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Mini Review

# Anesthetic Considerations for Advanced Neural Implants

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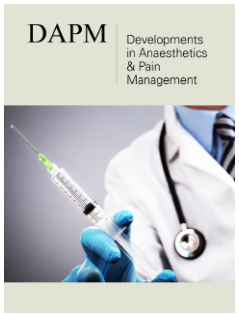
**ISSN: 2640-9399**

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**Submission:** September 24, 2025

**Published:** October 16, 2025

Volume 3 - Issue 1

**How to cite this article:** Kunal Kumar Sharma* and Bharti Chauhan. Anesthetic Considerations for Advanced Neural Implants. Dev Anesthetics Pain Manag. 3(1). DAPM. 000554. 2025.
DOI: 10.31031/DAPM.2025.03.000554



## Abstract

Spinal Cord Injury (SCI) imposes profound physical, socioeconomic and clinical burdens, with limited options for functional restoration. This manuscript explores the transformative potential of neurotechnology in addressing paralysis, spotlighting the NeuralEXO exoskeleton-a neuro-controlled, AI-integrated system designed to restore mobility by translating neural signals into mechanical motion. We examine the innovation landscape, including brain-computer interfaces, neuromodulation and regenerative therapies, supported by initiatives like the NIH BRAIN Initiative and DARPA's N3 program. A critical focus is placed on anesthetic management during spinal implant surgeries, comparing dexmedetomidine and propofol under target-controlled infusion paradigms. Dexmedetomidine demonstrates superior preservation of motor and somatosensory evoked potentials, reduced hemodynamic instability and enhanced recovery profiles, though propofol remains valuable for its titratability. Challenges such as autonomic dysreflexia, signal latency and device safety are addressed, emphasizing the need for interdisciplinary collaboration and robust clinical protocols. By integrating advanced neurotechnology with optimized intraoperative care, this work underscores a path toward redefining functional recovery in SCI.

**Keywords:** Spinal cord injuries; Exoskeleton device; Brain-computer interfaces; Neuromodulation

## Introduction

Spinal Cord Injury (SCI) remains one of the most devastating neurological conditions, frequently resulting in permanent paralysis, sensory loss and profound impairment of motor function. Traumatic disruption of descending neural pathways interrupts brain-derived motor commands, culminating in lifelong disability. Despite advances in surgery, intensive care and rehabilitation, functional restoration remains limited. Globally, traumatic SCI occurs at an estimated incidence of 11.5 cases per 100,000 persons per year, with lifetime costs ranging from € 91,000 to € 455,000 per patient depending on injury severity [1]. This socioeconomic and clinical burden underscores the urgent need for innovative strategies capable of restoring mobility and independence. Paralysis itself represents a "Blue Ocean" in healthcare innovation. The unmet clinical need is striking: few effective treatments exist to reverse paralysis, yet demand for solutions is immense among patients, families and health systems. In the United States alone, approximately 5.4 million individuals-about one in every fifty-live with some form of paralysis. Motor vehicle collisions account for 38% of new cases annually, followed by falls (30%), violence (13%), sports (9%) and medical or surgical complications (5%) [2]. Beyond physical limitations, paralysis carries deep socioeconomic consequences: 28.1% of households with affected members report annual incomes below $15,000, significantly higher than the general population [3]. Current management remains largely supportive, with modest competition in transformative interventions. Only a handful of companies-such as Medtronic, Natus and Neuralink-actively innovate in neurostimulation, neuroprosthetics or consciousness mapping [4].

Parallel efforts in anesthetic management and neuroprotective strategies aim to mitigate secondary injury, reduce neuroinflammation and promote neuroplasticity, though these remain early in translation. Simultaneously, societal focus on brain health and government-backed programs, such as the U.S. National Institutes of Health BRAIN Initiative, the Defense Advanced Research Projects Agency (DARPA) and the Next-Generation Nonsurgical Neurotechnology (N3) program, have accelerated the innovation pipeline [5,6]. Within this evolving landscape, advanced exoskeletons, brain-computer interfaces, neuromodulation platforms and regenerative therapies converge on the shared goal of restoring autonomy in paralysis. We highlight the intersection of cutting-edge neurotechnology, exemplified by the NeuralEXO exoskeleton project, with the anesthetic and intraoperative considerations required for safe implantation of spinal implants [7]. In particular, we focus on dexmedetomidine and propofol under Target-Controlled Infusion (TCI) paradigms, synthesizing evidence for their impact on evoked potential monitoring and clinical outcomes. Additionally, we project future directions, including closed-loop brain-spinal interfaces and non-invasive neuromodulation, underscoring how anesthetic management remains a cornerstone of innovation in neurorehabilitation.

## Innovation Landscape

The past decade has witnessed rapid growth in Artificial Intelligence (AI), neuromonitoring and digital therapeutics in neurocritical care. AI platforms increasingly support prediction of coma recovery, optimization of sedation and analysis of evoked potentials or Electro Encephalo Graphy (EEG). Intraoperative neuromonitoring is now integral to neurosurgery, enabling early detection of subarachnoid hemorrhage, vasospasm or infarction-sometimes preceding imaging. Predictive models for neuromonitoring [8,9] have proliferated in recent years, underscoring the clinical relevance of computational neuroscience. Brain-Computer Interfaces (BCIs) represent another transformative frontier, restoring motor functions and enabling communication in locked-in patients, including those with amyotrophic lateral sclerosis [10,11]. Concurrently, wearable neurotechnologies now permit home-based monitoring and neurofeedback for patients with disorders of consciousness [12]. However, most algorithms remain validated only in younger to middle-aged populations (14-60 years), raising concerns regarding generalizability to elderly cohorts where SCI is increasingly prevalent. Virtual Reality (VR) and Augmented Reality (AR) systems are emerging as critical tools for post-paralysis recovery, particularly in immersive rehabilitation environments. Predictive analytics platforms further extend value in intensive care units by enabling outcome stratification for comatose patients. On the regenerative horizon, stem cell therapy, gene editing and pharmacological neuroplasticity enhancers continue to advance, aiming to restore or augment neural circuitry after injury [13]. Together, these domains constitute an integrated innovation ecosystem spanning devices, software and biologics.

## Human-Centric Exoskeleton Innovation

NeuralEXO is envisioned as an advanced neuro-controlled exoskeleton aimed at restoring mobility and autonomy for individuals with paralysis. Unlike passive orthotic aids, it integrates Electro Encephalo Graphy (EEG) and Electro Myo Graphy (EMG) signals for real-time control, translating neural intent into mechanical motion. Iterative design leverages servo motors and actuators in modular frameworks, ensuring adaptability across diverse patient anatomies. Additive manufacturing and precision robotics support scalable production, while AI-driven signal decoding underpins exoskeletal actuation. Clinical integration will prioritize rehabilitation centers treating SCI, stroke, and neuromuscular disorders. Beyond healthcare, defense and veteran rehabilitation programs represent secondary markets, where restoring mobility aligns with functional reintegration goals. Core challenges include minimizing signal processing latency, adapting to patient-specific neurophysiology and reducing device weight while preserving structural integrity. Safety-critical features, such as emergency stop functions, actuator redundancies and predictive diagnostics, are mandatory for clinical trust. Compliance with ISO 13485 and IEC 60601 standards, alongside FDA 510(k) clearance, will ensure regulatory and patient safety benchmarks. Commercial strategies balance direct sales to hospitals with leasing models for clinics and home use. Service contracts covering software updates, recalibration and maintenance provide secondary revenue streams. Interdisciplinary teams are central to NeuralEXO's success, comprising neuroengineers, neuroanesthetists, neurologists, physiotherapists and roboticists. Human factors engineering, intuitive interface design, and clinician training programs will be essential for adoption. Performance indicators include prototype iteration cycles, successful clinical trial sessions and user training completion rates. Ultimately, NeuralEXO is designed to evolve through modular upgrades and continuous clinician-patient feedback.

## Anesthetic Considerations

While implant design and surgical precision are critical, anesthetic management during implantation plays an equally pivotal role. High-quality intraoperative neuromonitoring-particularly Motor Evoked Potentials (MEPs) and Somatosensory Evoked Potentials (SSEPs)-requires agents that preserve signal fidelity. Simultaneously, patients with SCI are vulnerable to hemodynamic instability due to autonomic dysfunction, making anesthetic choice a determinant of both safety and implant efficacy. Dexmedetomidine, a selective $\alpha_2$-adrenergic agonist, provides sedation, anxiolysis and analgesia with minimal respiratory depression. Its modest, dose-dependent effects on evoked potentials make it attractive for spinal surgery. The Hannivoort TCI model has demonstrated feasibility for plasma-site targeting, supporting integration into TCI paradigms. Propofol, a GABAA receptor agonist, remains a mainstay due to rapid onset and offset, enabling tight titration. However, its dose-dependently suppresses MEP amplitudes, particularly at higher

infusion rates, often necessitating "propofol-sparing" strategies. Hemodynamic instability-especially hypotension and respiratory depression-poses additional concerns in SCI. The Eleveld TCI model provides improved pharmacokinetic prediction across ages compared with Schnider models, with effect-site concentrations of 5-8μg/ml commonly used in spine surgery [14]. While sensory EPs may be preserved at moderate doses, motor EPs are more vulnerable. Recovery is typically rapid but opioid requirements are higher due to lack of intrinsic analgesia. Terao et al. [15] compared dexmedetomidine and propofol in patients undergoing various spinal surgeries.

The analysis revealed that dexmedetomidine provided superior sedation, less interference with evoked potentials and a reduced incidence of hypotension compared to propofol. Patients receiving dexmedetomidine also had a faster recovery time and lower postoperative pain scores [15]. Ter Bruggen et al. [16] found that dexmedetomidine, compared to propofol, was associated with improved intraoperative neuromonitoring outcomes, including better preservation of EP signals during spinal cord stimulator placement [16]. Mahamoud et al. [17] noted that propofol compromised EP clarity, while dexmedetomidine maintained stable recordings [17]. However, pediatric evidence remains mixed. Holt et al. [18] showed that dexmedetomidine at 0.3-0.5μg/kg/hr reduced MEP amplitudes during pediatric spine fusion, though SSEPs were unaffected [18]. Tobias et al. [19] using a combined propofol-remifentanil-dexmedetomidine protocol, demonstrated preserved neurophysiological monitoring when propofol dosing was adjusted [19]. A retrospective study by Beňuška et al. [20] highlighted the importance of integrating latency delays with amplitude reductions as alarm criteria during MEP monitoring. Such refinements illustrate how anesthetic protocols, signal thresholds and monitoring criteria converge to determine intraoperative safety [20]. Nevertheless, Sharma et al. [21] did not observe any significant alteration in the MEPs when using dexmedetomedine as the prime anesthetic induction and maintenance agent in their case series [21,22]. Liu et al. [23] found that propofol provides adequate sedation and amnesia and minimally affects amplitude and latency of sensory evoked potentials during the procedure [23]. However, Kim et al. [24] found that propofol infusion led to greater hemodynamic instability compared to other agents, such as dexmedetomidine, during surgeries that require constant neurological monitoring [24].

Propofol does not have the analgesic properties of dexmedetomidine and thus, postoperative pain management often requires additional analgesics. Wong et al. [25] observed that patients who received propofol for anesthesia required higher doses of postoperative opioids, which may lead to increased risk of opioid-related side effects and delayed recovery [25]. The implication from the work by Dooney et al. [26] emphasizes the need for continuous multimodal neurophysiological monitoring for patients with Deep Brain Stimulators (DBS) (Table 1), spinal cord stimulators or brain-computer interface electrodes, where anesthetic choice must preserve electrophysiologic signal fidelity and implant function. Mekkat et al. [27] have elaborated the clinical challenges associated with managing autonomic dysreflexia in patients with spinal cord injury. Autonomic dysreflexia also acts as a challenge with implant activation and brain stimulation during surgery. Thereby emphasizing vigilance to prevent dysreflexia or hypertensive crises during intraoperative testing. From the works by Bao & colleagues [28] on spinal cord injury patients, we can likewise emphasize the preference of TIVA for patients undergoing epidural stimulator implants and DBS placement. This primarily due to the issue that volatile anesthetic agents and $N_2O$ depress synaptic transmission thereby obscuring device calibration and evoked potentials. For cervical cord stimulators, neck stabilization, controlled induction and avoidance of fasciculations are essential to prevent lead displacement and neural interface microtrauma. The patients implanted with closed-loop spinal or cortical devices require stable perfusion to prevent ischemic signal distortion or electrode interface injury. The need for early mobilization and thromboprophylaxis while maintaining implant site sterility to prevent infection forms a critical aspect in these patients. Table 2 summarizes the implant related anesthetic considerations.

**Table 1:** Comparative summary between dexmedetomidine and propofol.

| Feature | Dexmedetomidine | Propofol |
|---|---|---|
| Mechanism | $\alpha_2$-adrenergic agonist | GABAA receptor agonist |
| Sedation/Analgesia | Sedation+intrinsic analgesia | Sedation only, no analgesia |
| Respiratory Effects | Minimal depression | Dose-dependent depression |
| Hemodynamics | Stable, less hypotension | Hypotension and bradycardia common |
| Effect on SEPs | Minimal to none | Minimal effect at moderate dose |
| Effect on TcMEPs | Stable | Dose-dependent suppression |
| TCI Model | Hannivoort | Eleveld (better than Schnider) |
| Recovery | Smooth, reduced opioids, shorter ICU stay | Rapid emergence, but higher opioid use |

**Table 2:** Summary table for neural implant–related anesthesia principles.

| Domain | Key Recommendation | Neural Implant Relevance |
|---|---|---|
| Monitoring | TIVA preferred for SSEP/MEP; avoid volatiles/$N_2O$ | Preserves signal integrity and avoids interference with implant telemetry |
| Airway | Awake fiberoptic or video-assisted, minimal neck movement | Prevents mechanical strain on leads or electrodes |
| Hemodynamics | Maintain MAP 85-90mmHg, normocapnia | Ensures optimal neural perfusion and device-tissue interface stability |
| Agents | Avoid succinylcholine; use propofol, ketamine, dexmedetomidine | Prevents hyperkalemia and facilitates evoked potential reliability |
| Autonomic Control | Deepen anesthesia, use hydralazine/nitroprusside for AD | Critical when device activation triggers sympathetic discharge |
| Postoperative | Watch for respiratory depression, thrombus, infection | Implant safety and neurointegrity depend on vigilant recovery management |

## Semantics

Emerging evidence suggests dexmedetomidine provides more stable hemodynamics and smoother recovery compared with propofol, making it attractive for advanced spinal implant surgeries. Nonetheless, propofol's titratability and established familiarity ensure its continued relevance. Direct randomized comparisons under TCI paradigms remain essential to establish evidence-based guidelines.

## sConclusion

The landscape of SCI rehabilitation is undergoing rapid transformation, driven by advances in neurotechnology, digital therapeutics and regenerative biology. NeuralEXO exemplifies the promise of human-centric, AI-integrated exoskeletal systems designed to restore mobility and independence. Yet the success of such devices depends not only on engineering precision and clinical design, but equally on anesthetic management during implantation. Incorporating conventional neuromonitoring techniques like regional oximetry for spine implants shall enhance their success further [29,30]. In light of emerging evidence in favor of dexmedetomidine, systematic randomized studies are required to formalize best practice for such procedures. The bridging of surgical precision, anesthetic safety and technological innovation shall ensure that the next generation of implants hold the potential to redefine functional recovery in spinal cord injury.

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