SAS Journal of Medicine
Abbreviated Key Title: SAS J Med
ISSN 2454-5112
Journal homepage: https://saspublishers.com

OPEN ACCESS

Anesthesia and Intensive Care

Postoperative Analgesia with Femoral Perineural Catheter for Major Knee Surgery: A Randomized Controlled Trial Comparing Ultrasound Guidance Versus Nerve Stimulation

B. Amziane[1*], M. Matouk[1]

[1]Department of Anesthesia and Intensive Care, University Hospital Douéra, Algeria

DOI: https://doi.org/10.36347/sasjm.2025.v11i12.014 | **Received:** 17.10.2025 | **Accepted:** 11.12.2025 | **Published:** 22.12.2025

***Corresponding author:** B. Amziane
Department of Anesthesia and Intensive Care, University Hospital Douéra, Algeria

Abstract **Original Research Article**

Background: Regional anesthesia using femoral perineural catheters (FPC) represents a cornerstone technique for postoperative pain management after major knee surgery. While nerve stimulation has traditionally guided catheter placement, ultrasound (US) guidance offers potential advantages through direct visualization of anatomical structures, theoretically improving safety, precision, and analgesic efficacy. ***Objective:*** To compare the analgesic efficacy, safety profile, and technical parameters of FPC placement under ultrasound guidance versus traditional nerve stimulation (NS) in patients undergoing major knee surgery. ***Methods:*** We conducted a prospective, randomized, single-center study at Douéra University Hospital, Algeria, including 92 patients (aged 18-80 years, ASA I-III) scheduled for major knee surgery (total knee arthroplasty, ligament reconstruction, or arthrolysis). Following informed consent, patients were randomly allocated to receive FPC placement using either ultrasound guidance (US group, n=46) or nerve stimulation (NS group, n=46). The primary outcome was pain intensity assessed using the Visual Analog Scale (VAS) at rest every 6 hours for 48 hours and during mobilization at 48 hours postoperatively. Secondary outcomes included procedure duration, local anesthetic consumption, complications, functional recovery parameters, and patient satisfaction scores. ***Results:*** Eighty-five patients completed the study protocol (NS=42, US=43). Baseline demographic and clinical characteristics were comparable between groups. VA score at rest were similar from hour 0 to hour 36 postoperatively. At 48 hours, the US group demonstrated significantly lower pain scores both at rest (1.95±1.1 vs 2.48±1.2; p=0.004) and during mobilization (3.37±1.0 vs 4.02±1.1; p=0.008). Procedure duration was significantly shorter with ultrasound guidance (4.9±1.0 vs 5.5±1.1 minutes; p=0.01). No major complications occurred in either group. Patient satisfaction was high and comparable (76.7% US vs 71.2% NS reported satisfied or very satisfied; p=0.77). ***Conclusion:*** Ultrasound guidance for femoral perineural catheter placement provides modestly superior analgesic efficacy at 48 hours postoperatively with reduced procedure time compared to nerve stimulation. Both techniques demonstrate excellent safety profiles and high patient satisfaction. These findings support ultrasound guidance as a valuable technique for regional analgesia in enhanced recovery protocols, though the modest clinical benefit should be balanced against equipment costs and training requirements.

Keywords: Knee surgery; Postoperative pain; Regional analgesia; Femoral perineural catheter; Ultrasound guidance; Nerve stimulation; Enhanced recovery after surgery.

INTRODUCTION

Major knee surgery, including total knee arthroplasty (TKA), cruciate ligament reconstruction, and arthrolysis, frequently results in significant postoperative pain that can impede early mobilization, delay rehabilitation, and compromise functional outcomes[1,2]. Effective pain management remains a critical component of perioperative care, with inadequate analgesia associated with increased opioid consumption, prolonged hospital stays, and reduced patient satisfaction [3,4].

Regional anesthesia techniques, particularly peripheral nerve blocks, have emerged as cornerstone strategies in multimodal analgesic protocols for orthopedic surgery[5,6]. The placement of continuous peripheral nerve catheters (PNC) enables prolonged postoperative analgesia, facilitating intensive physiotherapy while minimizing systemic opioid

requirements and their associated adverse effects[7,8]. Among various regional techniques, the femoral nerve block has been widely adopted for major knee surgery due to its ability to provide effective analgesia to the anterior and medial aspects of the knee joint [9,10].

Postoperative functional limitations, particularly joint stiffness following TKA, represent common complications that significantly impact patients' quality of life and long-term outcomes [11,12]. Optimal postoperative pain control is therefore essential not only for patient comfort but also for enabling early mobilization and aggressive physiotherapy, which are critical for preventing arthrofibrosis and achieving satisfactory range of motion [13,14]. This paradigm aligns closely with Enhanced Recovery After Surgery (ERAS) principles, which emphasize multimodal analgesia and early functional recovery [15,16].

Traditionally, femoral perineural catheter placement has been performed using nerve stimulation (NS) guidance, relying on motor response to electrical stimulation for nerve localization [17,18]. However, this technique presents several limitations, including inability to visualize surrounding anatomical structures, variable patient responses to stimulation, and reported catheter malposition rates reaching 30-40% [19,20]. Furthermore, nerve stimulation provides no information regarding needle trajectory relative to vascular structures or the final position of the catheter tip relative to the target nerve [21].

The introduction of ultrasound guidance has revolutionized regional anesthesia practice by enabling real-time visualization of anatomical structures, including nerves, vessels, and surrounding tissues [22,23]. Ultrasound-guided techniques theoretically offer several advantages: direct visualization of the target nerve and catheter placement, identification and avoidance of vascular structures, confirmation of local anesthetic spread, and potential reduction in procedure time and complications [24,25]. Multiple studies have demonstrated the superiority of ultrasound guidance for single-injection peripheral nerve blocks [26,27], yet comparative data regarding continuous catheter techniques remain limited and occasionally conflicting [28,29].

Despite the theoretical advantages of ultrasound guidance, questions remain regarding its clinical superiority for continuous femoral nerve catheter placement in terms of analgesic efficacy, safety, and cost-effectiveness compared to the established nerve stimulation technique [30,31]. The present study was designed to address this knowledge gap by comparing analgesic efficacy, safety profile, and technical parameters of femoral perineural catheter placement using ultrasound guidance versus nerve stimulation in patients undergoing major knee surgery.

1.1. MATERIALS AND METHODS

Study Design and Ethical Considerations

This prospective, randomized, single-center clinical trial was conducted at the Department of Orthopedic and Trauma Surgery "B" of Douéra University Hospital Center, Algeria, between January 2022 and December 2023. The study protocol was approved by the Ethics Committee of the Faculty of Medicine, Saad Dahleb University of Blida (approval number: [to be inserted]), and was conducted in accordance with the Declaration of Helsinki and Good Clinical Practice guidelines. The trial was registered at [registry name and number to be inserted]. All participants provided written informed consent after receiving detailed explanation of study procedures, potential risks, and benefits.

Study Population

Inclusion Criteria

Eligible patients met the following criteria:

- Age 18 to 80 years
- American Society of Anesthesiologists (ASA) physical status classification I-III
- Scheduled for elective major knee surgery, defined as total knee arthroplasty, anterior or posterior cruciate ligament reconstruction, or arthrolysis
- Ability to understand study procedures and provide informed consent
- Agreement to participate in postoperative follow-up assessments

Exclusion Criteria

Patients were excluded if they presented with:

- Patient refusal to participate or undergo regional anesthesia
- Local infection at the proposed puncture site
- Known allergy or contraindication to local anesthetics or study medications
- Current anticoagulation therapy or coagulopathy (INR >1.5, platelets <100,000/mm³)
- Pre-existing neurological pathology affecting the lower extremity
- Severe renal insufficiency (creatinine clearance <30 mL/min)
- Cognitive impairment preventing reliable pain assessment
- Body mass index >40 kg/m²
- Pregnancy or breastfeeding

Randomization and Allocation Concealment

Ninety-two eligible patients were enrolled and randomly allocated in a 1:1 ratio to either the nerve stimulation group (NS, n=46) or ultrasound guidance group (US, n=46). Randomization was performed using a computer-generated random number sequence with variable block sizes (4 and 6) to ensure allocation concealment. Group assignments were placed in

sequentially numbered, sealed, opaque envelopes that were opened immediately before catheter placement by the anesthesiologist performing the procedure. Due to the nature of the interventions, blinding of the proceduralist was not feasible. However, outcome assessors collecting pain scores and satisfaction data were blinded to group allocation whenever possible.

Anesthetic Protocol

Preoperative Management

All patients underwent standardized pre-anesthetic evaluation within 30 days before surgery. On the day of surgery, patients received premedication with hydroxyzine 1 mg/kg orally 90 minutes before the procedure. Standard monitoring included continuous electrocardiography, non-invasive blood pressure measurement, and pulse oximetry.

Spinal Anesthesia

After establishing intravenous access and administering 500 mL of crystalloid solution, all patients received standardized spinal anesthesia. With the patient in the sitting position, following strict aseptic technique, a 25-gauge Quincke spinal needle was inserted at the L3-L4 or L4-L5 interspace using a midline approach. The spinal anesthetic solution consisted of hyperbaric bupivacaine 0.5% (10 mg) combined with fentanyl (12.5 μg), injected over 15-20 seconds after confirmation of free-flowing cerebrospinal fluid.

Femoral Perineural Catheter Placement

Nerve Stimulation Technique (NS Group)

Following strict aseptic skin preparation with chlorhexidine 2% and sterile draping, the femoral artery was palpated at the level of the inguinal crease. The puncture site was located 1 cm lateral to the arterial pulsation, immediately below the inguinal ligament. After local infiltration with lidocaine 1%, an 18-gauge insulated stimulating needle (Stimuplex® A, B. Braun, Germany) connected to a nerve stimulator (Stimuplex® HNS 12, B. Braun) was introduced at a 45-60° angle cephalad.

The initial stimulation intensity was set at 1.5 mA (frequency 2 Hz, pulse duration 0.1 ms). The needle was advanced slowly while maintaining skin contact to the needle shaft to optimize current transmission. Correct needle positioning was confirmed by observing quadriceps muscle contraction with patellar elevation (femoral nerve stimulation). The stimulation intensity was then progressively decreased, with optimal positioning defined as maintaining visible motor response at 0.3-0.5 mA.

After negative aspiration for blood, 5 mL of 5% dextrose solution was injected to facilitate catheter threading. A 20-gauge polyamide catheter (Contiplex® D, B. Braun) was then advanced through the needle to extend 3-5 cm beyond the needle tip. The needle was carefully withdrawn while maintaining catheter position. Following additional negative aspiration, the initial bolus of local anesthetic (20 mL: 10 mL bupivacaine 0.5% + 10 mL lidocaine 1.5%) was administered in divided doses. The catheter was then secured with sterile adhesive dressing and a transparent film dressing.

Ultrasound-Guided Technique (US Group)

After identical aseptic preparation and draping, ultrasound examination was performed using a high-frequency linear transducer (6-13 MHz, SonoSite M-Turbo®, FUJIFILM SonoSite, USA). The probe was positioned in a transverse orientation at the inguinal crease to identify key anatomical structures: the femoral artery (pulsatile, non-compressible), femoral vein (compressible, medial to artery), and femoral nerve (hyperechoic, ovoid structure lateral to the artery, deep to the fascia iliaca).

Following local anesthetic infiltration, an 18-gauge non-stimulating Tuohy needle (Contiplex® C, B. Braun) was introduced using an in-plane technique (lateral to medial approach) under continuous real-time visualization. The needle trajectory was adjusted to position the tip immediately lateral and superficial to the femoral nerve, deep to the fascia iliaca. Correct positioning was confirmed by injecting 2-3 mL of 5% dextrose solution and observing its spread around the nerve with slight displacement of the nerve from the fascia iliaca.

A 20-gauge polyamide catheter was then advanced through the needle to extend 1-2 cm beyond the needle tip (shorter advancement than NS technique to minimize risk of vascular puncture under direct visualization). The needle was withdrawn while maintaining catheter position under ultrasound visualization. Catheter position was reconfirmed by injecting 5 mL of 5% dextrose solution and observing fluid spread around the nerve. The initial bolus of local anesthetic (20 mL: 10 mL bupivacaine 0.5% + 10 mL lidocaine 1.5%) was then administered incrementally with intermittent aspiration, with real-time visualization of local anesthetic spread. The catheter was secured identically to the NS technique.

Block Assessment

Sensory block was assessed at 5, 10, and 15 minutes after initial bolus injection using the cold test (application of ice along the anterior and medial thigh distribution) and pinprick test. Motor block was evaluated by assessing the patient's ability to extend the knee against resistance and to perform straight leg raise. Complete sensory block was defined as absence of cold sensation and pinprick response in the femoral nerve distribution. Complete motor block was defined as inability to extend the knee or perform straight leg raise. Block onset time was recorded as the interval between completion of local anesthetic injection and documentation of complete sensory and motor block.

Postoperative Analgesia Protocol

Continuous Perineural Infusion

Continuous perineural analgesia was initiated 4 hours after the initial bolus injection to allow for spinal anesthesia regression and baseline pain assessment. An elastomeric pump (Infusor® SV2, Baxter) was connected to the femoral catheter, delivering bupivacaine 0.125% at a continuous rate of 5 mL/hour. Patients were instructed on self-administration of bolus doses (5 mL of bupivacaine 0.125%) as needed for breakthrough pain, with a lockout interval of 45 minutes. The continuous infusion was maintained for 48 hours postoperatively, with catheter removal scheduled for the morning of postoperative day 3.

Multimodal Systemic Analgesia

All patients received standardized multimodal analgesia including:

- Acetaminophen (paracetamol) 1 g intravenously every 6 hours
- Diclofenac 100 mg suppository every 12 hours (unless contraindicated)
- Rescue analgesia with buprenorphine 0.2 mg subcutaneously every 8 hours as needed for VAS >4 despite catheter bolus

Outcome Measures

Primary Outcome

The primary outcome was pain intensity assessed using a 0-10 Visual Analog Scale (VAS), where 0 represents no pain and 10 represents the worst imaginable pain. Pain scores were recorded:

- At rest: every 6 hours for 48 hours postoperatively (H0, H6, H12, H18, H24, H30, H36, H42, H48)
- During mobilization (knee flexion to 45°): at H48

Secondary Outcomes

Technical Parameters:

- Procedure duration (time from skin preparation to catheter securement)
- Block onset time (time to complete sensory and motor block)
- Number of needle punctures required
- Number of needle redirections

Analgesic Efficacy:

- Total local anesthetic consumption over 48 hours
- Time to first analgesic request
- Number of catheter boluses administered
- Rescue analgesic consumption (buprenorphine doses)
- Proportion of patients with maximum VAS >4
- Mean VAS scores at postoperative days 1 and 2

Safety and Complications:

- Major complications (nerve injury, local anesthetic systemic toxicity, infection)
- Minor complications (catheter dislodgement, paresthesias, vascular puncture, hematoma)
- Technical failures requiring alternative analgesic technique

Functional Recovery:

- Knee flexion angle at postoperative days 2 and 5
- Time to first ambulation
- Hospital length of stay

Patient Satisfaction:

- Overall satisfaction with pain management rated on a 5-point Likert scale (very dissatisfied, dissatisfied, neutral, satisfied, very satisfied)

Data Collection

Data were collected by trained research personnel using standardized case report forms. Demographic and clinical data were obtained from medical records. Technical parameters were recorded in real-time by the proceduralist. Pain scores and analgesic consumption were documented by nursing staff using standardized protocols, with research personnel verifying data accuracy daily. Functional recovery parameters were assessed by physiotherapists blinded to group allocation when possible. Patient satisfaction was evaluated at 48 hours and at hospital discharge using structured interviews.

Sample Size Calculation

Sample size was calculated based on the primary outcome of VAS score at rest at 48 hours. Assuming a clinically meaningful difference of 1.0 point on the VAS scale, with a standard deviation of 1.5 (based on pilot data), an alpha error of 0.05, and power of 80%, we calculated that 37 patients per group would be required. Anticipating a 20% dropout rate, we planned to enroll 46 patients per group (total n=92).

Statistical Analysis

Statistical analyses were performed using SPSS version 20.0 (IBM Corp., Armonk, NY, USA). Data normality was assessed using the Shapiro-Wilk test and visual inspection of Q-Q plots. Continuous variables are presented as mean ± standard deviation for normally distributed data or median (interquartile range) for non-normally distributed data. Categorical variables are presented as frequencies and percentages.

Between-group comparisons were performed using:

- Independent samples t-test or Mann-Whitney U test for continuous variables
- Chi-square test or Fisher's exact test for categorical variables
- Repeated measures ANOVA for longitudinal pain score comparisons

Statistical significance was set at $p<0.05$ (two-tailed). All analyses were performed on an intention-to-treat basis, with missing data handled using last observation carried forward for pain scores.

RESULTS

Patient Flow and Baseline Characteristics

Between January 2022 and December 2023, 118 patients were assessed for eligibility. Of these, 26 patients were excluded (15 declined participation, 6 had contraindications to regional anesthesia, 3 had cognitive impairment, 2 were receiving anticoagulation). Ninety-two patients were randomized (46 to each group). Seven patients were excluded after randomization: 3 in the NS group (2 technical failures, 1 withdrew consent) and 4 in the US group (3 surgical cancellations, 1 converted to general anesthesia due to inadequate spinal anesthesia). Eighty-five patients completed the study protocol and were included in the final analysis (NS group : n=42, US group : n=43).

Baseline demographic, anthropometric, and clinical characteristics were comparable between groups (Table 1). The mean age was 45.7±20.9 years in the NS group and 48.9±22.3 years in the US group (p=0.49). The NS group included 66.7% males compared to 55.8% in the US group (p=0.31). ASA physical status classification and type of surgical procedure were similarly distributed between groups.

Table 1: Baseline Patient Characteristics

Characteristic	NS Group (n=42)	US Group (n=43)	p-value
Age (years), mean ± SD	45.7 ± 20.9	48.9 ± 22.3	0.49
Male sex, n (%)	28 (66.7)	24 (55.8)	0.31
Body mass index (kg/m²), mean ± SD	27.3 ± 4.2	26.8 ± 3.9	0.58
ASA classification, n (%)			0.76
- ASA I	18 (42.9)	20 (46.5)	
- ASA II	20 (47.6)	19 (44.2)	
- ASA III	4 (9.5)	4 (9.3)	
Type of surgery, n (%)			0.82
- Total knee arthroplasty	24 (57.1)	26 (60.5)	
- Ligament reconstruction	13 (31.0)	12 (27.9)	
- Arthrolysis	5 (11.9)	5 (11.6)	

Primary Outcome: Analgesic Efficacy

Pain Scores at Rest

Visual Analog Scale scores at rest demonstrated no significant differences between groups from H0 to H36 postoperatively (Figure 1). Both groups achieved excellent pain control during this early postoperative period, with median VAS scores consistently below 3.0. However, at 48 hours postoperatively, the US group demonstrated significantly lower pain scores at rest compared to the NS group (1.95±1.1 vs 2.48±1.2; mean difference -0.53, 95% CI -0.89 to -0.17; p=0.004).

Pain Scores During Mobilization

At 48 hours postoperatively, pain assessment during active knee mobilization (flexion to 45°) revealed significantly lower VAS scores in the US group compared to the NS group (3.37±1.0 vs 4.02±1.1; mean difference -0.65, 95% CI -1.13 to -0.17; p=0.008). This represents a clinically meaningful reduction in dynamic pain intensity.

Temporal Analysis

Mean VAS scores averaged across all time points on postoperative day 1 (H0-H24) were comparable between groups (NS: 2.1±0.8 vs US: 1.9±0.7; p=0.23). Similarly, mean scores on postoperative day 2 (H24-H48) showed no significant difference when analyzed globally (NS: 2.3±0.9 vs US: 2.0±0.8; p=0.12), though the H48 time point specifically favored the US group as noted above.

The proportion of patients experiencing maximum VAS scores >4 at any time point during the 48-hour observation period was low and comparable between groups (NS: 19.0% vs US: 14.0%; p=0.52).

Secondary Outcomes

Technical Parameters

Procedure duration was significantly shorter in the US group compared to the NS group (4.9±1.0 vs 5.5±1.1 minutes; mean difference -0.6 minutes, 95% CI -1.0 to -0.2; p=0.01), representing an approximately 11% reduction in procedure time (Table 2).

Block onset time, defined as time to achieve complete sensory and motor block, did not differ significantly between groups (US: 13.0±2.3 vs NS: 13.6±1.8 minutes; p=0.19).

The number of needle punctures and redirections were not systematically recorded but proceduralists reported successful catheter placement on the first attempt in 38/42 (90.5%) of NS procedures and 41/43 (95.3%) of US procedures (p=0.42).

Table 2. Technical Parameters and Analgesic Consumption

Parameter	NS Group (n=42)	US Group (n=43)	p-value
Procedure duration (min), mean ± SD	5.5 ± 1.1	4.9 ± 1.0	0.01
Block onset time (min), mean ± SD	13.6 ± 1.8	13.0 ± 2.3	0.19
Total LA consumption (mL), mean ± SD	200.0 ± 41.3	197.0 ± 46.7	0.75
Time to first analgesic request (h), mean ± SD	5.1 ± 5.9	3.5 ± 3.7	0.13
Number of catheter boluses, mean ± SD	3.8 ± 2.1	3.2 ± 1.9	0.17
Rescue opioid doses, mean ± SD	1.2 ± 1.4	0.9 ± 1.1	0.26

Analgesic Consumption

Total local anesthetic consumption over the 48-hour infusion period was comparable between groups (NS: 200.0±41.3 mL vs US: 197.0±46.7 mL; p=0.75). Time to first analgesic request after catheter activation showed no significant difference (NS: 5.1±5.9 hours vs US: 3.5±3.7 hours; p=0.13), nor did the number of self-administered catheter boluses (NS: 3.8±2.1 vs US: 3.2±1.9; p=0.17) or rescue opioid doses (NS: 1.2±1.4 vs US: 0.9±1.1; p=0.26).

Functional Recovery

Knee flexion range of motion at postoperative day 2 was comparable between groups (NS: 58.3±12.4° vs US: 61.2±13.1°; p=0.31). Similarly, at postoperative day 5, knee flexion showed no significant difference (NS: 78.5±14.2° vs US: 81.3±15.8°; p=0.40). Time to first ambulation was similar (NS: 18.2±6.3 hours vs US: 17.1±5.8 hours; p=0.42).

Hospital length of stay was significantly shorter in the NS group compared to the US group (7.8±4.0 vs 9.8±4.9 days; mean difference -2.0 days, 95% CI -3.8 to -0.2; p=0.04). This finding appears contradictory to the superior analgesic outcomes observed in the US group and is likely attributable to organizational and logistical factors rather than the catheter placement technique itself.

Safety and Complications

No major complications were observed in either group. Specifically, there were no cases of local anesthetic systemic toxicity, permanent nerve injury, deep infection, or epidural/spinal spread.

Minor complications and technical issues are summarized in Table 3. Accidental catheter dislodgement occurred with similar frequency in both groups (NS: 4/42, 9.5% vs US: 4/43, 9.3%; p=0.97). Transient paresthesias during catheter placement were reported by 3 patients (7.1%) in the NS group compared to none in the US group (p=0.11). Inadvertent vascular puncture occurred in 2 patients (4.8%) in the NS group and none in the US group (p=0.24), though this difference did not reach statistical significance.

Table 3: Complications and Safety Outcomes

Complication	NS Group (n=42)	US Group (n=43)	p-value
Major complications	0 (0%)	0 (0%)	-
Catheter dislodgement	4 (9.5%)	4 (9.3%)	0.97
Paresthesias	3 (7.1%)	0 (0%)	0.11
Vascular puncture	2 (4.8%)	0 (0%)	0.24
Hematoma	1 (2.4%)	0 (0%)	0.49
Local infection	0 (0%)	0 (0%)	-

Patient Satisfaction

Overall patient satisfaction with pain management was high in both groups. In the NS group, 71.2% of patients reported being satisfied or very satisfied, compared to 76.7% in the US group (p=0.77). Distribution across all satisfaction categories showed no significant differences between groups (Table 4).

Table 4: Patient Satisfaction with Pain Management

Satisfaction Level	NS Group (n=42)	US Group (n=43)	p-value
Very dissatisfied	2 (4.8%)	1 (2.3%)	0.77
Dissatisfied	4 (9.5%)	3 (7.0%)	
Neutral	6 (14.3%)	6 (14.0%)	
Satisfied	18 (42.9%)	20 (46.5%)	
Very satisfied	12 (28.6%)	13 (30.2%)	

DISCUSSION

This randomized controlled trial demonstrates that ultrasound guidance for femoral perineural catheter placement provides modestly superior analgesic efficacy at 48 hours postoperatively with reduced procedure duration compared to traditional nerve stimulation guidance. Both techniques proved safe and effective, with high patient satisfaction and comparable overall analgesic performance during the first 48 hours after major knee surgery.

Principal Findings

The primary finding of significantly lower pain scores at rest and during mobilization at 48 hours in the ultrasound-guided group represents a clinically relevant observation, though the magnitude of benefit was modest (approximately 0.5-0.65 points on the VAS scale). This late-emerging advantage, absent during the first 36 hours, suggests that ultrasound guidance may facilitate more precise and stable catheter positioning, maintaining analgesic efficacy as the continuous infusion progresses [32,33]. The absence of early differences indicates that both techniques achieve adequate initial nerve blockade, but the sustained superiority of ultrasound guidance at 48 hours may reflect reduced catheter migration or more optimal positioning relative to the target nerve [34].

The 0.6-minute reduction in procedure duration with ultrasound guidance, while statistically significant, translates to approximately 11% time savings. This finding aligns with previous studies reporting 20-30% reductions in procedure time with ultrasound-guided techniques [35,36]. The clinical significance of this time saving should be considered in the context of operating room efficiency, particularly in high-volume centers where cumulative time savings across multiple procedures may be substantial [37].

Comparison with Existing Literature

Our findings are consistent with several studies demonstrating advantages of ultrasound guidance for peripheral nerve catheter placement [38,39], though the magnitude of clinical benefit observed in our study was more modest than some previous reports [40,41]. A meta-analysis by Abrahams *et al.,* (2009) found that ultrasound guidance improved block success rates and reduced procedure time for single-injection peripheral nerve blocks, with more variable results for continuous catheter techniques [42]. Similarly, Mariano *et al.,* (2009) reported improved catheter positioning with ultrasound guidance but noted that clinical outcomes were not consistently superior [43].

The absence of significant differences in local anesthetic consumption, time to first analgesic request, and rescue medication requirements between our groups contrasts with some studies suggesting that ultrasound guidance reduces local anesthetic requirements [44,45]. This discrepancy may reflect our use of a standardized infusion protocol that did not allow for dose adjustment based on catheter positioning, potentially masking differences in block efficiency [46].

Our observation of comparable complications between techniques, with numerically lower rates of paresthesias and vascular puncture in the ultrasound group, supports the safety profile of both approaches [47,48]. The overall low complication rate in both groups reflects contemporary improvements in regional anesthesia techniques and standardized safety protocols [49,50].

Unexpected Finding: Hospital Length of Stay

The significantly shorter hospital length of stay in the nerve stimulation group (7.8 vs 9.8 days) appears paradoxical given the superior analgesic outcomes at 48 hours in the ultrasound group. This finding likely reflects organizational and logistical factors unrelated to catheter placement technique, including bed availability, social circumstances, discharge planning efficiency, and physiotherapy scheduling. The extended postoperative stay in both groups compared to contemporary enhanced recovery protocols (typically 3-5 days for TKA) [51,52] suggests opportunities for improvement in our institutional discharge pathways. This discrepancy highlights the multifactorial nature of hospital length of stay and the importance of comprehensive enhanced recovery protocols beyond optimal pain management alone [53,54].

Mechanisms Underlying Ultrasound Advantages

The late-emerging superiority of ultrasound guidance at 48 hours may be explained by several mechanisms. First, direct visualization enables more precise catheter tip positioning relative to the femoral nerve, potentially maintaining optimal alignment despite catheter migration during patient movement and physiotherapy [55,56]. Second, ultrasound allows confirmation of catheter position through injection of test solution with real-time visualization of spread pattern, enabling repositioning if suboptimal [57,58]. Third, the ability to visualize anatomical variations and adjust needle trajectory accordingly may result in more consistent catheter placement across patients with diverse body habitus [59,60].

The comparable local anesthetic consumption and rescue medication requirements between groups, despite the improved pain scores in the ultrasound group at 48 hours, suggest that the difference lies primarily in catheter positioning rather than pharmacological factors. This interpretation is supported by studies demonstrating that catheter tip location relative to the target nerve is a critical determinant of continuous peripheral nerve block efficacy [61,62].

Clinical Implications and Cost-Effectiveness Considerations

The modest clinical benefit observed with ultrasound guidance must be balanced against practical considerations including equipment costs, training requirements, and workflow integration [63,64]. Ultrasound machines represent significant capital investment, and proficiency in ultrasound-guided regional anesthesia requires dedicated training and practice [65,66]. In resource-limited settings, where nerve stimulation equipment may already be available and staff familiar with the technique, the incremental

benefit of ultrasound guidance at 48 hours may not justify immediate transition.

However, in high-volume centers and within established ERAS pathways where early mobilization and rapid recovery are prioritized, the combination of reduced procedure time and improved late analgesia may translate to meaningful clinical and economic benefits[67,68]. Furthermore, the trend toward lower complication rates with ultrasound guidance, though not statistically significant in our study, may become more apparent in larger cohorts and represents an important safety consideration[69,70].

Integration with Enhanced Recovery Protocols

Our findings support the integration of femoral perineural catheters, placed with either technique, into multimodal analgesic strategies for major knee surgery. The excellent pain control achieved in both groups during the first 36 hours facilitated early physiotherapy and mobilization, core components of ERAS pathways[71,72]. The superior pain control at 48 hours with ultrasound guidance may be particularly relevant in contemporary fast-track protocols where patients are expected to achieve specific functional milestones before discharge[73,74].

The high patient satisfaction rates in both groups reflect the overall effectiveness of regional analgesia techniques and underscore the importance of continuous catheter techniques for optimizing patient experience[75,76]. This finding is particularly relevant in the context of patient-centered care and value-based healthcare models[77,78].

Future Directions

Future research should investigate several important questions arising from our findings. First, studies with extended follow-up beyond 48 hours would clarify whether the observed advantages of ultrasound guidance persist throughout the critical early rehabilitation period[79,80]. Second, comparative effectiveness research examining the impact of catheter placement technique on functional outcomes, chronic pain development, and long-term patient-reported outcomes would provide valuable data for clinical decision-making[81,82].

Third, cost-effectiveness analyses incorporating equipment costs, training expenses, procedure time savings, and clinical outcomes are needed to guide resource allocation decisions [83,84]. Fourth, investigation of hybrid techniques combining ultrasound visualization with nerve stimulation confirmation may optimize the benefits of both approaches [85,86]. Finally, research on educational strategies and learning curves for ultrasound-guided techniques would inform training program development [87,88].

Study Limitations

This study has several limitations that warrant consideration. First, the single-center design limits generalizability to different institutional settings, patient populations, and healthcare systems. Multicenter trials would enhance external validity and allow examination of technique-specific effects across diverse practice environments[89,90].

Second, blinding of proceduralists was not feasible given the nature of the interventions, introducing potential performance bias. However, the use of objective outcome measures (VAS scores, procedure duration) and blinding of outcome assessors where possible minimizes this limitation [91,92].

Third, our sample size, while adequate for detecting differences in the primary outcome, may have been insufficient to detect differences in secondary outcomes and rare complications. The low event rate for complications prevented meaningful statistical comparison of safety endpoints[93,94].

Fourth, the standardized local anesthetic infusion protocol, while ensuring protocol consistency, may have masked potential differences in block efficiency between techniques. Titrated dosing regimens based on pain scores might reveal greater differences in analgesic requirements[95,96].

Fifth, we did not systematically assess catheter tip position using ultrasound imaging after placement, which would have provided objective confirmation of positioning accuracy and catheter migration over time [97,98]. Future studies incorporating systematic catheter position verification would enhance understanding of mechanism underlying clinical differences.

Sixth, the unexpected finding of shorter hospital stay in the nerve stimulation group highlights the complexity of this outcome measure, which is influenced by numerous non-clinical factors. More granular assessment of discharge readiness criteria would provide clearer insights into the relationship between catheter technique and recovery trajectory[99,100].

Finally, we did not assess long-term outcomes such as chronic pain development, functional recovery beyond hospital discharge, or patient quality of life measures. These outcomes are increasingly recognized as important endpoints in evaluating perioperative analgesic strategies[101,102].

CONCLUSION

This randomized controlled trial demonstrates that ultrasound guidance for femoral perineural catheter placement offers modest but statistically significant advantages over nerve stimulation guidance, specifically in reducing procedure time and improving analgesic

efficacy at 48 hours postoperatively. Both techniques demonstrated excellent safety profiles with no major complications and comparable high patient satisfaction rates.

The clinical significance of these findings must be interpreted in context. The half-point reduction in VAS scores at 48 hours, while statistically significant, represents a modest clinical benefit that may be most relevant in the context of enhanced recovery protocols emphasizing early functional recovery. The 11% reduction in procedure time, though small in absolute terms, may accumulate to meaningful efficiency gains in high-volume practices.

For institutions and practitioners already equipped with ultrasound and trained in ultrasound-guided techniques, our findings support the use of ultrasound guidance for femoral perineural catheter placement. However, for settings where nerve stimulation is the established practice and resources for ultrasound equipment and training are limited, our results suggest that nerve stimulation remains a safe and effective alternative.

The choice between techniques should consider multiple factors including institutional resources, practitioner expertise, equipment availability, training infrastructure, and patient-specific considerations. In resource-rich settings with established ultrasound programs, the combination of improved late analgesia, reduced procedure time, and trend toward fewer vascular complications favors ultrasound guidance. In resource-limited settings, the excellent safety and efficacy of nerve stimulation guidance supports its continued use.

Future research should focus on long-term functional outcomes, cost-effectiveness analyses, and strategies for optimizing training in ultrasound-guided regional anesthesia. As the field continues to evolve, integration of both techniques within comprehensive multimodal analgesic protocols will remain essential for optimizing pain management and recovery after major knee surgery.

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