

Article

Postoperative Multimodal Approach to Pain Control in Anterior Cruciate Ligament Autograft Surgery: A Single-Center Series

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Abstract: Background: Anterior cruciate ligament (ACL) injuries are prevalent and represent a significant socioeconomic burden, as ACL injuries account for nearly 60% of all knees joint traumas. The purpose of this study is to emphasize the role of arthroscopic ACL reconstruction and the challenges in postoperative pain management. Methods: This study involved 90 patients undergoing ACL reconstruction, categorized into three groups receiving different pain management protocols. The focus was on evaluating the efficacy of multimodal analgesia using lidocaine and magnesium sulfate. The main outcome was pain assessment using the Visual Analog Scale (VAS). Results: Patients receiving fentanyl, lidocaine, and magnesium sulfate (FLM) reported significantly lower pain scores in the postoperative period. Minimal use of additional opioids was observed, suggesting effective pain management with the multimodal analgesia regimen. Conclusions: The study showed that multimodal analgesia, including FLM, effectively manages postoperative pain following ACL reconstruction. This study showed significantly lower pain scores with FLM, highlighting its potential in early postoperative pain relief. Future research should consider long-term outcomes and cost-effectiveness, emphasizing the need for more comprehensive evaluations of multimodal analgesia's impact.

Keywords: pain control; surgery; anterior cruciate ligament; autograft surgery; multimodal approach



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1. Introduction

The knee joint, the largest in the human body, has limited resistance. Studies indicate that up to 70% of people will experience knee joint pain and impairment during their lifetime [1]. Among these concerns, injuries to the anterior cruciate ligament (ACL) are common reasons for seeking medical attention. This prominence is largely due to the vital role played by the knee joint, enduring significant stress as one of the body's most heavily used articulations [2].

The ACL, a key stabilizing structure within the knee joint, plays a critical role in preserving joint integrity [2,3]. Alarming, ACL injuries account for 60% of all knee joint traumas [4]. These injuries predominantly affect individuals in their prime, often of working age, and are more prevalent among males, making ACL injuries a significant medical and socioeconomic concern [1].

Arthroscopic ACL reconstruction is common in traumatology and sports medicine. Notably, approximately 80% of patients who undergo ACL reconstruction return to their pre-injury levels of physical activity, including sports [5]. However, relevant data suggest that inadequate postoperative rehabilitation can predispose individuals to recurrent ACL injuries [6,7]. This underscores the critical importance of early postoperative rehabilitation, ensuring a comfortable recovery period devoid of common complications such as severe

pain (defined as over 5 points on the Visual Analog Scale (VAS)), postoperative nausea and vomiting (PONV), and shivering [8].

The use of opioid analgesics during the postoperative period significantly increases the risk of chronic pain, delays and complicates rehabilitation, prolongs hospital stays, and escalates healthcare costs [9]. In the intraoperative context, opioids impede the awakening process after surgery, leading to drowsiness, respiratory depression, and a higher likelihood of PONV and shivering [10]. To mitigate these adverse effects and enhance postoperative care, the concept of multimodal analgesia has been introduced. This approach involves the intraoperative use of adjuvants such as lidocaine and magnesium sulfate, as outlined in our study.

Our hypothesis is that the combination of magnesium sulfate and lidocaine infusion may exert a more pronounced influence on postoperative pain control, deliver anti-inflammatory benefits, and enhance antihyperalgesic effects compared to conventional approaches. This hypothesis is grounded in prior research highlighting the potential of these compounds to ameliorate postoperative pain, reduce opioid consumption, and facilitate smoother recoveries in orthopedic surgery and other fields [10–12]. Magnesium sulfate, commonly known as Epsom salt, is a naturally occurring mineral with diverse applications in medicine, agriculture, and industry [13]. In medical practice, magnesium sulfate has garnered considerable attention for its multifaceted properties and potential therapeutic benefits. It is an inorganic salt composed of magnesium, sulfur, and oxygen, existing in various forms, including as heptahydrate crystals ($\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$) [14].

In our pursuit of improved patient outcomes, it is crucial to explore innovative postoperative care methods that not only alleviate pain but also reduce the reliance on opioid analgesics. The early postoperative period is pivotal in a patient's recovery journey, and ensuring comfort, effective pain management, and a swift return to normal life presents a multifaceted challenge. This challenge propels us to delve into the potential of alternative interventions. In pain management and anesthesia, magnesium sulfate has gained attention as a potential adjunct to conventional approaches. Some studies suggest that magnesium sulfate exhibits neuroprotective properties and may help reduce perioperative pain, decrease opioid requirements, and enhance postoperative recovery [13]. The exact mechanisms behind these effects are not fully understood, but they are believed to involve the modulation of N-methyl-D-aspartate (NMDA) receptors and calcium channel blockade. These properties make magnesium sulfate an intriguing candidate for inclusion in multimodal analgesia regimens, where a combination of drugs targets pain through different mechanisms [15]. Furthermore, magnesium sulfate is recognized for its potential to mitigate PONV, a common complication following anesthesia and surgery. PONV can be distressing for patients and even lead to prolonged hospital stays in some cases. The administration of magnesium sulfate may help reduce the incidence of PONV and improve the overall comfort of patients during the recovery phase [16]. This mineral's versatility extends beyond pain management. Magnesium sulfate has found applications in obstetrics for preventing seizures in women with pre-eclampsia and eclampsia, as well as in the treatment of preterm labor to protect the health of premature babies [17].

Despite these promising characteristics, it is important to underscore that the administration of magnesium sulfate in a clinical setting is not without considerations and potential side effects. The precise dosages, timing, and administration routes must be carefully evaluated, and patient-specific factors should be considered.

Our study investigates the impact of intravenous infusions of lidocaine and magnesium sulfate on pain management during the early postoperative period following autologous hamstring tendon graft ACL reconstruction (ACL-ACL) surgery. The purpose of this study is to understand its potential in the multimodal analgesic approach and its influence on postoperative recovery, with the overarching goal of improving patient experiences and outcomes. Beyond pain management, we explore the multifaceted implications of these interventions on the postoperative journey. Our study extends to factors such

as PONV, shivering, and the potential for recurrent ACL injuries. These elements are interconnected and integral to a patient's overall experience and prognosis [18].

2. Materials and Methods

2.1. Study Population and Ethics Committee

Ninety male and female patients, aged 16 to 50 with ASA I-II physical status, scheduled for isolated arthroscopic ACL reconstruction, were selected. The peroneus longus tendon was chosen as the autograft source, diverging from traditional choices like hamstring or patellar tendons. This decision was driven by emerging research and clinical experiences suggesting the peroneus longus tendon offers comparable tensile strength, reduced donor site morbidity, and a lower incidence of postoperative pain and complications. Furthermore, the anatomical characteristics and size of the peroneus longus tendon provide sufficient graft length and diameter, making it a suitable alternative for effective ACL reconstruction. This study was conducted from August 2022 to July 2023, with each patient providing informed consent. The study adhered to the Helsinki Declaration of 2013 and relevant national laws and regulations.

2.2. Detailed Methodology, Randomization, and Allocation

In the preoperative room, all patients received training on reporting pain intensity using the VAS, where 0 represents no pain and 10 the worst imaginable pain. Training included practical exercises on placing a peripheral venous catheter.

Patients were randomly allocated to three groups using a parallel design and a computer-generated randomization method. Randomly generated numbers were placed in sealed, opaque envelopes, which were opened on the day of surgery.

2.3. Method Overview

A total of 90 patients were randomly assigned to three groups (30 per group) for this study, all undergoing isolated arthroscopic ACL reconstruction. Each group received a distinct combination of anesthetic and analgesic protocols, with consistent anesthesia induction and postoperative pain management strategies. Anesthesia and analgesia protocols (as shows in Table 1 in details) were as follows:

- Group 1 (Fentanyl Only): Received a pre-anesthetic bolus of 10 mL 0.9% NaCl, followed by placebo infusions mimicking the timing of active drug administrations in the other groups. Intravenous fentanyl boluses of 100 µg were administered as needed for hemodynamic stability.
- Group 2 (Fentanyl + Lidocaine): Began with an intravenous lidocaine bolus of up to 1.5 mg/kg (max 150 mg), then a continuous infusion at 2 mg/kg/h (max 200 mg/h), alongside placebo infusions mimicking the magnesium sulfate rate in Group 3.
- Group 3 (Fentanyl + Lidocaine + Magnesium Sulfate): Received identical lidocaine dosing as Group FL and a continuous magnesium sulfate infusion at 70 mg/kg/h. Both medications were administered intravenously using separate syringe pumps.

Table 1. All three anesthesia and analgesia protocols.

Group	Medication	Initial Dose	Maintenance Dose	Route of Administration
Group 1	Fentanyl	N/A	100 µg boluses as needed	Intravenous
Group 2	Fentanyl + Lidocaine	N/A Up to 1.5 mg/kg (max 150 mg)	100 µg boluses as needed 2 mg/kg/h (max 200 mg/h)	Intravenous
Group 3	Fentanyl + Lidocaine + Magnesium Sulfate	N/A Up to 1.5 mg/kg (max 150 mg) N/A	100 µg boluses as needed 2 mg/kg/h (max 200 mg/h) 70 mg/kg/h	Intravenous

2.3.1. Common Anesthesia Technique across Groups

Anesthesia was induced with intravenous propofol (2 mg/kg) and fentanyl (200 µg), followed by muscle relaxation with rocuronium bromide (0.6 mg/kg). Airway management utilized an i-gel laryngeal mask, and anesthesia maintenance involved inhaled sevoflurane (target Minimum Alveolar Concentration 0.6). Monitoring included Electrocardiogram (ECG), non-invasive Blood Pressure, pulse oximetry, capnography, and neuromuscular blockade, with depth of anesthesia assessed using Train-of-Four (TOF) and Bispectral Index (BIS) monitoring.

2.3.2. Surgical and Postoperative Care

The ACL reconstruction utilized an autograft from the long head of the gastrocnemius muscle, fixed in both femoral and tibial tunnels with appropriate hardware. Partial meniscectomy was performed as needed. Postoperative pain was managed with intramuscular nonsteroidal anti-inflammatory drugs (NSAIDs) (ketoprofen 100 mg twice daily) for 2–3 days, supplemented with opioids for VAS scores over 5. Baseline and during-surgery anesthesia protocols included boluses and infusions tailored to each group's regimen, with adjustments for muscle relaxation and hemodynamic stability, as necessary. Neostigmine and atropine were used for neuromuscular blockade reversal and extubation was conducted when patients were conscious.

2.4. Data Analysis Overview

Our data analysis rigorously evaluated the effectiveness of different analgesic protocols on postoperative pain management. Descriptive statistics, including means, standard deviations, frequencies, and percentages, summarized patient demographics and clinical characteristics. Such an approach provided a clear overview of the patient population and allowed the identification of any underlying patterns or anomalies in the data. Table 2 shows all the details.

Table 2. Overall study population.

Category	Description	Median/Means $\pm$ SD
Total Patients	Number of participants	90
Gender Distribution	Percentage male/female	Male: 70%; female: 30%
Age Range	Age range and median age	16–59 years (mean 35 years $\pm$ 10 years)
Groups	Number of participants for groups	Group 1 (N = 30); Group 2 (N = 30); Group 3 (N = 30)
Catheter Sizes	Range and median size	Range: 1–7; 4 $\pm$ 1.5
Average VAS Score	Post-surgery score	Median 3.5 $\pm$ 1.2
Fentanyl Dosage (mg)	Median dosage used	0.55 mg $\pm$ 0.15 mg
Operation Time (min)	Median operation time	25–90 min (median 60 min $\pm$ 20 min)
Periods of Measurement	Specified measurement times	30 min after surgery, morning, evening (N/A)
High VAS Instances	Percentage of high VAS scores	15%
% of Absences	Percentage of absences	2.22%
Non-Numerical Data	Presence of non-numerical data	100% at the beginning
Unique Meanings	Variability across categories	Varied across categories
Scale Type	Type of data scale used	Nominal and number

2.5. Descriptive Statistics

Mean and Standard Deviation (SD): Used to describe the central tendency and dispersion for normally distributed continuous variables such as age, VAS scores, and operation times.

Median: Used for non-normally distributed variables to provide a measure of central tendency.

Standard Error of the Mean (SEM): Calculated to provide an estimate of the accuracy of the mean.

The significance threshold was set at $p < 0.05$ for all statistical tests. This threshold indicates that the probability of observing the results by chance is less than 5%, thus providing evidence against the null hypothesis.

2.6. Comparative Analysis

Comparative analyses employed independent *t*-tests for normally distributed variables like age and VAS scores, and the Mann–Whitney U test for non-normally distributed data. Chi-square tests and Fisher’s exact tests were used for categorical variables, while a repeated measures ANOVA was used to assess pain scores over time. Multivariate regression models controlled for confounders, with a significance threshold set at $p < 0.05$.

Additionally, adjustments for multiple comparisons were made where necessary to control the Type I error rate, ensuring the robustness of our findings. All statistical analyses were conducted using Excel and SPSS software version 25.0, leveraging their advanced features for accurate and efficient data processing.

The Kruskal–Wallis test was employed for comparing median values across multiple groups. In our study, the test was used for analyzing data that are not normally distributed and where the assumption of homogeneity of variances across groups. This includes variables such as the duration of surgery, VAS, and clinical recovery outcome time (CROT).

The Chi-square test was utilized to examine the relationship between categorical variables, such as gender distribution and assessing whether the distribution of these variables differs significantly across the three study groups (Fentanyl Group, Fentanyl + Lidocaine Group, and Fentanyl + Lidocaine and Magnesium Sulfate Group). This will help in determining if any observed effects in postoperative outcomes are associated with these categorical variables. The Friedman test reported the repeated measures design of our study, where pain scores (VAS) were assessed at multiple time points (30 min, 6 h, and 18 h post-surgery), the Friedman test was applied. It will allow us to detect changes in VAS scores over time within each group and compare these changes across the groups.

2.7. Assessment of Postoperative Pain Control

The VAS was employed at predetermined time points (30 min, 6 h, and 18 h post-surgery) to measure pain intensity. This scale, where 0 represents “no pain” and 10 signifies “the worst imaginable pain”, allowed patients to self-report their pain levels, facilitating an objective evaluation of postoperative pain management strategies. The 30 min checkpoint was particularly crucial as it aligned with the pharmacokinetics of lidocaine and magnesium sulfate. The Aldrete Scale served as a supplementary measure. Subsequent checkpoints at 6 and 18 h provided insights into the longevity of pain relief. To avoid biased self-reporting, patients were instructed to base their pain ratings on both observation and VAS scales. The average awakening times were comparable across all groups: 3 min 58 s $\pm$ 1 min 51 s for Group 1, 4 min 08 s $\pm$ 1 min 48 s for Group 2, and 3 min 59 s $\pm$ 1 min 54 s for Group 3 from wound closure (Figure 1).

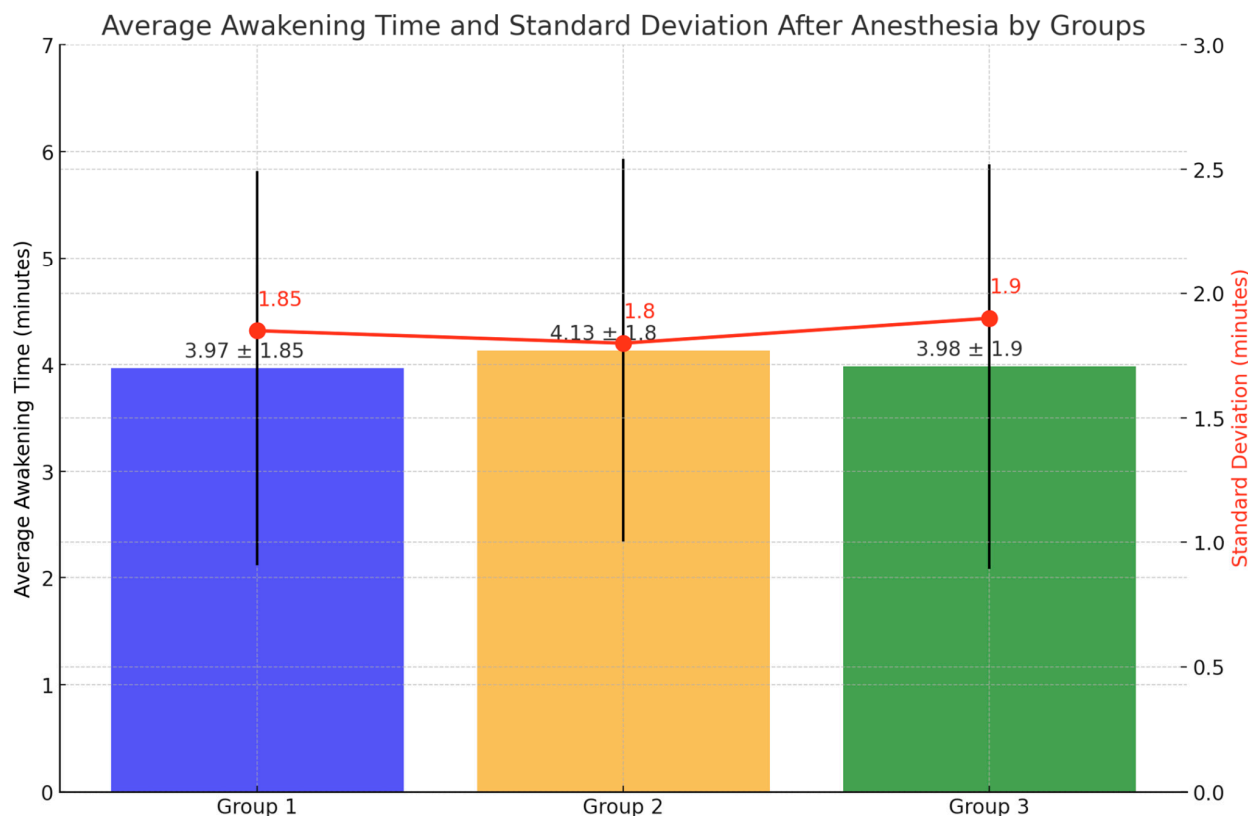


Figure 1. Average awakening time and standard deviation after anesthesia by groups. Group 1 received fentanyl only, Group 2 received fentanyl and lidocaine, and Group 3 received fentanyl, lidocaine, and magnesium sulfate. The bar chart shows the average awakening times with error bars representing the standard deviation (SD). Group 1: 3.97 ± 1.85 min, Group 2: 4.13 ± 1.8 min, Group 3: 3.98 ± 1.9 min. The line plot with red markers shows the standard deviation for each group, providing a clear view of the variability in awakening times.

3. Results

The groups were comparable in age, gender distribution, surgical duration, and intraoperative opioid use. This suggests that the patient groups were well-matched in terms of baseline characteristics, enhancing the validity of the study's findings (Figure 2).

The average VAS scores post-ACL surgery showed statistically significant differences among groups. In the FLM group (fentanyl, lidocaine, magnesium sulfate), lower VAS scores were observed 30 min after awakening. Table 3 details the mean VAS scores at each control point.

Table 3. Mean values of the VAS score at control points.

Group	Indicator	M ± S, Control Point One	M ± S (%), Control Point Two	M ± S (%), Control Point Three	Value p
1 Group (Fentanyl)	VAS	4.03 ± 1.52	2.70 ± 1.29 (−33.06%)	1.97 ± 1.10 (−51.24%)	<0.0001
2 Group (Fentanyl + Lidocaine)	VAS	3.73 ± 1.55	2.83 ± 1.18 (−24.11%)	1.87 ± 1.01 (−50.00%)	<0.0001
3 Group (Fentanyl + Lidocaine + Magnesium Sulfate)	VAS	2.97 ± 1.90	2.50 ± 1.11 (−15.73%)	1.77 ± 1.07 (−40.45%)	0.0007

VAS scores at three control points (30 min, 6 h, and 18 h post-surgery) across the three groups. Error bars represent the SD. Significant differences in VAS scores between groups at each control point are shown ($p < 0.05$).

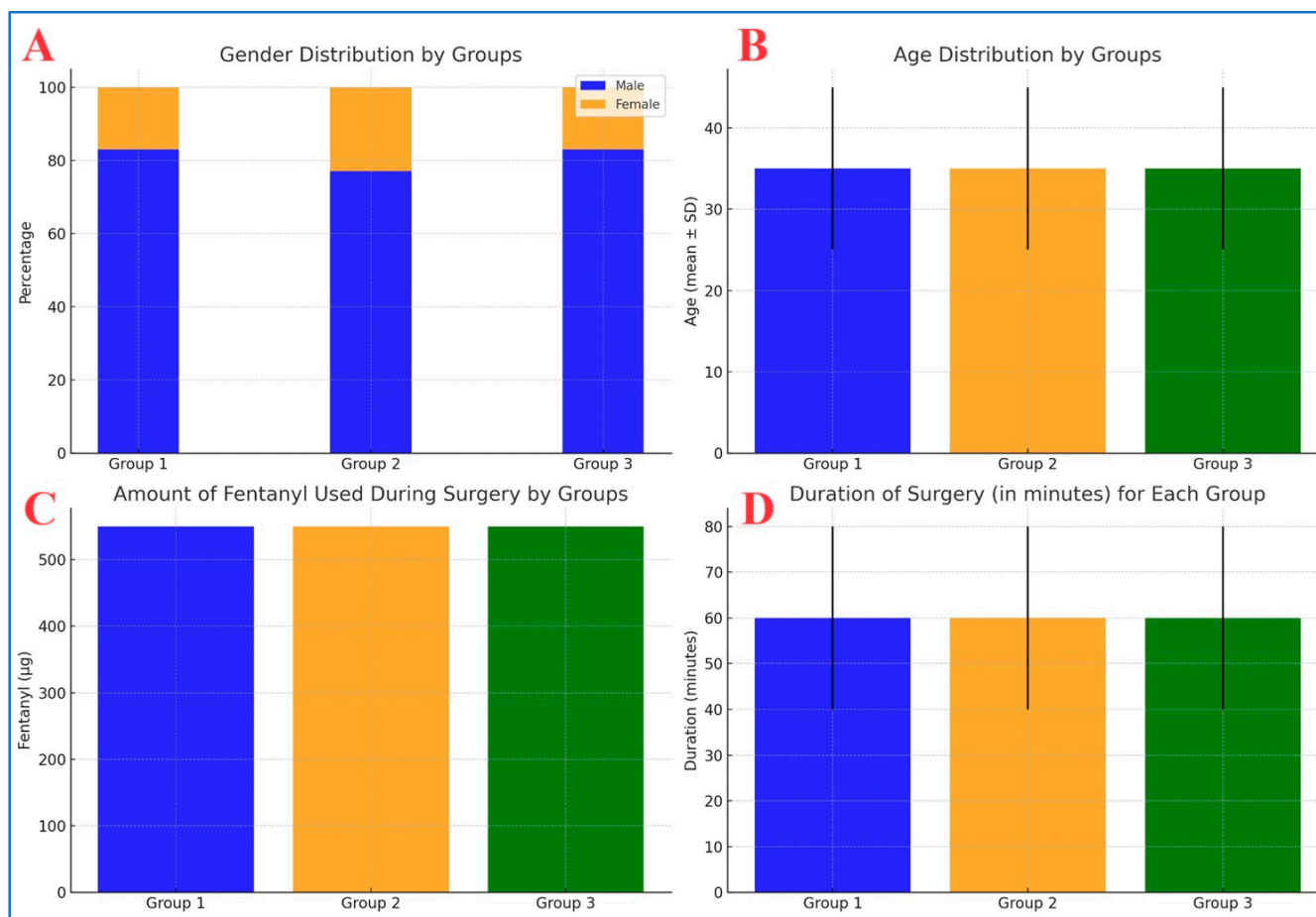


Figure 2. (A) Gender Distribution by Groups. Group 1 had 83% males and 17% females, Group 2 had 77% males and 23% females, and Group 3 had 83% males and 17% females. (B) Age Distribution by Groups. The average age was 35 years with a standard deviation of 10 years across all groups. (C) Amount of Fentanyl Used During Surgery by Groups. Each group used an average of 550 µg of fentanyl. (D) Duration of Surgery (in minutes) for Each Group. The average surgical duration was 60 min with a standard deviation of 20 min for all groups.

Assessments of nighttime activity and the Critical-Care Pain Observation Tool (CPOT) scale did not yield statistically significant results. Additional analgesia, in the form of opioid analgesics, was used only in Group 1 in 6.6% of cases.

The patient demographics, surgical duration, and intraoperative fentanyl use were consistent across the three groups. This uniformity in baseline characteristics suggests that any observed differences in outcomes can more confidently be attributed to the interventions themselves rather than confounding variables. Gender distribution across the groups was well balanced, with a male predominance in each group (approximately 83% in Groups 1 and 3 and about 77% in the Group 2), and a corresponding minority of female participants (approximately 17% in Groups 1 and 3 and 23% in the Group 2). The mean VAS scores, used to assess pain postoperatively, were statistically significantly different across the groups at the first control point, 30 min after awakening from anesthesia. Group 3, receiving FLM, reported the lowest pain scores (mean VAS 2.9), compared to Group 1 (4.0) and Group 2 (3.7), with a highly significant p -value of 0.0007.

Significant differences in VAS scores among the groups were determined using appropriate statistical tests with p -values < 0.05 indicating statistical significance. For instance, VAS scores showed significant differences between groups at various control points, with p -values of <0.0001 and 0.0007, respectively, indicating highly significant differences in pain levels postoperatively.

VAS scores significantly decreased over time within each group, as shown by further analysis. By the third control point, all groups had experienced over a 40% reduction in pain scores, with Group 1 showing the most considerable decrease of over 50%. Additional evaluations, such as nighttime activity and the CPOT scale, did not reveal any statistically significant differences, with a *p*-value of 0.873, suggesting that these parameters were not significantly affected by the pain management protocols. Additional opioid analgesia was used in only 6.6% of Group 1 cases, upon request.

4. Discussion

Our study shows a significant advantage of using lidocaine and magnesium sulfate as adjuvants in the early postoperative period (first assessment at 30 min). However, pain levels were similar at 6 and 18 h postoperatively, suggesting that these medications might be more effective if administered as continuous infusions in the postoperative period. The hemodynamic stability observed intraoperatively across all groups indicates the safety of these medications at the administered dosages. This suggests that lidocaine and magnesium sulfate can be safely incorporated into clinical practice as part of a multimodal analgesic approach, providing better pain control in the early postoperative phase.

Our findings on postoperative pain management following ACL reconstruction add to the evidence supporting multimodal analgesia [19,20]. The significantly lower pain scores observed at the first control point in the group receiving FLM (fentanyl, lidocaine, magnesium sulfate) align with Safavi et al. [21], who reported enhanced pain control with a combination of analgesics in ACL reconstruction. Advances in ACL reconstruction pain management have validated the importance of tailoring analgesic strategies to individual patient needs. Recent studies exploring the genetic underpinnings of pain perception and response to analgesics suggest a future where pain management can be highly personalized based on genetic profiling, potentially revolutionizing postoperative care [22–24].

Moreover, non-pharmacological interventions such as cryotherapy, physical therapy, and psychological support contribute positively to pain reduction and overall recovery [25]. Integrating these modalities with pharmacological approaches could offer a more holistic and patient-centered strategy for postoperative care.

The predominantly male gender distribution in our study reflects the demographic most commonly associated with ACL injuries [26]. Future research should include a more balanced gender representation to explore potential differences in pain perception and management efficacy. The sustained reduction in VAS scores across all groups corroborates studies by Gupta et al. [27], which emphasized the effectiveness of continuous pain management protocols. Our results showed over a 40% reduction in reported pain levels, supporting the notion that multimodal analgesia can sustain its efficacy over time [28–30].

The minimal use of additional opioids (6.6% in Group 1) is promising, indicating effective pain management and reduced risk of opioid-related side effects and dependency, a concern highlighted by Forlenza et al. [31]. This is particularly pertinent given the current climate of opioid stewardship in postoperative care [32]. However, our findings that nighttime activity and CPOT scores did not differ significantly between groups present an intriguing contradiction to Li et al. [33], who found a correlation between effective pain management and improved patient mobility. This discrepancy may be due to the timing of assessments or the sensitivity of the CPOT scale in a postoperative ACL population, an area warranting further investigation [34].

Our study did not include long-term follow-up data, which could provide insights into the prolonged effects of the analgesia regimen, as proposed by Bolia et al. [35]. Additionally, our sample size, while adequate for initial observations, may not capture the full spectrum of variability in postoperative pain experiences, an issue that can be addressed in larger-scale studies [36,37]. The use of multimodal analgesia also invites an examination of the cost-effectiveness of such approaches [35,36]. While FLM regimens may offer superior pain control, the economic implications of these treatments are not insignificant. Cost-benefit analyses, such as those conducted by Pershad et al. [38], could inform healthcare providers

about the most economically viable pain management strategies without compromising patient care [39–41]. The economic implications of multimodal analgesia also warrant consideration. While the initial costs associated with comprehensive analgesic regimens may be higher, the potential for reduced opioid use, shorter hospital stays, and faster return to normal activities presents a compelling argument for their cost-effectiveness in the long term [42]. Future research should aim to provide a more detailed cost–benefit analysis, taking into account the broader socioeconomic impacts of enhanced recovery protocols. The limitations of our study, such as the short-term follow-up and lack of a more diverse patient population, highlight the need for ongoing research. Extensive follow-up studies with larger and more diverse cohorts are essential to fully understand the long-term outcomes of multimodal analgesia on ACL reconstruction recovery. Another avenue of research that has yet to be thoroughly pursued involves the role of genetics in pain perception and opioid efficacy [42,43]. Recent genomic studies have suggested that genetic variants may influence individual responses to pain and analgesics [24]. This emerging field of pharmacogenomics could pave the way for personalized pain management protocols that are tailored to individual genetic profiles, potentially revolutionizing postoperative care [25,44].

Recent advancements in ACL reconstruction techniques aim to minimize tissue trauma and enhance the biological healing process, which can significantly impact postoperative pain levels. Techniques such as the use of smaller, more precise instruments and the adoption of minimally invasive procedures have been shown to reduce tissue damage and inflammation, leading to lower pain scores and a quicker recovery [45,46]. Additionally, the exploration of novel graft preparation methods that promote faster integration and healing of the graft may also contribute to reduced pain and improved functional outcomes [47].

Rehabilitation plays a pivotal role in managing postoperative pain and facilitating recovery after ACL reconstruction. Early mobilization and the use of targeted physical therapy protocols can not only aid in pain reduction but also prevent stiffness and improve joint function [48]. Recent studies have emphasized the importance of personalized rehabilitation programs, which are tailored to the patient’s specific needs, pain levels, and recovery progress, thereby enhancing the overall effectiveness of postoperative care [49].

The field of pain management has seen significant advancements in both pharmacological and non-pharmacological interventions. The development of longer-acting local anesthetics and the introduction of new analgesic agents offer more options for effective pain control with fewer side effects [50,51]. The decision to employ neostigmine, in combination with atropine, for the reversal of neuromuscular blockade was based on its established efficacy in ensuring complete recovery from muscle relaxation, a critical aspect in the postoperative management of patients undergoing ACL reconstruction. The inclusion of atropine alongside neostigmine serves to counteract the muscarinic effects of neostigmine, such as bradycardia, thereby enhancing the safety profile of the reversal regimen. While it is recognized that neostigmine can potentially contribute to PONV and shivering, these side effects are not universally observed and can be effectively managed with appropriate prophylactic and therapeutic interventions. In our study, the dosing of neostigmine and atropine was carefully titrated based on the extent of neuromuscular blockade and the individual patient’s physiological response, aiming to minimize adverse effects while ensuring effective reversal of muscle relaxation.

The integration of technology into postoperative care has opened new avenues for managing pain and monitoring recovery after ACL reconstruction. Wearable devices, telemedicine and mobile applications can now track patients’ pain levels, activity, and rehabilitation exercises in real-time, providing valuable data for personalized care adjustments [52–55]. Our study provides evidence supporting the enhanced efficacy of a multimodal analgesic regimen that includes a combination of fentanyl, lidocaine, and magnesium sulfate, compared to simpler analgesic protocols. The novelty of our research lies in the comprehensive evaluation of how the addition of each analgesic component contributes to improved postoperative pain management, specifically following ACL re-

construction. While previous studies have individually assessed the analgesic effects of fentanyl, lidocaine, and magnesium sulfate, our research uniquely integrates these agents into a single, cohesive regimen, demonstrating a synergistic effect that significantly reduces pain scores compared to the use of fentanyl alone or fentanyl with lidocaine. The incremental approach to analgesia, starting from a baseline of fentanyl only and sequentially adding lidocaine and magnesium sulfate, allows us to delineate the specific contribution of each drug to the overall pain management strategy. This methodical addition highlights the enhanced analgesic effect achieved with each subsequent inclusion, providing clear evidence of the cumulative benefit of a multimodal approach. The innovative aspect of our study is not just in showing that more drugs mean better pain control but in demonstrating how the strategic combination of these specific analgesics can optimize postoperative pain management, leading to a potentially faster recovery and improved patient outcomes. The reduced reliance on opioid analgesics and the consequent mitigation of their side effects, such as opioid-induced hyperalgesia, nausea, and constipation, further emphasize the clinical relevance of our findings.

Limitations of the Study

Despite providing initial evidence for the efficacy of a multimodal analgesia regimen following ACL reconstruction, this study has several limitations. The sample size, although sufficient for initial analysis, was limited and predominantly male, which may affect the generalizability of the results across a more diverse population. Furthermore, the study's follow-up was restricted to the immediate postoperative period, precluding insights into the long-term effectiveness and sustainability of pain management strategies. Quality of life, a primary concern for patients undergoing such procedures, was not assessed, leaving a gap in understanding the broader impact of pain on patients' day-to-day well-being.

Conducted within a single institution, the study's findings may not reflect variations in clinical practice and patient demographics encountered in other settings, potentially affecting the external validity of the results. Unmeasured confounders, such as individual pain thresholds, comorbidities, or prior medication use, were not accounted for, which could influence outcomes. Additionally, the absence of a cost-effectiveness analysis leaves the economic implications of the analgesic strategies unexplored [56,57]. The genetic factors that contribute to pain perception and medication efficacy were not considered, representing an area of pharmacogenomics that could significantly influence individualized patient care. Non-pharmacological interventions, which may enhance or diminish the need for drugs, were also not evaluated in this study.

The study may have been underpowered for detecting small yet clinically important differences, particularly in secondary outcomes like nocturnal activity, due to multiple comparisons across groups. Reliance on the VAS for pain assessment, though a validated tool, introduces subjectivity to the measurement of pain intensity. No placebo control was included, which is considered the gold standard in clinical efficacy trials. Intraoperative factors, such as specific surgical techniques used and the surgeon's expertise, which could impact postoperative pain, were not controlled for in this analysis.

The short-term postoperative observation period, confined to the initial 24 h after surgery, limits our understanding of the long-term effects of the analgesic regimen. Future research should aim to include longer follow-up periods to assess the persistence of pain relief, patient satisfaction, and any delayed complications or readmissions, providing a more comprehensive evaluation of postoperative analgesia regimens following ACL reconstruction.

Reporting bias may have influenced how patients self-reported their pain levels. Future studies should use blinded assessors or more objective measures of pain to mitigate this bias. Similarly, the assumption of strict adherence to the analgesic protocol does not account for potential deviations in practice, which might affect outcomes. These limitations highlight the need for more comprehensive, multi-center, randomized controlled trials with

larger, more diverse populations, and longer follow-up periods to fully elucidate the effects of multimodal analgesia on post-ACL reconstruction recovery.

5. Conclusions

This study provides valuable insights into the effectiveness of multimodal analgesia, particularly a regimen of fentanyl, lidocaine, and magnesium sulfate (FLM), in managing postoperative pain following ACL reconstruction. Patients receiving FLM experienced significantly lower pain scores shortly after surgery compared to those who did not. The study's predominantly male demographic reflects the higher incidence of ACL injuries in males. Further research should include a more balanced gender distribution to enhance the generalizability of the results. The sustained reduction in VAS scores across all groups highlights the potential of multimodal analgesia for prolonged pain control. This is particularly important given the current focus on reducing opioid use and its associated risks, as evidenced by the low incidence of additional opioid requirements in our study.

The lack of significant differences in nighttime activity and CPOT scores, combined with the study's short-term follow-up, suggests that FLM's benefits may be limited to direct pain relief rather than broader recovery outcomes. The short-term nature of the study limits our understanding of the long-term implications of FLM use.

Future research should include long-term follow-up assessments, quality of life metrics, and cost-effectiveness analyses to comprehensively evaluate the impact of multimodal analgesia. Additionally, expanding the demographic diversity and including a larger sample size would help in validating these findings across different populations. This would not only enhance the generalizability of the results but also ensure that the conclusions drawn are robust and applicable to a wider patient population.

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