selected physiological responses, providing a more comprehensive evaluation of pain. These instruments typically assess posture, mobility, interaction, vocalization, response to palpation, mental status, and, in some cases, physiological variables such as heart rate and respiratory rate. By combining multiple indicators, multidimensional scales improve both the sensitivity and reliability of pain assessment and are therefore preferred for clinical decision-making [43, 50].

Among currently available instruments, the **Glasgow Composite Measure Pain Scale–Short Form (CMPS-SF)** is widely regarded as the gold standard for assessing acute postoperative pain in dogs. The scale evaluates six behavioral categories—posture, mobility, vocalization, attention to the wound, response to palpation, and overall demeanor—with a maximum score of 24. Rescue analgesia is generally recommended at scores of $\geq 6/24$, making the CMPS-SF an invaluable tool for perioperative analgesic management [47].

Other validated multidimensional instruments include the **Melbourne Pain Scale**, which combines physiological and behavioral variables; the **Colorado State University Acute Pain Scale**, which emphasizes posture and behavioral responses in both dogs and cats; and the **UNESP-Botucatu Multidimensional Composite Pain Scale**, developed specifically for feline pain assessment [43, 50].

Although each scoring system possesses distinct strengths and limitations, all share the common objective of providing standardized, reproducible pain assessment that facilitates appropriate analgesic intervention and improves postoperative patient management.

4.5. Objective pain assessment techniques. Although behavioral assessment remains the foundation of pain evaluation in veterinary medicine, its subjective nature has stimulated the development of objective techniques capable of quantifying pain-

related functional impairment and nociceptive responses. These methods provide reproducible measurements that complement behavioral observations and validated pain scoring systems, particularly in orthopedic patients, where functional recovery is closely associated with postoperative pain control.

4.5.1. Force plate analysis. Force plate analysis is considered the reference standard for objectively evaluating pain-related limb dysfunction in dogs. By measuring ground reaction forces generated during locomotion, this technique quantifies weight-bearing capacity and gait symmetry through variables such as peak vertical force (PVF) and vertical impulse (VI). Painful limbs typically exhibit reduced loading, and improvements in these parameters following analgesic treatment provide objective evidence of functional recovery. Consequently, force plate analysis is widely used in experimental orthopedic studies despite limitations associated with high equipment costs, specialized facilities, repeated measurements, and the requirement for standardized walking speed [51–53].

4.5.2. Pressure-sensitive walkway systems. Pressure-sensitive walkway systems provide a practical alternative to traditional force plates by simultaneously evaluating all four limbs during natural locomotion. These systems record paw placement, pressure distribution, stride length, stance time, swing time, and gait symmetry, allowing comprehensive assessment of locomotor function. Their ability to detect subtle gait abnormalities has made them increasingly valuable for monitoring postoperative orthopedic recovery, osteoarthritis progression, and responses to analgesic therapy. However, measurement accuracy remains dependent on standardized testing conditions, including walking speed, handler interaction, and patient cooperation [53].

4.5.3. Activity monitoring using accelerometers. Wearable accelerometers have emerged as valuable tools for continuously monitoring spontaneous activity under home or hospital conditions. These devices quantify movement intensity, duration, frequency, and daily activity patterns over prolonged periods, providing information that cannot be obtained during brief clinical examinations. Following orthopedic surgery, dogs commonly demonstrate reduced mobility, decreased activity, and prolonged resting periods, making accelerometry a useful objective measure of functional recovery. Although activity patterns are influenced by age, temperament, environmental conditions, and owner-related factors, accelerometers have become increasingly important outcome measures in veterinary analgesic research [53].

4.5.4. Infrared thermography. Infrared thermography is a completely non-invasive imaging modality that detects infrared radiation emitted from body surfaces to generate thermal maps reflecting regional skin temperature. Because inflammation increases local blood flow through vasodilation, painful musculoskeletal tissues frequently exhibit elevated surface temperatures. Thermography has therefore been investigated for the assessment of postoperative inflammation, joint disease, soft tissue injury, and musculoskeletal disorders in dogs. Its principal advantages include rapid image acquisition, absence of ionizing radiation, and non-invasive application. However, image interpretation is influenced by environmental temperature, coat

characteristics, humidity, camera positioning, and patient movement, limiting its ability to directly quantify pain [54, 55].

4.5.5. Heart rate variability. Heart rate variability (HRV) provides indirect information regarding autonomic nervous system activity by quantifying beat-to-beat fluctuations in cardiac rhythm. Acute pain increases sympathetic tone while reducing parasympathetic activity, generally resulting in decreased HRV. Experimental studies have demonstrated associations between reduced HRV and nociceptive stimulation, suggesting its potential value as a non-invasive indicator of acute pain. Nevertheless, HRV is simultaneously affected by respiration, cardiovascular disease, body position, emotional stress, anesthetic depth, and pharmacological agents, limiting its specificity for routine clinical pain assessment [56, 57].

4.5.6. Pupillary pain index. Pain-induced sympathetic activation also produces measurable changes in pupil diameter. The Pupillary Pain Index (PPI) quantifies these responses following standardized noxious stimulation and has been proposed as a rapid, non-invasive method for assessing intraoperative nociception. Although initially developed for human anesthesia, interest in veterinary applications has increased in recent years. However, pupillary responses are influenced by ambient light, sedatives, opioids, anesthetic drugs, and ocular disease, and further validation is required before routine clinical implementation in veterinary patients [58].

4.5.7. Nociception monitoring systems. Advances in perioperative monitoring have led to the development of integrated nociception monitoring systems designed to estimate the balance between nociceptive stimulation and antinociceptive treatment during anesthesia. Technologies such as the Analgesia Nociception Index (ANI), Surgical Pleth Index (SPI), Nociception Level (NoL) Index, and Parasympathetic Tone Activity (PTA) Monitor combine physiological signals—including heart rate variability, photoplethysmography, skin conductance, and pulse wave amplitude—to generate composite indices of nociceptive activity [59, 60].

These systems have shown promising results in human anesthesia; however, their application in veterinary medicine remains limited by species-specific physiological differences, variations in anesthetic protocols, and the absence of validated reference values. Continued improvements in sensor technology, computational analysis, and machine-learning algorithms are expected to enhance their clinical applicability in veterinary anesthesia and analgesia [57].

4.6. Future perspectives and clinical integration. Objective assessment techniques provide quantitative information regarding locomotor function, autonomic regulation, tissue inflammation, and nociceptive processing, thereby complementing traditional behavioral assessment. Nevertheless, no currently available technique possesses sufficient sensitivity and specificity to independently quantify pain under all clinical conditions. Accordingly, contemporary evidence supports a multimodal assessment strategy integrating behavioral evaluation, validated composite pain scales, physiological variables, objective functional assessment techniques, and emerging molecular biomarkers. Such an integrated approach offers the most comprehensive

evaluation of postoperative pain and provides the strongest foundation for individualized analgesic management in dogs undergoing orthopedic surgery.

Conclusion. Postoperative pain following canine orthopedic surgery remains a major clinical challenge because of its complex pathophysiology, multifactorial nature, and substantial impact on patient welfare and surgical outcomes. Current evidence demonstrates that postoperative pain extends beyond a simple consequence of tissue injury, involving intricate interactions among peripheral nociceptive activation, inflammatory processes, spinal modulation, supraspinal integration, and neuroplastic changes. If inadequately managed, these mechanisms may delay functional recovery, impair rehabilitation, and contribute to the development of persistent pain states.

Accurate pain assessment therefore represents a fundamental prerequisite for effective analgesic management. However, no single assessment method is capable of reliably reflecting pain intensity under all clinical circumstances. Behavioral observations remain the cornerstone of pain evaluation in veterinary medicine, while physiological variables, validated pain scoring systems, and objective functional assessment techniques provide complementary information that enhances clinical decision-making. Recent advances in objective monitoring technologies and the growing interest in molecular biomarkers further support the transition toward more comprehensive and individualized approaches to pain assessment.

The increasing understanding of pain neurobiology has also strengthened the rationale for multimodal analgesia, in which different pharmacological and non-pharmacological interventions target multiple components of the nociceptive pathway simultaneously. Such strategies not only improve postoperative comfort but may also reduce peripheral and central sensitization, thereby decreasing the risk of chronic pain development and facilitating earlier functional recovery after orthopedic procedures.

Future research should focus on validating objective pain assessment tools, identifying reliable and clinically applicable biomarkers, and integrating behavioral, physiological, functional, and molecular data into standardized multimodal assessment protocols. Advances in wearable technologies, artificial intelligence-assisted behavioral analysis, and biomarker discovery are expected to improve the accuracy of pain recognition and enable more personalized analgesic management in veterinary patients.

In conclusion, effective postoperative pain management in canine orthopedic surgery requires a multidimensional approach that integrates current knowledge of pain physiology with validated clinical assessment methods and emerging objective technologies. Continued progress in this field will not only improve animal welfare but also optimize surgical outcomes, rehabilitation, and long-term quality of life for canine patients.

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ПІСЛЯОПЕРАЦІЙНИЙ БІЛЬ В ОРТОПЕДИЧНІЙ ХІРУРГІЇ СОБАК: МЕХАНІЗМИ, ОЦІНЮВАННЯ ТА ПЕРСПЕКТИВИ РОЗВИТКУ

Анотація

Післяопераційний біль залишається однією з найактуальніших проблем ортопедичної хірургії собак через складну патофізіологію та значний вплив на добробут тварин, відновлення функцій і довготривалі клінічні результати. Ортопедичні втручання супроводжуються значним ушкодженням кісток, окістя, м'язів, зв'язок, сухожилків та навколишніх м'яких тканин, що запускає каскад запальних і ноцицептивних процесів. За неналежного лікування вони можуть призвести до периферичної та центральної сенсibilізації. Досягнення нейробіології болю змінили уявлення про післяопераційний біль: від простого наслідку ушкодження тканин до багатовимірного процесу, що охоплює взаємодію периферичних ноцицепторів, ноцицептивних шляхів спинного мозку, супраспинальної модуляції, нейропластичності та когнітивно-емоційних механізмів.

Ці знання стали науковим підґрунтям сучасних мультимодальних стратегій знеболювання, спрямованих не лише на полегшення болю, а й на запобігання його хронізації. Точне оцінювання болю є необхідною умовою ефективного знеболювання, проте у ветеринарній медицині воно особливо складне, оскільки тварини не можуть вербально повідомити про свій біль. Тому клініцисти мають поєднувати кілька взаємодоповнювальних методів оцінювання.

В огляді узагальнено сучасні знання про фізіологічні механізми післяопераційного болю у собак після ортопедичних операцій і критично проаналізовано наявні підходи до його оцінювання, зокрема поведінкову оцінку, фізіологічні показники, валідовані комплексні шкали болю та методи об'єктивної функціональної оцінки. Також розглянуто нові можливості, які надають силові платформи, тензометричні доріжки для ходьби, носимі акселерометри, інфрачервона термографія, варіабельність серцевого ритму, пупілометрія та інтегровані системи моніторингу ноцицепції, з акцентом на їхньому клінічному застосуванні, перевагах і сучасних обмеженнях.

Наприкінці обговорено перспективи подальших досліджень, зокрема молекулярні біомаркери, носимі технології та розпізнавання болю за допомогою штучного інтелекту, які, як очікується, підвищать об'єктивність і точність оцінювання післяопераційного болю. Загалом сучасні дані свідчать на користь мультимодального підходу, що поєднує поведінкові, фізіологічні, функціональні та новітні об'єктивні показники, для оптимізації післяопераційної аналгезії, поліпшення реабілітації та підвищення якості життя собак після ортопедичних операцій.

Ключові слова: ортопедична хірургія собак, післяопераційний біль, оцінювання болю, мультимодальна аналгезія

Стаття надійшла до редакції 15.07.2026

Стаття пройшла рецензування 17.08.2026

Стаття опублікована 30.09.2026