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REVIEW ARTICLE

Adjuvant Strategies for Spinal Anesthesia in Knee Arthroscopy: A Comparative Review of Dexmedetomidine, Magnesium Sulphate, and Fentanyl

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ABSTRACT

Background: Knee arthroscopy is a standard orthopedic procedure that requires an anesthetic technique with rapid onset, stable hemodynamics, and minimal side effects to allow early mobilization and discharge. Selective spinal anesthesia (SSA) using low-dose hyperbaric bupivacaine has gained interest for its ability to provide targeted blockade and faster recovery compared with conventional spinal anesthesia, though its relatively short and sometimes inconsistent duration remains a limitation. To address this, several intrathecal adjuvants have been evaluated, and this review aims to compare the efficacy and safety of dexmedetomidine, magnesium sulphate, and fentanyl when combined with low-dose bupivacaine in SSA for knee arthroscopy.

Conclusion: Current evidence suggests that dexmedetomidine provides the most consistent prolongation of block and superior analgesia, though bradycardia and hypotension may occur. Fentanyl offers rapid and dense analgesia with minimal motor prolongation but carries opioid-related side effects, while magnesium provides modest block extension with a favorable safety profile. Tailored adjuvant use optimizes anesthetic efficacy and recovery outcomes.

Keywords: Spinal Anesthesia, Knee Arthroscopy, Dexmedetomidine, Magnesium Sulphate, Fentanyl.

INTRODUCTION

Knee arthroscopy is one of the most frequently performed minimally invasive orthopedic procedures, used for diagnostic and therapeutic purposes, such as meniscal repair, ligament reconstruction, and cartilage surgery. Although the procedure is relatively short, the anesthetic technique must provide a rapid onset, a reliable sensory block, hemodynamic stability, effective postoperative analgesia, and early ambulation to support enhanced recovery pathways. Conventional options, including general anesthesia or standard-dose spinal anesthesia, can achieve adequate surgical conditions but are often associated with drawbacks such as prolonged motor block, urinary retention, postoperative nausea, and delayed discharge—limitations that are particularly relevant in ambulatory surgery settings [1,2].

Selective spinal anesthesia (SSA) with low-dose hyperbaric bupivacaine has gained popularity as an alternative that provides sufficient anesthesia for lower-limb procedures while minimizing motor impairment and systemic side effects. By restricting the block to the dermatomes required for surgery, SSA offers faster mobilization, reduced complications, and higher patient satisfaction [3]. However, its primary limitation is a relatively short and sometimes inadequate block duration, which may not reliably cover procedures extending beyond 45–60 minutes. This has increased interest in using intrathecal adjuvants to enhance block quality and prolong analgesia [4].

Several pharmacological agents have been investigated as intrathecal adjuvants. Fentanyl, a lipophilic μ-opioid receptor agonist, augments local anesthetic action and improves intraoperative analgesia, but its use may be complicated by side effects such as pruritus, nausea, and the risk of respiratory depression [5]. Dexmedetomidine, a highly selective α2-adrenergic agonist, has shown consistent efficacy in prolonging sensory and motor block, improving analgesia, and providing sedation without respiratory compromise, though bradycardia and hypotension remain potential concerns [6]. Magnesium sulphate, which exerts its effects through NMDA receptor antagonism and calcium channel modulation, has demonstrated the ability to enhance spinal block and reduce analgesic requirements, though evidence supporting its clinical role is less robust compared with fentanyl and dexmedetomidine [7].

While multiple randomized controlled trials and meta-analyses have evaluated these agents, findings remain heterogeneous, and no clear consensus exists regarding the optimal intrathecal adjuvant for SSA in knee arthroscopy. Some studies favor dexmedetomidine for its prolonged block duration and stable analgesia, while others highlight fentanyl for its rapid intraoperative benefits or magnesium for its opioid-sparing potential [6,7]. These conflicting results underscore the need for a comprehensive appraisal of available evidence.

The present review aims to evaluate and compare the efficacy and safety of dexmedetomidine, magnesium sulphate, and fentanyl when combined with low-dose hyperbaric bupivacaine in selective spinal anesthesia for knee arthroscopy. By examining pharmacological properties, clinical outcomes, and adverse effect profiles, the article seeks to guide optimal anesthetic practice and highlight areas where further research is required to refine evidence-based strategies.

Spinal anesthesia has long been a standard technique for lower-limb surgery, but conventional doses of local anesthetics often result in an extensive block associated with prolonged motor impairment and delayed recovery. Selective spinal anesthesia (SSA) was developed to overcome these drawbacks by administering lower doses of local anesthetics, thereby limiting the block to specific dermatomes and reducing unwanted effects [8].

SSA using low-dose hyperbaric bupivacaine has gained particular interest in ambulatory knee arthroscopy, where rapid onset, reliable analgesia, and early mobilization are essential. The technique provides adequate surgical conditions while minimizing complications such as urinary retention, hypotension, and delayed discharge [9,10]. In addition, patients receiving SSA generally report greater satisfaction due to faster return of motor function and reduced need for prolonged observation in recovery units.

Despite these advantages, the main limitation of SSA is its relatively short duration of anesthesia and postoperative analgesia. Procedures lasting more than 45–60 minutes may exceed the effective window of a low-dose block, leading to intraoperative discomfort or the need for supplemental anesthesia. This challenge has prompted the incorporation of intrathecal adjuvants with local anesthetics to extend block duration, enhance intraoperative conditions, and improve postoperative pain control [11,12].

Intrathecal Adjuvants in Selective Spinal Anesthesia

The most frequently studied intrathecal adjuvants include opioids, α2-adrenergic agonists, and NMDA receptor antagonists. Fentanyl, a lipophilic opioid, enhances sensory block and reduces the need for systemic analgesics, though side effects such as pruritus, nausea, and occasional respiratory depression remain concerns [13]. Dexmedetomidine, a highly selective α2-agonist, has shown consistent efficacy in prolonging sensory and motor block while providing mild sedation and stable respiratory function, albeit with risks of bradycardia and hypotension [14]. Magnesium sulphate, through NMDA receptor antagonism

and calcium channel modulation, can modestly extend block duration and provide an opioid-sparing effect, though its clinical adoption has been more cautious due to concerns about delayed onset and variable efficacy [15].

Although each adjuvant has demonstrated advantages, head-to-head comparisons reveal variability in outcomes. Therefore, the selection of an optimal adjuvant depends on the procedure length, patient comorbidities, and institutional emphasis on either rapid recovery or extended postoperative pain relief [15].

Pharmacology of Hyperbaric Bupivacaine

Bupivacaine is a long-acting amide local anesthetic that remains the cornerstone of spinal anesthesia because of its favorable balance between sensory and motor block. When rendered hyperbaric by adding dextrose, its spread in the cerebrospinal fluid becomes gravity-dependent, allowing clinicians to manipulate block height through patient positioning—an essential feature in selective spinal anesthesia (SSA) [16].

At the neuronal level, bupivacaine blocks voltage-gated sodium channels, preventing depolarization and impulse propagation. Smaller unmyelinated C fibers and thinly myelinated Aδ fibers are more sensitive than motor fibers, enabling low-dose selective sensory blockade [17]. Compared with lidocaine, bupivacaine has a slower onset but provides a more prolonged effect, making it well-suited for orthopedic procedures.

The duration of the block varies with dose, baricity, cerebrospinal fluid volume, and posture. Standard intrathecal doses typically provide anesthesia for 90–180 minutes, whereas the reduced doses used in SSA shorten block duration. This is why adjuvants are often required to extend the block's clinical utility [18].

Adverse effects are largely dose-related. Higher concentrations may cause significant sympathetic block, hypotension, and delayed ambulation, while rare cardiotoxicity is linked mainly to systemic absorption. Using low-dose hyperbaric bupivacaine minimizes these risks, supporting its role in ambulatory knee arthroscopy [19].

Pharmacology of Dexmedetomidine

Dexmedetomidine is a highly selective α2-adrenergic receptor agonist, with a receptor affinity ratio of about 1600:1 compared with α1 receptors, making it more specific than clonidine. This selectivity reduces unwanted cardiovascular effects while preserving its sedative and analgesic actions [20].

Its analgesic effect is mediated by presynaptic inhibition of norepinephrine release in the dorsal horn and postsynaptic hyperpolarization, leading to prolonged sensory and motor blockade. Systemic absorption is minimal when given intrathecally, and its action is localized to spinal receptors, providing prolonged analgesia without respiratory depression [21].

Pharmacokinetically, intravenous administration produces a rapid distribution and a half-life of 2–3 hours, with hepatic metabolism and renal excretion of inactive metabolites. Intrathecal dosing bypasses systemic effects, though the main risks remain bradycardia and hypotension due to central sympatholysis [22].

Clinically, dexmedetomidine has been shown to prolong block duration and postoperative analgesia more consistently than fentanyl or magnesium sulphate in SSA. Its sedative properties may also reduce intraoperative anxiety, though the potential for delayed recovery in ambulatory cases warrants caution [23].

Pharmacology of Magnesium Sulphate

Magnesium sulphate is an inorganic salt with notable roles in anesthesia and critical care. Its primary mechanism involves antagonism of N-methyl-D-aspartate (NMDA) receptors and inhibition of voltage-gated calcium channels, thereby decreasing excitatory neurotransmitter release, such as glutamate and substance P. This action reduces central sensitization and contributes to its analgesic properties [24].

Pharmacokinetically, magnesium is not metabolized, is excreted unchanged by the kidneys, and has a distribution half-life of 2.5–4 hours when given intravenously. After

intrathecal administration, systemic absorption is minimal, and the effect remains confined to the spinal cord. While magnesium alone does not induce motor block, it enhances the depth and duration of sensory block when combined with local anesthetics [25].

Clinical data suggest that intrathecal magnesium may prolong postoperative analgesia and delay the need for rescue analgesics, with an opioid-sparing effect. However, compared to dexmedetomidine or fentanyl, its onset of action is slower, and efficacy results across studies have been inconsistent. Concerns about neurotoxicity were raised in experimental models, though human trials at typical doses (50–100 mg) have not demonstrated significant neurological harm [26].

Magnesium is a relatively safe adjuvant with modest block prolongation and limited systemic side effects. Its role in SSA for knee arthroscopy remains supportive rather than primary, particularly where opioid-related adverse effects are undesirable [27].

Pharmacology of Fentanyl

Fentanyl is a synthetic, lipophilic opioid that acts primarily on μ-opioid receptors in the dorsal horn of the spinal cord. It suppresses nociceptive transmission and produces rapid, potent analgesia by inhibiting presynaptic calcium influx and enhancing postsynaptic potassium efflux [28].

Its high lipid solubility allows for a fast onset of action following intrathecal administration, with clinical effects typically lasting 2–4 hours due to redistribution and systemic absorption. Unlike local anesthetics, fentanyl does not induce motor block but synergistically enhances sensory block when combined with agents such as bupivacaine [29].

Intrathecal fentanyl is valued for improving intraoperative analgesia, reducing shivering, and decreasing systemic opioid requirements. However, side effects such as pruritus, nausea, vomiting, urinary retention, and dose-dependent respiratory depression remain concerns, although the latter is rare at low intrathecal doses (10–25 μg) [30].

In selective spinal anesthesia for knee arthroscopy, fentanyl is especially advantageous for short procedures. It provides dense analgesia without prolonging motor block, enabling faster recovery and early ambulation, which is critical in ambulatory settings [31].

Comparative Efficacy with Hyperbaric Bupivacaine

The addition of intrathecal adjuvants to low-dose hyperbaric bupivacaine has transformed the clinical utility of selective spinal anesthesia (SSA), particularly in ambulatory orthopedic surgery such as knee arthroscopy, where short to intermediate block duration, rapid onset, and early mobilization are priorities. Comparative evaluation of dexmedetomidine, magnesium sulphate, and fentanyl demonstrates distinct differences in their influence on block characteristics, hemodynamic profile, sedation, and recovery outcomes [32].

Hemodynamic Stability

Maintenance of stable cardiovascular parameters is central to the safety of SSA. Fentanyl, lacking direct sympatholytic properties, typically exerts little influence on systemic blood pressure or heart rate and therefore contributes to predictable intraoperative hemodynamics. Dexmedetomidine, although effective in prolonging block duration, may cause bradycardia and hypotension secondary to α2-mediated sympatholysis; these effects are usually manageable but can be problematic in elderly or hypovolemic patients. Through calcium channel modulation and mild vasodilatory activity, magnesium sulfate generally preserves cardiovascular stability when used in low intrathecal doses, with minimal clinically significant hypotension reported [33].

Analgesic Efficacy and Block Duration

Among the studied adjuvants, dexmedetomidine provides the most consistent and clinically meaningful sensory and motor block prolongation, often extending adequate analgesia by 2–4 hours compared with bupivacaine alone. Fentanyl is characterized by

a very rapid onset and dense intraoperative analgesia, but its relatively short duration of 90–150 minutes limits its usefulness in longer operations. In contrast, magnesium sulphate provides modest prolongation of sensory block with minimal extension of motor block, offering an intermediate balance between efficacy and recovery [34].

Sedation Profiles

Sedative effects vary among these agents and may influence patient comfort. Dexmedetomidine produces a cooperative sedation resembling physiologic sleep, which can reduce anxiety and improve tolerance of regional anesthesia but requires vigilant monitoring for bradycardia. Intrathecal fentanyl at typical doses does not confer significant sedation, while magnesium sulphate is not associated with sedative properties when administered intrathecally [35].

Recovery Characteristics

Recovery and discharge readiness are key determinants in ambulatory knee arthroscopy. Fentanyl facilitates early mobilization by enhancing analgesia without prolonging motor block, thus supporting same-day discharge. Dexmedetomidine, although superior in prolonging analgesia, may delay mobilization due to motor block extension and sedative effects, which can be undesirable in outpatient practice. Magnesium sulphate provides a compromise, modestly lengthening analgesia without substantial interference in motor recovery [36].

In summary, dexmedetomidine offers the most potent prolongation of analgesia, fentanyl provides rapid onset and quicker recovery, and magnesium sulphate delivers intermediate benefits with a favorable safety margin. Optimal adjuvant selection should be individualized according to surgical duration, patient comorbidities, and the institutional emphasis on extended analgesia or fast-track recovery [36].

Evidence from Clinical Trials and Meta-Analyses

Early randomized trials in ambulatory knee arthroscopy established that combining low-dose hyperbaric bupivacaine with intrathecal fentanyl provides dependable surgical anesthesia with fast-track recovery. In particular, a regimen using 3 mg hyperbaric bupivacaine + 10 µg fentanyl delivered adequate intraoperative conditions, minimal adverse effects, and timely discharge readiness, helping define the selective spinal anesthesia (SSA) paradigm for outpatient arthroscopy [37]. Subsequent studies reinforced these findings, showing longer time to first analgesic request and reduced need for supplemental analgesia when fentanyl accompanies low-dose bupivacaine, while preserving rapid ambulation and short stays [37].

The introduction of intrathecal magnesium sulphate added an opioid-sparing option. A prospective randomized trial in arthroscopic knee surgery demonstrated that 50 mg intrathecal magnesium significantly prolonged fentanyl-mediated analgesia without neurological sequelae [38]. Additional lower-limb data suggest that magnesium, when combined with bupivacaine (often alongside fentanyl), modestly extends sensory block and delays rescue analgesic requirements, albeit with a tendency toward a slower onset and heterogeneous effect sizes across studies [38].

Among intrathecal adjuvants, dexmedetomidine has accumulated the strongest pooled evidence. Meta-analyses consistently show that adding dexmedetomidine to bupivacaine prolongs sensory and motor block, lengthens postoperative analgesia, and reduces shivering, with no apparent excess of hypotension or bradycardia at low intrathecal doses in aggregate data—though individual trials still warrant vigilance for bradycardia [38]. Compared head-to-head with fentanyl in low-dose spinal settings, dexmedetomidine generally yields more prolonged analgesia and a more durable block, while fentanyl achieves quicker onset and facilitates earlier mobilization—a trade-off that is particularly relevant in ambulatory arthroscopy [38].

Two recently published articles provide further context and strengthen the present analysis of

intrathecal adjuvants for selective spinal anesthesia in knee arthroscopy. The first, a 2024 systematic review in *Cureus*, synthesized contemporary randomized trials and concluded that intrathecal dexmedetomidine yields the most consistent prolongation of both sensory and motor block, extending adequate analgesia by roughly 2–4 hours beyond local anesthetic alone, while maintaining an acceptable safety margin despite a moderate risk of bradycardia and hypotension [39]. Fentanyl was highlighted for its rapid onset and dense intraoperative analgesia, but with earlier postoperative analgesic requirements, whereas magnesium sulphate demonstrated modest, dose-dependent extension of block duration with minimal side effects and notable opioid-sparing potential [39,40]. These pooled findings echo our observations that dexmedetomidine offers the longest and most stable block, fentanyl is optimal for short procedures demanding swift recovery, and magnesium serves as a safe alternative when minimizing opioid or α2-agonist exposure is desirable.

Complementing these results, an original clinical study published in Zagazig University Medical Journal in 2025 underscored the practical importance of balancing sensory block prolongation with ambulation and discharge readiness [40]. That work showed that extending the sensory block by approximately 2–3 hours significantly enhanced patient satisfaction and reduced rescue analgesic requirements without materially delaying motor recovery or discharge. The authors specifically recommended tailoring adjuvant choice to the anticipated procedure duration and patient comorbidities, a conclusion consistent with our recommendation to individualize intrathecal adjuvant selection. Collectively, these recent reports reinforce the present review's central message: adjuvant choice should be guided by procedural length, desired postoperative analgesia, and patient-specific recovery goals, and future multicenter trials with standardized dosing and validated recovery metrics are warranted to refine these strategies.

Synthesizing the evidence: fentanyl remains the adjuvant of choice when rapid onset and early discharge are priorities; dexmedetomidine is preferred when prolonged postoperative analgesia is desired; and magnesium offers a safe, opioid-sparing adjunct with modest block extension but variable magnitude of effect. Notably, peri- or intra-articular strategies with these agents (outside the intrathecal route) also demonstrate analgesic benefits in arthroscopy and can complement SSA pathways, although they fall beyond the scope of the intrathecal focus here. Current data support tailoring the adjuvant to procedure length, recovery goals, and patient comorbidity profiles.

The current body of literature provides an insight into the comparative efficacy of dexmedetomidine, magnesium sulphate, and fentanyl as intrathecal adjuvants for selective spinal anesthesia in knee arthroscopy. Strengths of this evidence include the presence of randomized controlled trials with standardized dosing regimens and multiple systematic reviews and meta-analyses, which allow pooled evaluation of efficacy and safety. Together, these data provide a strong foundation for guiding clinical practice in ambulatory orthopedic anesthesia.

However, several limitations warrant consideration. Many trials are small, single-center studies with variable methodological quality, leading to heterogeneity in reported outcomes. Differences in local anesthetic doses, patient populations, and recovery endpoint definitions complicate direct comparison across studies. In addition, most available trials focus on short—to intermediate-duration procedures, with less evidence in prolonged arthroscopic or complex knee surgeries, limiting generalizability.

Future research should focus on larger, multicenter randomized studies that directly compare adjuvants using standardized dosing protocols, validated recovery metrics, and patient-reported outcomes. Network meta-analyses may also help clarify comparative efficacy when head-to-head trials are lacking. Furthermore, long-term safety monitoring,

particularly for repeated intrathecal exposure to agents such as magnesium, remains an area in need of more robust evidence. These refinements would strengthen the ability to provide individualized, evidence-based recommendations for adjuvant selection in knee arthroscopy.

CONCLUSION

Selective spinal anesthesia with low-dose hyperbaric bupivacaine is well-suited for knee arthroscopy, providing reliable anesthesia with faster recovery than conventional techniques. Its main limitation is short duration, which has led to using intrathecal adjuvants to extend block efficacy and postoperative pain relief. Dexmedetomidine consistently offers the most remarkable prolongation of sensory and motor block with enhanced analgesia, though risks of bradycardia and hypotension must be considered. Fentanyl delivers rapid onset and dense intraoperative analgesia without delaying motor recovery, making it ideal for short procedures and ambulatory care, but side effects such as pruritus and nausea remain concerns. Magnesium sulphate provides modest block extension with an opioid-sparing profile and good safety record, yet its slower onset and variable efficacy limit wider use.

Current evidence shows no universal “best” adjuvant. Instead, choice should be tailored: dexmedetomidine for longer procedures or when analgesia is a priority, fentanyl for rapid discharge, and magnesium when opioid-related side effects should be minimized. Intrathecal adjuvants thus enhance the performance of SSA, and future research should refine dosing strategies, explore combination regimens, and establish long-term safety to optimize their role in clinical practice.

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