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Advances in Regional Anesthesia for Modern Perioperative Pain Management

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Abstract: Perioperative pain management has shifted from opioid-centered rescue analgesia toward multimodal, opioid-sparing strategies that support early rehabilitation. Intravenous patient-controlled analgesia remains useful, but it cannot fully prevent early breakthrough pain and is limited by opioid-related adverse effects. Regional anesthesia, including peripheral nerve and fascial plane blocks, provides procedure-specific analgesia with reduced systemic drug exposure. The wider adoption of ultrasound guidance, long-acting local anesthetic formulations, selected adjuvants, and continuous perineural infusion has expanded the role of regional techniques in enhanced recovery pathways. This review summarizes the rationale, technical advances, procedure-specific applications, and implementation challenges of regional anesthesia in modern perioperative analgesia. Emphasis is placed on sensory-motor balance, patient selection, geriatric and critically ill populations, nerve injury surveillance, prevention of local anesthetic systemic toxicity, and data-driven pain assessment. Standardized training, structured outcome monitoring, and information-supported decision-making are needed to translate regional anesthesia into consistent and safe perioperative outcomes.

Keywords: Regional anesthesia; Peripheral nerve block; Perioperative analgesia; Ultrasound guidance; Enhanced recovery after surgery; Opioid-sparing analgesia

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1. Introduction

Effective perioperative analgesia is no longer judged only by the reduction of pain scores. Contemporary perioperative care also requires early mobilization, preservation of respiratory and gastrointestinal function, reduced opioid exposure, and rapid recovery after surgery. Opioid-based patient-controlled analgesia has played an important role in postoperative pain management, but it is mainly a rescue strategy after pain has already occurred. The time lag between pain onset, patient reporting, nursing assessment, and dose adjustment can lead to breakthrough pain, delayed mobilization, nausea, vomiting, ileus, sedation, and other opioid-related adverse effects.

Regional anesthesia offers a complementary strategy by blocking nociceptive transmission close to the surgical site. When appropriately selected, peripheral nerve blocks and fascial plane blocks can provide targeted analgesia, reduce systemic opioid requirements, and preserve function needed for rehabilitation. Ultrasound guidance has improved visualization of the needle, target structures, and spread of local anesthetic, but it does not eliminate the need for standardized training, careful dosing, and postoperative neurological monitoring. This review discusses the current role of regional anesthesia in modern perioperative pain management, with attention to clinical indications, technical progress, risk control, and implementation challenges.

2. Rationale and driving factors for regional anesthesia in perioperative analgesia

2.1. Limitations of opioid-centered perioperative analgesia

In traditional perioperative analgesic models, intravenous opioid PCA is commonly used after surgery and adjusted according to patient-reported pain. This approach is practical, but it is reactive rather than preventive. Many patients experience an analgesic gap during emergence from anesthesia and early recovery, particularly when pain scores are measured intermittently or when the patient is unable to communicate discomfort clearly. In addition, individual opioid sensitivity varies widely; a fixed regimen may cause excessive sedation in some patients while failing to relieve pain in others [1].

A purely systemic opioid strategy also does not address local nociceptive input from the surgical field. Opioid-related adverse effects, including postoperative nausea and vomiting, bowel dysfunction, pruritus, urinary retention, respiratory depression, and delayed ambulation, may conflict with the goals of enhanced recovery. These limitations support the development of multimodal analgesic strategies in which regional anesthesia is used to reduce, rather than simply replace, systemic analgesics.

2.2. Clinical demand within enhanced recovery after surgery pathways

Enhanced Recovery After Surgery (ERAS) pathways emphasize early mobilization, early oral intake, preservation of organ function, and avoidance of unnecessary opioid exposure. Inadequate pain control can prolong bed rest, impair pulmonary function, delay gastrointestinal recovery, and increase the length of hospital stay. Regional anesthesia fits this clinical demand because it can provide site-specific analgesia while supporting opioid-sparing multimodal regimens.

For abdominal surgery, the transversus abdominis plane block can reduce pain arising from the abdominal wall and may facilitate earlier sitting, coughing, and mobilization when combined with systemic non-opioid analgesics. For knee arthroplasty, the adductor canal block is often preferred over the femoral nerve block because it can provide analgesia while better preserving quadriceps strength, although mild motor weakness can still occur. These examples show that regional anesthesia should be selected according to the balance between analgesic coverage and functional preservation, rather than applied as a uniform intervention for all patients.

2.3. Precision pain management and sensory-motor balance

The concept of precision analgesia requires regional anesthesia to move beyond broad “regional paralysis” toward targeted sensory blockade with limited motor impairment. A technically successful block should answer three clinical questions: how long analgesia is needed, which anatomical region must be covered,

and how much motor function should be preserved for rehabilitation. The ideal block is therefore procedure-specific, patient-specific, and time-specific.

This principle is particularly important in lower limb surgery, thoracic surgery, and elderly patients. For example, excessive motor blockade after lower limb surgery may delay ambulation and increase fall risk, whereas insufficient analgesic coverage may increase opioid rescue requirements. Similarly, paravertebral and fascial plane blocks for thoracic or abdominal surgery must be selected according to incision site, expected dermatomal coverage, hemodynamic reserve, coagulation status, and institutional expertise [2].

3. Technical advances in regional anesthesia

3.1. Ultrasound-guided visualization

Ultrasound guidance has changed regional anesthesia from landmark-based localization to real-time image-guided intervention. The operator can identify nerves, fascial planes, vessels, pleura, and adjacent organs; track the needle tip during advancement; and observe the spread of local anesthetic after injection. This visualization improves technical precision and may reduce complications such as intravascular injection, pneumothorax, or unintended spread, especially in deep or anatomically variable blocks.

However, ultrasound guidance is not a substitute for anatomical knowledge or technical training. Poor image interpretation, failure to maintain needle-tip visualization, excessive injection pressure, and overconfidence may still lead to nerve injury or local anesthetic systemic toxicity. Therefore, the value of ultrasound guidance depends on standardized scanning protocols, image documentation, and competency-based training.

3.2. Long-acting local anesthetic formulations and adjuvants

Long-acting local anesthetics and new formulations have been explored to extend the duration of single-injection blocks. Liposomal bupivacaine may prolong analgesia in selected clinical settings, but its benefit is procedure-dependent and should be interpreted cautiously rather than described as universally superior [2]. Clinicians also use adjuvants such as dexamethasone or dexmedetomidine to extend block duration, but the route of administration, dose, and safety profile require careful evaluation.

The clinical goal is not simply to prolong numbness, but to provide analgesia during the period of greatest postoperative pain while preserving motor function and minimizing toxicity. Dose selection should consider patient age, body weight, hepatic and cardiac function, total local anesthetic exposure, and the possibility of repeated or combined blocks.

3.3. Continuous perineural infusion and patient-controlled regional analgesia

Continuous perineural catheter techniques and patient-controlled regional analgesia can extend analgesia beyond the duration of a single injection. A basal infusion combined with patient-controlled boluses may help manage fluctuating pain intensity, reduce nighttime breakthrough pain, and lower opioid requirements after major limb surgery. Compared with constant high-rate infusion, patient-controlled bolus strategies may reduce unnecessary local anesthetic accumulation when pain is mild.

Nevertheless, catheter-based analgesia requires careful management. Catheter displacement, infection, pump malfunction, excessive motor blockade, falls, and delayed recognition of nerve injury are important concerns. Institutions should establish protocols for catheter fixation, dose limits, neurological examination,

discharge education, and follow-up after catheter removal [3].

4. Procedure-specific applications of regional anesthesia

4.1. Limb surgery

Regional anesthesia for limb surgery should be selected according to the surgical site, expected pain distribution, and need for postoperative motor function. For shoulder surgery, interscalene brachial plexus block provides effective analgesia but is associated with a high incidence of ipsilateral phrenic nerve paresis; it should be used cautiously in patients with limited respiratory reserve. For surgery below the elbow, supraclavicular, infraclavicular, or axillary approaches can provide distal upper limb coverage, and the choice depends on surgical location, patient anatomy, respiratory risk, and operator experience.

In lower limb surgery, motor preservation is often a major consideration. The adductor canal block is commonly used after knee arthroplasty because it provides predominantly sensory analgesia while better preserving quadriceps function than the femoral nerve block. For ankle and foot surgery, a popliteal sciatic nerve block combined with a saphenous nerve block can cover both posterior/lateral and medial territories. When multiple blocks are combined, the total local anesthetic dose must be calculated before injection to avoid exceeding safe limits [4].

Across all limb blocks, the minimum technical requirements include clear visualization of relevant anatomy, continuous or frequently confirmed needle-tip imaging, negative aspiration before injection, incremental injection, observation of local anesthetic spread, and documentation of preoperative and postoperative neurological function.

4.2. Thoracic and abdominal surgery

Thoracic and abdominal procedures often require analgesia across the paraspinal, intercostal, and abdominal wall regions. Thoracic paravertebral block can provide unilateral somatic and sympathetic blockade and may be useful for thoracic surgery or breast surgery, but it requires careful attention to pleural anatomy and hemodynamic effects. Erector spinae plane block and other fascial plane techniques are increasingly used because they are technically simpler in some settings, although the consistency and extent of dermatomal spread may vary.

For abdominal surgery, the transversus abdominis plane block, the rectus sheath block, and the quadratus lumborum block should be selected according to incision location and expected pain source. The TAP block is most useful for abdominal wall somatic pain and does not reliably treat visceral pain. Subcostal approaches may be considered for upper abdominal incisions, whereas lateral or posterior approaches may be more relevant for lower abdominal surgery. The operator should identify the external oblique, internal oblique, and transversus abdominis muscles, confirm needle-tip position in the correct fascial plane, and inject incrementally while observing spread [5].

4.3. Geriatric and critically ill patients

Elderly patients often have reduced physiological reserve, altered pharmacokinetics, frailty, cognitive vulnerability, and coexisting cardiopulmonary disease. Regional anesthesia can reduce opioid exposure and support rehabilitation, but the block plan should be individualized. Local anesthetic dose should generally be calculated conservatively, and lower concentrations may be used when motor preservation is important.

Preoperative cognitive assessment is also valuable because delirium risk may influence the choice between single-shot and continuous catheter techniques.

Critically ill patients require even more cautious selection. Patients with hemodynamic instability may not tolerate blocks associated with sympathetic blockade. Patients with coagulation dysfunction or therapeutic anticoagulation should generally avoid deep, non-compressible blocks such as paravertebral or lumbar plexus block; superficial fascial plane blocks or wound infiltration may be safer alternatives after individualized risk assessment. In all high-risk patients, the expected analgesic benefit must be weighed against bleeding, infection, nerve injury, and monitoring feasibility [6].

4.4. Integration with multimodal analgesia

Regional anesthesia should be integrated into a multimodal analgesic plan rather than used in isolation. When appropriate, a block may be performed after anesthesia induction and before incision to reduce early nociceptive input. Non-opioid systemic analgesics, such as acetaminophen and nonsteroidal anti-inflammatory drugs, can be used as baseline analgesics when there are no contraindications. Opioids should be reserved for rescue treatment of breakthrough pain and reassessed according to pain scores at rest and during movement.

The timing of rescue medication should be linked to the expected duration of the block and the patient's functional goals. For example, analgesia should be reassessed before the block is expected to regress, particularly before physiotherapy, coughing, turning, or ambulation. A simplified procedure-specific framework is shown in **Table 1**.

Table 1. Procedure-specific integration of regional anesthesia into multimodal perioperative analgesia

Surgical setting	Common regional technique	Preferred timing	Baseline analgesics	Rescue and monitoring focus
Knee arthroplasty	Adductor canal block, with or without posterior knee analgesic strategy	After induction or before incision	Acetaminophen and/or NSAID if not contraindicated	Assess quadriceps strength, fall risk, and pain during physiotherapy
Cesarean section or lower abdominal surgery	TAP block, quadratus lumborum block, or wound infiltration according to incision and institutional protocol	After delivery or at the end of surgery, when appropriate	Acetaminophen and NSAID if compatible with obstetric and surgical status	Monitor visceral pain, ambulation, and cumulative local anesthetic dose
Thoracoscopic surgery	Paravertebral block, erector spinae plane block, or intercostal/fascial plane block	Before incision or before emergence, according to the workflow	Acetaminophen and selected non-opioid analgesics	Assess respiratory function, cough pain, hypotension, and pneumothorax-related symptoms
Upper limb surgery below the elbow	Supraclavicular, infraclavicular, or axillary brachial plexus block	Before incision or as part of an anesthetic plan	Acetaminophen and NSAID if appropriate	Monitor sensory recovery, motor recovery, and signs of local anesthetic toxicity

Note: The table provides a general framework rather than a fixed protocol. The final plan should be adjusted according to surgical trauma, local anesthetic type and dose, comorbidities, anticoagulation status, and institutional expertise.

5. Implementation challenges and optimization strategies

5.1. Standardized training and competency assessment

The safety and efficacy of regional anesthesia depend heavily on operator skill. A traditional apprenticeship alone is insufficient because the number of supervised cases does not necessarily reflect competence. A

standardized training pathway should include anatomy review, ultrasound image acquisition, needling practice on simulation models, supervised clinical practice, and periodic reassessment.

Competency assessment should focus on image optimization, anatomical recognition, needle-tip control, injection safety, complication management, and clinical decision-making. Each block should be recorded in a procedural log that includes indication, technique, dose, ultrasound image, block success, adverse events, and postoperative neurological findings. Such documentation supports quality improvement and helps identify high-risk procedures or training gaps.

5.2. Monitoring and prevention of perioperative nerve injury

Perioperative nerve injury may be related to surgical traction, positioning, tourniquet use, compression, patient comorbidity, or regional anesthesia itself. Early symptoms can be masked by dressings, postoperative pain, residual block, or sedation. Therefore, a structured neurological assessment should be performed before the block when feasible, after emergence from anesthesia, and at regular postoperative intervals.

The assessment should include sensory testing in the relevant nerve territory and motor function testing appropriate to the limb or surgical site. Persistent motor dysfunction, progressive sensory deficit, severe neuropathic pain, or symptoms lasting beyond the expected duration of local anesthetic action should trigger timely evaluation. Institutions should develop escalation pathways involving anesthesiology, surgery, neurology, and neurophysiology, and should maintain a nerve injury registry for quality control [4–5].

5.3. Pharmacokinetic risk management of local anesthetic systemic toxicity

Local anesthetic systemic toxicity is uncommon but potentially life-threatening. Risk increases with excessive total dose, intravascular injection, highly vascular injection sites, extremes of age, pregnancy, low cardiac output, hepatic dysfunction, and repeated or combined blocks. Before injection, clinicians should confirm the planned drug, concentration, volume, maximum safe dose, and cumulative exposure from all regional techniques.

Risk reduction requires ultrasound guidance when appropriate, aspiration before injection, incremental injection, attention to injection pressure, and continuous clinical monitoring. Early warning symptoms such as tinnitus, perioral numbness, metallic taste, agitation, seizures, arrhythmia, or cardiovascular collapse must be recognized promptly. Lipid emulsion rescue should be immediately available in all locations where regional anesthesia is performed, and staff should be trained in the institutional LAST response protocol.

5.4. Dynamic analgesic assessment and information-supported decision-making

Paper-based pain records often fail to capture the dynamic course of postoperative pain. Intermittent pain scores at rest may underestimate movement-related pain, breakthrough pain, or block regression. An integrated information platform can link block type, local anesthetic dose, timing, pain scores at rest and during activity, opioid consumption, motor function, adverse events, and catheter status on a single timeline.

Such a system can generate alerts when pain scores remain high, when rescue opioids are repeatedly required, when motor block persists longer than expected, or when cumulative local anesthetic dose approaches the safety limit [7]. Artificial intelligence may assist with ultrasound image recognition, needle-nerve relationship assessment, and decision support, but it should be regarded as an aid rather than a replacement for clinical judgment [8]. Future implementation should prioritize data quality, patient privacy, interoperability, and prospective validation of decision-support rules.

6. Conclusion

Regional anesthesia has become an important component of opioid-sparing perioperative analgesia and enhanced recovery pathways. Its value depends on careful procedure selection, sensory-motor balance, ultrasound-guided precision, safe local anesthetic dosing, and standardized postoperative monitoring. Current challenges include uneven training quality, limited neurological follow-up, inconsistent documentation of outcomes, and incomplete integration with digital pain assessment systems. Future multicenter studies should define procedure-specific protocols, compare regional techniques using functional recovery outcomes, and evaluate information-supported decision-making in real clinical workflows. With these improvements, regional anesthesia can move from an isolated technical procedure toward a reproducible perioperative care strategy.

Disclosure statement

The author declares no conflict of interest.

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