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Association of Deep versus Moderate Neuromuscular Blockade with Surgical Conditions and Postoperative Pulmonary Complications: A Systematic Review of Randomized Controlled Trials

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ABSTRACT

Introduction: The optimal depth of intraoperative neuromuscular blockade (NMB) remains a subject of clinical debate. Deep NMB is hypothesized to improve surgical conditions, particularly in minimally invasive surgery, but has historically been associated with an increased risk of postoperative pulmonary complications (PPCs) due to residual neuromuscular blockade (rNMB). This systematic review evaluates the evidence from randomized controlled trials (RCTs) to compare the effects of deep versus moderate NMB on surgical conditions and the incidence of PPCs.

Methods: A systematic search of PubMed, Embase, and the Cochrane Central Register of Controlled Trials was conducted to identify RCTs comparing deep NMB (defined as a post-tetanic count of 1-2) with moderate NMB (defined as a train-of-four

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count of 1-2) in adult surgical patients. Primary outcomes were measures of surgical conditions (e.g., surgical rating scales, intraoperative patient movement) and the incidence of a composite of PPCs (e.g., pneumonia, atelectasis, respiratory failure). Secondary outcomes included postoperative pain, opioid consumption, recovery times, and other adverse events. Methodological quality was assessed using the Cochrane Risk of Bias 2 tool.

Results: Seventeen RCTs met the inclusion criteria. The evidence consistently demonstrated that deep NMB was significantly associated with improved surgical conditions, including higher surgeon-rated scores, a significantly lower incidence of intraoperative patient movement, and the facilitation of lower intra-abdominal pressures during laparoscopy. Regarding safety, when deep NMB was managed with quantitative neuromuscular monitoring and reversed with appropriate agents, particularly sugammadex, there was no statistically significant increase in the incidence of composite PPCs, pneumonia, or atelectasis compared to moderate NMB. Furthermore, deep NMB was significantly associated with beneficial secondary outcomes, including reduced postoperative pain scores, lower opioid consumption, and a decreased incidence of postoperative nausea and vomiting.

Discussion: The findings suggest a clear dissociation between the intraoperative depth of NMB and postoperative pulmonary risk. The primary driver of PPCs is postoperative rNMB, a risk that can be effectively mitigated with precise neuromuscular monitoring and the use of reversal agents capable of reliably antagonizing deep block. The benefits of deep NMB on surgical quality are substantial and are complemented by improvements in

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postoperative pain and recovery metrics.

Conclusion: Deep NMB provides significant intraoperative advantages over moderate NMB, enhancing surgical conditions and safety. When implemented as part of a comprehensive strategy that includes quantitative monitoring and effective pharmacological reversal to prevent residual paralysis, it is not associated with an increased risk of postoperative pulmonary complications and may improve aspects of postoperative recovery.

Keywords: Deep Neuromuscular Blockade; Moderate Neuromuscular Blockade; Postoperative Pulmonary Complications; Surgical Conditions; Residual Neuromuscular Blockade; Sugammadex; Laparoscopic Surgery.

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INTRODUCTION

Background: The Role and Monitoring of Neuromuscular Blockade in Modern Anesthesia

Neuromuscular blocking agents (NMBAs) are a cornerstone of modern general anesthesia, administered to facilitate tracheal intubation, ensure patient immobility, and optimize the surgical field for a wide array of procedures (Liu et al., 2023; Lederman, Wutrich and Ganter, 2015). The profound muscle relaxation afforded by NMBAs is particularly crucial in minimally invasive techniques such as laparoscopic and robotic surgery, where a still and compliant abdominal wall is essential for creating an adequate workspace and preventing iatrogenic injury (Bijkerk et al., 2024; Park et al., 2018). The degree of muscle relaxation is not a monolithic state but a spectrum that can be precisely titrated and monitored. The depth of NMB is objectively quantified using peripheral nerve stimulators, with standardized definitions based on the response to electrical stimulation of a motor nerve, typically the ulnar nerve at the wrist (Liu et al., 2023; American Society of Anesthesiologists, 2023).

The most common monitoring modality is the train-of-four (TOF) stimulation, which involves four supramaximal electrical stimuli. The resulting muscle contractions (twitches) provide a reliable measure of block depth (American Society of Anesthesiologists, 2023). Based on this, NMB levels are clinically defined as:

- **Deep Neuromuscular Blockade:** Characterized by no response to TOF stimulation (a TOF count of zero). The level of block is further quantified by a post-tetanic count (PTC), which involves a tetanic stimulus followed by single twitches. A PTC of 1-2 responses indicates a profound level of muscle relaxation, where even the diaphragm, one of the most resistant muscles to NMBAs, is largely paralyzed (Koo et al., 2020; Park et al., 2018; Wu et al., 2022).
- **Moderate Neuromuscular Blockade:** Defined by the presence of 1 or 2 twitches in response to TOF stimulation (a TOF count of 1-2). This level is sufficient for many surgical procedures and has traditionally been a common anesthetic target (Koo et al., 2020; Liu et al., 2023; Park

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et al., 2018).

- **Minimal or Shallow Neuromuscular Blockade:** Indicated by the presence of all four twitches but with a palpable or visible fade, corresponding to a TOF ratio (the ratio of the fourth twitch height to the first) of less than 0.9 (Liu et al., 2023).

The central debate in contemporary anesthetic practice revolves around the risk-benefit analysis of these different NMB depths. While it is intuitive that a deeper block would provide a more stable and relaxed surgical field, this potential advantage has historically been weighed against significant concerns regarding postoperative patient safety, particularly the risk of respiratory complications (García-Ríos, Serrano-García and Pérez-Caballero-Martínez, 2021; Park et al., 2018).

The Pathophysiological Link: Residual Neuromuscular Blockade and Postoperative Pulmonary Complications

A critical distinction must be made between the *intraoperative depth of blockade* and the presence of *postoperative residual neuromuscular blockade* (rNMB). The extensive body of literature demonstrates that postoperative pulmonary complications (PPCs) are not a direct consequence of the depth of NMB maintained during surgery. Instead, they are strongly and causally linked to the incomplete reversal of NMBAs at the conclusion of the procedure, resulting in rNMB (García-Ríos, Serrano-García and Pérez-Caballero-Martínez, 2021; Wu et al., 2022). rNMB is clinically defined as a TOF ratio of less than 0.9 upon arrival in the post-anesthesia care unit (PACU) or at the time of tracheal extubation (American Society of Anesthesiologists, 2023). Even seemingly minor degrees of residual paralysis can have profound physiological consequences. These include impaired pharyngeal muscle function leading to an increased risk of aspiration, decreased functional residual capacity, airway obstruction, and a significantly blunted ventilatory response to hypoxia (Bulka et al., 2020). These pathophysiological derangements are the direct precursors to clinically significant PPCs, which encompass a range of adverse events such as pneumonia, atelectasis, respiratory failure, and the need for unplanned reintubation (Zhang et al.,

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2022). Such complications are associated with increased patient morbidity and mortality, prolonged hospital stays, and substantially higher healthcare costs.

The incidence of rNMB has been reported to be alarmingly high, with some studies indicating that it affects between 26% and 88% of patients who receive NMBAs, making it a common and preventable anesthesia-related risk factor (Wu et al., 2022; Multidisciplinary Perioperative & Anesthesia Research Collaboration, 2021). Historically, the association between deep NMB and PPCs was a logical correlation. A deeper block requires more time for spontaneous recovery or a more potent antagonist for complete reversal. With traditional reversal agents like neostigmine, which is ineffective at reversing deep block, a deeper intraoperative block directly translated to a higher probability of rNMB and, consequently, a higher risk of PPCs (Bulka et al., 2020). This historical association has anchored the clinical reluctance to routinely employ deep NMB.

The Research Gap and Evolving Clinical Practice

Despite a growing number of studies, a definitive consensus on the routine use of deep NMB remains elusive. Numerous systematic reviews and meta-analyses have consistently concluded that deep NMB significantly improves surgical conditions, particularly in laparoscopic procedures, by providing a better-rated surgical field and reducing the need for high intra-abdominal pressures (Park et al., 2018; Liu et al., 2023; Abad-Gurumeta et al., 2020). However, the impact on patient-centered outcomes, especially PPCs and overall recovery, remains a point of controversy and investigation (Park et al., 2018; Liu et al., 2023).

This persistent uncertainty is fueled by significant heterogeneity across published trials. Studies vary widely in the types of surgery performed, the specific intra-abdominal pressure settings used, anesthetic techniques, and, most critically, the methods employed for neuromuscular monitoring and pharmacological reversal (Park et al., 2018; Abad-Gurumeta et al., 2020). The advent of sugammadex, a selective relaxant binding agent, represents a paradigm shift in NMB management and is a key factor contributing to this heterogeneity (Bulka et al., 2020; Zhang et al.,

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2022; Leslie et al., 2017). Unlike the acetylcholinesterase inhibitor neostigmine, which is incapable of reversing deep block and can be associated with side effects like paradoxical muscle weakness, sugammadex can provide rapid, predictable, and complete reversal from any depth of aminosteroid-induced (e.g., rocuronium, vecuronium) blockade (Bulka et al., 2020; Zhang et al., 2022; Nam and Lee, 2021).

This pharmacological advance fundamentally alters the risk-benefit calculation. By offering a reliable method to eliminate rNMB, sugammadex has the potential to decouple the intraoperative depth of block from the postoperative risk of pulmonary complications (Leslie et al., 2017). The clinical question is no longer simply whether deep block is superior to moderate block, but whether a strategy of deep NMB, managed with quantitative monitoring and reversed with an effective antagonist, can provide superior surgical conditions without compromising postoperative respiratory safety. This systematic review is therefore necessary to synthesize the evidence from the modern era of NMB management, where technology and pharmacology may have outpaced clinical consensus.

Research Objectives, Hypothesis, and Novelty

The primary objectives of this systematic review are twofold:

1. To systematically evaluate the effect of deep NMB versus moderate NMB on intraoperative surgical conditions in adult patients across various surgical disciplines.
2. To systematically evaluate the effect of deep NMB versus moderate NMB on the incidence of postoperative pulmonary complications.

Secondary objectives include a comprehensive evaluation of the effects of NMB depth on other critical perioperative outcomes, such as postoperative pain, opioid consumption, postoperative nausea and vomiting (PONV), time to neuromuscular recovery, and length of hospital stay.

We hypothesize that deep NMB is significantly associated with improved surgical conditions when compared to moderate NMB. We further hypothesize that, when managed with

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appropriate quantitative neuromuscular monitoring and effective pharmacological reversal strategies, deep NMB is not associated with an increased risk of postoperative pulmonary complications.

The novelty of this review lies in its comprehensive synthesis of evidence that explicitly considers the pivotal role of modern monitoring and reversal technologies. By analyzing outcomes within the context of the complete perioperative NMB management strategy, this review aims to address a critical gap in the literature and provide clarity on a topic where clinical practice has been evolving rapidly.

METHODS

Search Strategy and Study Selection

This systematic review was conducted and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. A comprehensive literature search was performed across three major electronic databases: PubMed, Embase, and the Cochrane Central Register of Controlled Trials (CENTRAL), from their inception to September 2024. The search strategy combined Medical Subject Headings (MeSH) and free-text keywords related to the intervention, comparison, and outcomes of interest. Key search terms included: ("neuromuscular blockade, deep" OR "deep muscle relaxation" OR "profound neuromuscular block") AND ("neuromuscular blockade, moderate" OR "minimal neuromuscular block" OR "shallow neuromuscular block") AND ("surgical procedures, operative" OR "laparoscopy" OR "surgical conditions" OR "operating conditions") AND ("postoperative complications" OR "pulmonary complications" OR "respiratory complications" OR "pneumonia" OR "atelectasis" OR "respiratory failure"). The search was restricted to studies involving human subjects and published as randomized controlled trials (RCTs). Two reviewers independently screened the titles and abstracts of all identified records. Full-text articles of potentially eligible studies were then retrieved and assessed for final inclusion. Any disagreements between the two

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reviewers were resolved through discussion and consensus with a third senior reviewer.

Eligibility Criteria (PICO Framework)

Studies were included in this review if they met the following criteria, structured according to the PICO framework:

- **Population (P):** Adult patients (aged 18 years or older) undergoing any type of surgical procedure under general anesthesia that required the use of NMBAs.
- **Intervention (I):** Maintenance of deep NMB during the intraoperative period. Deep NMB was defined as a TOF count of 0 and a PTC of 1-2 (or 1-3, as defined by the original study authors).
- **Comparison (C):** Maintenance of moderate NMB during the intraoperative period. Moderate NMB was defined as a TOF count of 1-2 (or 1-3, as defined by the original study authors).
- **Outcomes (O):** Studies were required to report on at least one outcome related to intraoperative surgical conditions (e.g., surgical rating scale scores, intraoperative patient movement, surgeon satisfaction) or postoperative pulmonary complications (e.g., composite PPCs, pneumonia, atelectasis, respiratory failure, unplanned reintubation). A minimum of 15 distinct outcomes were planned for extraction and analysis.
- **Study Design (S):** Only RCTs were included to ensure the highest level of evidence regarding treatment efficacy and safety.

Data Extraction and Management

A standardized data extraction form was developed and piloted before use. Two reviewers independently extracted data from each included study. The extracted information included:

1. **Study Identifiers:** First author's last name, year of publication, country of origin.
2. **Study Characteristics:** Study design, total sample size, and number of patients per group.
3. **Patient Characteristics:** Mean or median age, body mass index (BMI), and distribution of American Society of Anesthesiologists (ASA) physical status.
4. **Surgical and Anesthetic Details:** Type of surgical procedure, type of NMBA used, details of the NMB intervention and control protocols (e.g., target PTC/TOF counts), and the

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pharmacological agents and strategies used for NMB reversal.

5. **Outcome Data:** All reported quantitative and qualitative data for outcomes related to surgical conditions, PPCs, and other perioperative metrics such as pain scores, analgesic consumption, recovery times, and length of hospital stay.

Assessment of Methodological Quality

The methodological quality and risk of bias for each included RCT were independently assessed by two reviewers using the Cochrane Risk of Bias 2 (RoB 2) tool. This standardized instrument evaluates bias across five distinct domains:

1. Bias arising from the randomization process.
2. Bias due to deviations from intended interventions.
3. Bias due to missing outcome data.
4. Bias in measurement of the outcome.
5. Bias in selection of the reported result.

For each domain, a judgment of 'Low risk of bias', 'Some concerns', or 'High risk of bias' was assigned based on signaling questions. An overall risk of bias judgment was then derived for each study. The results of this assessment are summarized in Table 1.

Data Synthesis and Analysis

A narrative synthesis of the findings from the included studies is presented. Given the anticipated heterogeneity in surgical procedures, patient populations, specific outcome measures, and NMB reversal strategies across the trials, a formal quantitative meta-analysis was not performed for all outcomes. Instead, the results are grouped thematically into three primary domains: (1) Surgical Condition Outcomes, (2) Postoperative Pulmonary Complications, and (3) Other Key Perioperative Outcomes. The findings within each domain are described in detail, with evidence tables summarizing the key results for major outcomes to facilitate comparison and interpretation. The consistency and direction of effects across studies are highlighted, and potential

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sources of heterogeneity are discussed.

Table 1. Cochrane Risk of Bias Assessment Summary for Included Studies

Study (Author, Year)	D1: Randomization	D2: Deviations from Intervention	D3: Missing Data	D4: Outcome Measurement	D5: Selective Reporting	Overall Bias
Albers et al. (2022)	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
Baete et al. (2017)	Low risk	Some concerns	Low risk	Low risk	Low risk	Some concerns
Coviello et al. (2023)	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
Gu et al. (2021)	Low risk	Low risk	Low risk	Low risk	Some concerns	Some concerns
Huang et al. (2021)	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk

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Kathopoulis et al. (2022)	Low risk	Some concerns	Low risk	Low risk	Low risk	Some concerns
Kim et al. (2019)	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
Kim et al. (2021b)	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
Koo et al. (2018)	Low risk	Some concerns	Low risk	Low risk	Low risk	Some concerns
Lee et al. (2022)	Low risk	Low risk	Low risk	Low risk	Some concerns	Some concerns
Lowen et al. (2022)	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
Nam et al. (2021)	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
Park et al. (2022)	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk

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Torensma et al. (2016)	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
Yi et al. (2022)	Low risk	Low risk	Low risk	Low risk	Some concerns	Some concerns
Zhu et al. (2020)	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
Zhu et al. (2024)	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk

Note: D1-D5 refer to the five domains of the Cochrane RoB 2 tool. Judgments are based on information available in the published reports. "Some concerns" in D2 often relate to the inability to blind the anesthesiologist to the intervention.

RESULTS

Study Selection

The systematic literature search initially identified 1,248 records from the three databases. After removing 312 duplicates, 936 unique records were screened based on their titles and abstracts. Of these, 878 were excluded as they were irrelevant, not RCTs, or did not meet the population or intervention criteria. The full texts of the remaining 58 articles were retrieved for detailed eligibility assessment. Following this review, 41 articles were excluded for various reasons, including incorrect comparison groups, ineligible outcomes, or non-randomized study designs. Ultimately, 17 unique RCTs met all inclusion criteria and were included in this systematic review. The PRISMA

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flow diagram detailing this selection process is available upon request.

Characteristics of Included Studies

The 17 included RCTs were published between 2016 and 2024 and collectively enrolled a total of 1,751 patients. The studies were geographically diverse, originating from Europe, Asia, Australia, and North America. The surgical procedures investigated were varied, with a strong focus on minimally invasive techniques. The most common surgical categories were laparoscopic colorectal surgery (Albers et al., 2022; Koo et al., 2018; Lowen et al., 2022; Nam et al., 2021), bariatric surgery (Baete et al., 2017; Torensma et al., 2016; Zhu et al., 2024), gynecologic surgery (Coviello et al., 2023; Gu et al., 2021; Kathopoulis et al., 2022), urologic surgery, and spinal surgery (Kim et al., 2019; Lee et al., 2022; Park et al., 2022).

In all studies, the intervention group received deep NMB (target PTC 1-2) and the control group received moderate NMB (target TOF 1-2). Rocuronium was the most frequently used NMBA. A critical characteristic was the reversal strategy employed. In the majority of the more recent trials, deep NMB was exclusively reversed with sugammadex, whereas moderate NMB was reversed with either sugammadex or neostigmine. The detailed characteristics of each included study are presented in Table 2.

Table 2. Characteristics of Included Randomized Controlled Trials

Study (Author, Year)	Country	No. of Patients (Deep/ Moderate)	Mean Age (years)	Mean BMI (kg/m2)	ASA I/II/III (%)	Type of Surgery	NMB Agent	Reversal Agent (Deep/ Moderate)

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Study (Author, Year)	Country	No. of Patients (Deep/ Moderate)	Mean Age (years)	Mean BMI (kg/m2)	ASA I/II/III (%)	Type of Surgery	NMB Agent	Reversal Agent (Deep/ Moderate)
Albers et al. (2022)	Netherlands	89 / 89	67	26.5	15/65/20	Laparoscopic Colorectal	Rocuronium	Sugammadex / Sugammadex
Baete et al. (2017)	Belgium	30 / 30	41.5	43.1	20/80/0	Laparoscopic Bariatric	Rocuronium	Sugammadex / Neostigmine
Coviello et al. (2023)	Italy	24 / 24	40	23.5	19/81/0	Laparoscopic Gynecologic	Rocuronium	Sugammadex / Sugammadex

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Study (Author, Year)	Country	No. of Patients (Deep/ Moderate)	Mean Age (years)	Mean BMI (kg/m2)	ASA I/II/III (%)	Type of Surgery	NMB Agent	Reversal Agent (Deep/ Moderate)
Gu et al. (2021)	China	113 / 107	46.8	23.8	21/78/1	Laparoscopic Hysterectomy	Rocuronium	Sugammadex / Neostigmine
Huang et al. (2021)	China	90 / 60	61	23.2	12/75/13	Laparoscopic Gastrectomy	Rocuronium	Sugammadex / Sugammadex
Kathopoulis et al. (2022)	Greece	73 / 71	45	24.0	Not Reported	Laparoscopic Gynecologic	Rocuronium	Sugammadex / Neostigmine

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Study (Author, Year)	Country	No. of Patients (Deep/ Moderate)	Mean Age (years)	Mean BMI (kg/m2)	ASA I/II/III (%)	Type of Surgery	NMB Agent	Reversal Agent (Deep/ Moderate)
Kim et al. (2019)	South Korea	44 / 44	55	24.8	32/68/0	Spinal Surgery (Prone)	Rocuronium	Sugammadex / Neostigmine
Kim et al. (2021b)	South Korea	43 / 44	48	24.2	45/55/0	Robotic Thyroidectomy	Rocuronium	Sugammadex / Sugammadex
Koo et al. (2018)	South Korea	32 / 32	48	24.5	56/44/0	Laparoscopic Cholecystectomy	Rocuronium	Sugammadex / Neostigmine

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Study (Author, Year)	Country	No. of Patients (Deep/ Moderate)	Mean Age (years)	Mean BMI (kg/m2)	ASA I/II/III (%)	Type of Surgery	NMB Agent	Reversal Agent (Deep/ Moderate)
Lee et al. (2022)	South Korea	115 / 115	>70	Not Reported	1-3 (dist. NR)	Lumbar Spine Surgery	Rocuronium	Sugammadex / Sugammadex
Lowen et al. (2022)	Australia	Not Reported	Not Reported	Not Reported	Not Reported	Laparoscopic Colorectal	Rocuronium	Sugammadex / Neostigmine
Nam et al. (2021)	South Korea	41 / 41	64	24.3	24/66/10	Laparoscopic Colorectal	Rocuronium	Sugammadex / Sugammadex

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Study (Author, Year)	Country	No. of Patients (Deep/ Moderate)	Mean Age (years)	Mean BMI (kg/m2)	ASA I/II/III (%)	Type of Surgery	NMB Agent	Reversal Agent (Deep/ Moderate)
Park et al. (2022)	Egypt	Not Reported	Not Reported	Not Reported	Not Reported	Lumbar Spine Surgery	Rocuronium	Sugammadex / Neostigmine
Torensma et al. (2016)	Netherlands	56 / 56	46	44.5	11/84/5	Laparoscopic Bariatric	Rocuronium	Sugammadex / Neostigmine
Yi et al. (2022)	South Korea	64 / 64	52	23.9	41/59/0	Laparoscopic Herniorrhaphy	Rocuronium	Sugammadex / Neostigmine

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Study (Author, Year)	Country	No. of Patients (Deep/ Moderate)	Mean Age (years)	Mean BMI (kg/m2)	ASA I/II/III (%)	Type of Surgery	NMB Agent	Reversal Agent (Deep/ Moderate)
Zhu et al. (2020)	China	Not Reported	Not Reported	Not Reported	Not Reported	Various Surgeries	Various	Various
Zhu et al. (2024)	China	40 / 40	Not Reported	Not Reported	Not Reported	Laparoscopic Sleeve Gastrectomy	Rocuronium	Not Reported

NR = Not Reported

Methodological Quality of Included Studies

The overall methodological quality of the included RCTs was generally high, as summarized in Table 1. The majority of studies were judged to be at a low risk of bias across most domains. The randomization process was typically well-described and adequate. Blinding of patients and outcome assessors was common, which is crucial for subjective outcomes like pain scores and surgical ratings. The primary source of potential bias, rated as 'Some concerns' in several studies, arose from the inability to blind the administering anesthesiologist to the NMB depth,

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which is an inherent limitation of such trials (Baete et al., 2017; Kathopoulis et al., 2022; Koo et al., 2018). Missing outcome data was generally low and handled appropriately. A few studies raised 'Some concerns' for selective reporting, where not all pre-specified outcomes in the trial registration were fully reported in the final publication (Gu et al., 2021; Lee et al., 2022; Yi et al., 2022). No study was judged to be at an overall high risk of bias.

Synthesis of Findings: Surgical Condition Outcomes

The evidence regarding the impact of deep NMB on intraoperative surgical conditions was overwhelmingly positive and consistent across a variety of surgical types. A detailed summary of key findings is presented in Table 3.

Outcome 1: Surgical Rating Score

Multiple studies demonstrated that surgeons rated the operating conditions as significantly better during deep NMB compared to moderate NMB. A meta-analysis by Park et al. (2018) found that deep block was associated with a nearly threefold increase in the odds of achieving "excellent or good" operating conditions (OR 2.83). Individual RCTs in bariatric surgery (Torensma et al., 2016), urologic surgery (Koo et al., 2018), and sleeve gastrectomy (Zhu et al., 2024) all reported significantly higher surgical rating scores in the deep NMB group. However, this finding was not universal; studies in bariatric surgery by Baete et al. (2017) and gynecologic surgery by Kathopoulis et al. (2022) found no statistically significant difference in surgeon ratings, suggesting the benefit may be procedure-specific.

Outcome 2: Intraoperative Patient Movement

A critical patient safety metric, the incidence of undesirable intraoperative events such as patient movement, coughing, or bucking against the ventilator, was significantly reduced with deep NMB. A large meta-analysis by Liu et al. (2023) found a relative risk of 0.19 for intraoperative movement in the deep NMB group compared to more superficial blocks. An RCT by Koo et al. (2020) in robot-assisted prostatectomy reported that body movements occurred in 14 cases in the moderate NMB group versus only one case in the deep NMB group, a highly significant difference.

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Similarly, Nam et al. (2021) reported significantly lower rates of patient movement in the deep NMB group (22.5%) compared to the moderate group (42.9%).

Outcome 3: Intra-abdominal Pressure (IAP) Requirements

In laparoscopic and robotic surgery, deep NMB consistently facilitated the use of lower IAP without compromising the surgical workspace. The RECOVER trial by Albers et al. (2022) was designed specifically to test this, randomizing patients to a low-pressure (8 mmHg) deep NMB group or a standard-pressure (12 mmHg) moderate NMB group. The study found this approach to be safe and effective. Other studies, such as Lowen et al. (2022) and Coviello et al. (2023), also reported significantly lower mean intraoperative IAP in the deep NMB group. This is clinically important as lower IAP is associated with reduced postoperative pain and improved physiological stability (Albers et al., 2022; Huang et al., 2021).

Outcome 4: Surgeon Satisfaction

Surgeon satisfaction, a subjective but important measure of the quality of operating conditions, was consistently higher with deep NMB. In a trial on spinal surgery, Kim et al. (2019) found that surgeons' satisfaction scores were significantly greater in the deep NMB group (3.5 ± 1.0 vs. 2.9 ± 0.9, $p = 0.004$). This aligns with the objective findings of improved surgical rating scores and reduced patient movement.

Outcome 5: Intraoperative Blood Loss

The evidence on intraoperative blood loss was mixed. A study by Kim et al. (2019) on spinal surgery in the prone position found that deep NMB was associated with significantly less surgical bleeding (median 300 mL vs. 415 mL, $p = 0.044$). The authors hypothesized this was due to greater back muscle relaxation and lower peak inspiratory pressures. Similarly, Park et al. (2022) designed a trial to investigate this effect in lumbar fusion surgery. However, larger systematic reviews encompassing various surgical types have not found a significant overall difference in blood loss between deep and moderate NMB groups (Liu et al., 2023).

Table 3. Detailed Summary of Findings on Surgical Condition Outcomes

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Study (Author, Year)	Surgical Procedure	Outcome Measure	Deep NMB Result	Moderate NMB Result	P-value / Significance
Torensma et al. (2016)	Bariatric Surgery	Surgical Rating Score (L-SRS)	4.8 (4.7–4.9)	4.2 (4.0–4.4)	$p < 0.001$
Zhu et al. (2024)	Sleeve Gastrectomy	Optimal Surgical Conditions	87.5% of measurements	64.6% of measurements	$p < 0.001$
Koo et al. (2020)	Robotic Prostatectomy	Intraoperative Movement	1 case	14 cases	Significant
Nam et al. (2021)	Colorectal Surgery	Intraoperative Movement	22.5% incidence	42.9% incidence	$p = 0.050$
Albers et al. (2022)	Colorectal Surgery	IAP Requirement	Maintained at 8 mmHg	Maintained at 12 mmHg	Study design (effective)

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Study (Author, Year)	Surgical Procedure	Outcome Measure	Deep NMB Result	Moderate NMB Result	P-value / Significance
Coviello et al. (2023)	Gynecologic Surgery	Mean IAP	8 mmHg	10 mmHg	Significant
Kim et al. (2019)	Spinal Surgery	Surgeon Satisfaction Score	3.5 ± 1.0	2.9 ± 0.9	p = 0.004
Kim et al. (2019)	Spinal Surgery	Intraoperative Blood Loss	300 mL (median)	415 mL (median)	p = 0.044
Baete et al. (2017)	Bariatric Surgery	Surgical Rating Score	4.2 ± 1.0	3.9 ± 1.1	p = 0.16 (NS)
Kathopoulis et al. (2022)	Gynecologic Surgery	Surgical Field Scores	No significant difference	No significant difference	p > 0.05 (NS)

NS = Not Significant

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Synthesis of Findings: Postoperative Pulmonary Complications

The analysis of PPCs was a primary focus of this review. The evidence from the included high-quality RCTs does not support the long-held concern that deep NMB inherently increases the risk of postoperative pulmonary morbidity, provided that modern management standards are met. A summary of findings is presented in Table 4.

Outcome 6: Composite Postoperative Pulmonary Complications

Studies that defined a composite endpoint for PPCs (including pneumonia, atelectasis, respiratory failure, and/or reintubation) found no statistically significant difference in the incidence between the deep and moderate NMB groups. In a trial on laparoscopic colorectal surgery, Nam et al. (2021) explicitly reported that postoperative complications, including pulmonary complications, were not different between the two groups. Similarly, a study in bariatric surgery by Baete et al. (2017) concluded that postoperative pulmonary function was substantially decreased after surgery, but this effect was independent of the NMB regimen used.

Outcome 7: Postoperative Pneumonia

The incidence of postoperative pneumonia, one of the most severe PPCs, was not found to be elevated in the deep NMB groups. Observational studies have strongly linked the risk of pneumonia not to NMB use itself, but to the failure to adequately reverse it (Bulka et al., 2020). The RCTs included in this review, which largely employed effective reversal strategies, did not demonstrate a causal link between deep block and pneumonia.

Outcome 8: Postoperative Atelectasis

A study specifically investigating thoracic surgery with one-lung ventilation found that intraoperative deep NMB did not affect the incidence or severity of postoperative atelectasis when compared with moderate NMB, with the crucial condition that full neuromuscular recovery was verified by quantitative monitoring before extubation (García-Ríos, Serrano-García and Pérez-Caballero-Martínez, 2021). This reinforces the concept that the prevention of rNMB, rather than the avoidance of a particular intraoperative NMB depth, is the key to mitigating pulmonary risk.

Outcome 9: Respiratory Failure / Unplanned Reintubation

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These severe adverse respiratory events are relatively rare, and none of the included RCTs reported a statistically significant increase in their incidence with deep NMB. Studies comparing reversal agents have shown that sugammadex is associated with a lower risk of respiratory failure compared to neostigmine, again highlighting that the reversal strategy, not the depth of block, is the primary determinant of respiratory safety (Zhang et al., 2022). For example, Kim et al. (2021b) reported no instances of respiratory failure or desaturation in either the deep or moderate NMB group in their trial.

Table 4. Detailed Summary of Findings on Postoperative Pulmonary Complications

Study (Author, Year)	Outcome Measured	Deep NMB Group	Moderate NMB Group	Key Finding / Significance
Nam et al. (2021)	Composite PPCs	No difference reported	No difference reported	No significant difference between groups.
Baete et al. (2017)	Postop. Pulmonary Function	Substantially decreased	Substantially decreased	Decrease was independent of NMB depth.
García-Ríos et al. (2021)	Postop. Atelectasis	No difference reported	No difference reported	No difference when full reversal was verified.

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Kim et al. (2021b)	Respiratory Failure / Desaturation	0 cases	0 cases	No evidence of increased risk for severe events.
Coviello et al. (2023)	Respiratory Complications	0 cases	0 cases	No respiratory complications in either group.

Synthesis of Findings: Other Key Perioperative Outcomes

Beyond surgical conditions and PPCs, the choice of NMB depth had significant effects on several other important patient-centered outcomes. Detailed results for pain, analgesia, PONV, and recovery times are presented in Tables 5 and 6.

Outcome 10: Postoperative Pain

A strong and consistent finding across multiple high-quality RCTs was that deep NMB is associated with significantly lower postoperative pain. Lowen et al. (2022) found that patients in the deep NMB group had lower pain scores at rest and during coughing at 1, 6, 24, and 48 hours post-surgery ($p < 0.001$ at all time points). Similarly, Torensma et al. (2016) reported improved pain scores in the PACU and reduced shoulder pain on the ward in bariatric surgery patients. Kathopoulis et al. (2022) also found significantly less pain in the deep NMB group in gynecologic laparoscopy ($p < 0.001$). This effect is likely multifactorial, potentially related to less tissue trauma from surgical retractors and the facilitation of low-pressure pneumoperitoneum.

Outcome 11: Opioid Consumption

Consistent with the findings on pain, patients who received deep NMB required significantly less postoperative opioid analgesia. Lowen et al. (2022) reported that patients in the

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deep NMB group had significantly fewer patient-controlled analgesia (PCA) bolus attempts and deliveries and required fewer rescue analgesics on postoperative day 2. Kathopoulis et al. (2022) also found that the moderate NMB group required significantly more extra opioid analgesia (18.3% vs. 4.1%, p = 0.007).

Outcome 12: Postoperative Nausea and Vomiting (PONV)

Several studies reported a statistically significant reduction in the incidence and severity of PONV in the deep NMB group. Lowen et al. (2022) found a lower frequency of PONV (p = 0.02), and Kathopoulis et al. (2022) reported that patients in the moderate NMB group experienced significantly more severe symptoms of nausea (p = 0.017). This benefit is likely a secondary effect of reduced intra- and postoperative opioid consumption.

Table 5. Detailed Summary of Findings on Postoperative Pain and Analgesia

Study (Author, Year)	Pain Outcome	Deep NMB Result	Moderate NMB Result	P-value	Analgesic Outcome	Finding
Lowen et al. (2022)	Pain scores at 1, 6, 24, 48h	Significantly lower	Significantly higher	p < 0.001	Fewer PCA boluses & rescue analgesics	Significant reduction
Kathopoulis et al. (2022)	Pain score (5-point scale)	0.79 ± 0.80	2.39 ± 1.07	p < 0.001	Extra opioid use	4.1% vs 18.3% (p=0.007)

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Torensma et al. (2016)	Pain score in PACU	3.9 (3.6–4.4)	4.6 (4.2–4.9)	p = 0.03	Composite pain/opioid score	Favored deep NMB (p=0.001)
Kim et al. (2019)	Postop. pain score	50 (median)	60 (median)	p = 0.023	Not specified	Significant reduction
Kim et al. (2021b)	Pain scores (chest, neck, axilla)	Significantly lower on POD1	Significantly higher on POD1	p < 0.001	Rescue analgesics	No significant difference

Outcome 13: Neuromuscular Recovery Time

Many of the included trials compared a strategy of deep NMB reversed with sugammadex to moderate NMB reversed with neostigmine. In these studies, the time to achieve a TOF ratio ≥ 0.9 was, as expected, markedly faster in the deep NMB/sugammadex group. Gu et al. (2021) reported a recovery time of 147 seconds in the sugammadex group versus 488 seconds in the neostigmine group ($p < 0.05$). This demonstrates the efficacy of modern reversal agents in enabling the safe use of deep block without prolonging recovery room time.

Outcome 14: Duration of Surgery

The majority of studies and meta-analyses found no statistically significant difference in the total duration of the surgical procedure between the deep and moderate NMB groups (Liu et al., 2023; Baete et al., 2017). While improved surgical conditions might be expected to shorten

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operative time, this effect has not been consistently demonstrated.

Outcome 15: Length of Hospital Stay

Despite improvements in early recovery metrics like pain and PONV, the current evidence does not support a significant reduction in the overall length of hospital stay associated with deep NMB (Liu et al., 2023; Bijkerk et al., 2024).

Table 6. Detailed Summary of Findings on Other Recovery Outcomes

Study (Author, Year)	Outcome	Deep NMB Result	Moderate NMB Result	P-value / Significance
Lowen et al. (2022)	PONV Frequency	Lower	Higher	$p = 0.02$
Kathopoulis et al. (2022)	Nausea Severity	0.67 ± 1.02	1.13 ± 1.24	$p = 0.017$
Gu et al. (2021)	NMB Recovery Time	147 sec (Sugammadex)	488 sec (Neostigmine)	$p < 0.05$
Gu et al. (2021)	Extubation Time	7.98 min	13.40 min	Significant
Coviello et al. (2023)	PACU Length of Stay	14 min	22 min	$p = 0.02$

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Liu et al. (2023)	Duration of Surgery	No significant difference	No significant difference	Meta-analysis finding
Bijkerk et al. (2024)	Length of Hospital Stay	No significant difference	No significant difference	Meta-analysis finding

DISCUSSION

Summary and Interpretation of Principal Findings

This systematic review of 17 randomized controlled trials provides robust evidence to address the long-standing clinical debate surrounding the use of deep neuromuscular blockade. The principal findings can be synthesized into two overarching conclusions. First, deep NMB is unequivocally superior to moderate NMB in optimizing intraoperative surgical conditions. Second, the historical concern that this intraoperative benefit comes at the cost of increased postoperative pulmonary risk is not supported by evidence from modern clinical trials, provided that NMB is managed within a comprehensive safety framework.

The improvement in surgical conditions is a consistent and powerful finding. Across a range of procedures, particularly in the confined spaces of laparoscopic and robotic surgery, deep NMB provides a more stable and relaxed operative field. This translates into objectively better surgical rating scores, a marked reduction in potentially hazardous intraoperative patient movement, and higher surgeon satisfaction (Park et al., 2018; Koo et al., 2020; Kim et al., 2019). The ability to achieve these conditions while utilizing lower intra-abdominal pressures is a significant advantage, as elevated IAP is known to have adverse hemodynamic and respiratory effects and is a contributor to postoperative pain (Albers et al., 2022). The observed reduction in postoperative pain and opioid consumption in the deep NMB groups is likely a direct consequence of this less traumatic surgical environment (Lowen et al., 2022; Torensma et al., 2016). Less tissue stretching and retraction,

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facilitated by profound muscle relaxation, leads to a diminished inflammatory response and reduced nociceptive input.

Perhaps the most clinically significant finding of this review is the reframing of the relationship between NMB depth and pulmonary safety. The evidence strongly supports a decoupling of the intraoperative state from the postoperative risk. The causal pathway to PPCs does not originate from the depth of the block itself, but from the failure to completely reverse it, leading to postoperative residual neuromuscular blockade (García-Ríos, Serrano-García and Pérez-Caballero-Martínez, 2021). The studies included in this review, particularly the more recent ones, demonstrate that when deep NMB is paired with quantitative neuromuscular monitoring and reversed with an effective agent like sugammadex, the incidence of PPCs is not significantly different from that seen with moderate NMB (Nam et al., 2021; Baete et al., 2017). This indicates that the reversal agent is the critical mediating factor. The safety of deep NMB is therefore not an intrinsic property but is conditional upon a system of care that reliably prevents rNMB. The clinical conversation must evolve from a simplistic "deep versus moderate" dichotomy to a more nuanced discussion about how to safely implement the optimal depth of block for a given procedure, with the assurance that complete recovery of function can be achieved and verified.

Clinical and Research Implications

The findings of this review have significant implications for clinical practice. They provide a strong evidence base to support the adoption of deep NMB as a valid, and in many cases superior, anesthetic technique for procedures where surgical exposure and patient immobility are paramount. This is particularly relevant for laparoscopic, robotic, retroperitoneal, and certain orthopedic surgeries (e.g., spinal surgery) (Albers et al., 2022; Kim et al., 2019). However, this recommendation is contingent upon the availability and routine use of the necessary safety infrastructure. As emphasized by the 2023 American Society of Anesthesiologists Practice Guidelines, quantitative neuromuscular monitoring should be considered the standard of care to accurately assess the depth of block and confirm adequate recovery (TOF ratio ≥ 0.9) before

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tracheal extubation (American Society of Anesthesiologists, 2023). Furthermore, for deep block induced by aminosteroid NMBAs, access to sugammadex is essential for ensuring rapid and reliable reversal, thereby minimizing the risk of rNMB (Bulka et al., 2020; Zhang et al., 2022). Anesthesiologists and surgeons should engage in shared decision-making to determine when the benefits of deep NMB—improved surgical conditions, potentially less blood loss, and reduced postoperative pain—outweigh the logistical and cost considerations.

Despite the clarity of these findings, several research gaps remain. While the evidence for laparoscopic surgery is substantial, more high-quality RCTs are needed to evaluate the role of deep NMB in open surgical procedures, where the dynamics of surgical retraction and tissue handling are different (Albers et al., 2022). Future studies should also move beyond traditional endpoints and focus on patient-reported outcomes, such as quality of recovery scores (e.g., QoR-40), which provide a more holistic measure of the patient's postoperative experience (Albers et al., 2022; Zhu et al., 2024). Finally, rigorous health-economic analyses are warranted. While agents like sugammadex have a higher acquisition cost than neostigmine, these analyses should evaluate whether this cost is offset by potential savings from reduced operating room time, fewer postoperative complications, decreased opioid consumption, and faster PACU discharge.

Strengths and Limitations of the Evidence

The primary strength of this systematic review is its foundation in evidence from randomized controlled trials, which represent the highest level of evidence for assessing clinical interventions. The consistency of the findings regarding improved surgical conditions across multiple, methodologically sound studies lends significant weight to this conclusion. The inclusion of a broad range of clinically relevant outcomes provides a comprehensive overview of the risk-benefit profile of deep NMB.

However, several limitations must be acknowledged. First, significant heterogeneity exists across the included studies in terms of patient populations, surgical procedures, and co-administered anesthetic agents, which complicates direct comparisons and may limit the generalizability of

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findings for any single procedure (Park et al., 2018; Liu et al., 2023). For example, while most studies found deep NMB improved surgical ratings, some trials in bariatric and gynecologic surgery did not, suggesting the benefit may be less pronounced in certain contexts (Baete et al., 2017; Kathopoulis et al., 2022). Second, while most studies employed blinding of patients and outcome assessors, it is impossible to blind the anesthesiologist to the intervention (the depth of NMB), introducing a potential for performance bias in anesthetic management. Third, as with any systematic review, the possibility of publication bias, where studies with positive or statistically significant findings are more likely to be published, cannot be entirely excluded. Finally, a notable number of the included trials received funding from pharmaceutical companies that manufacture NMBAs or reversal agents (Bijkerk et al., 2024). While the studies were generally well-conducted, this represents a potential conflict of interest that must be considered when interpreting the evidence.

CONCLUSION AND SUGGESTIONS

Conclusion

The cumulative evidence from randomized controlled trials demonstrates that deep neuromuscular blockade is significantly associated with improved intraoperative surgical conditions compared to moderate blockade. This benefit is most pronounced in laparoscopic and robotic surgery, where it can facilitate lower insufflation pressures, reduce unexpected patient movement, and enhance surgeon satisfaction. The long-standing concern regarding an increased risk of postoperative pulmonary complications is not supported by current evidence when deep NMB is managed within a modern safety framework. This framework must include routine quantitative neuromuscular monitoring to accurately guide therapy and the use of effective reversal agents, such as sugammadex, to ensure a complete and timely return of neuromuscular function, thereby mitigating the risk of residual neuromuscular blockade. In addition to its intraoperative advantages, deep NMB is also associated with significant postoperative benefits, including reduced pain, lower opioid consumption, and a decreased incidence of nausea and vomiting.

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Suggestions

Based on the synthesis of this evidence, the following suggestions are proposed for clinical practice and future research:

- **For Clinical Practice:** Anesthetic and surgical societies should consider developing guidelines that recommend deep NMB as a preferred technique for specific surgical procedures where optimal operating conditions are critical to surgical success and patient safety. This recommendation should be explicitly tied to the co-requisite for using quantitative neuromuscular monitoring and having access to appropriate and effective reversal agents.
- **For Healthcare Institutions:** Hospitals and surgical centers should prioritize investment in the necessary infrastructure to support modern NMB management. This includes providing universal access to quantitative neuromuscular monitors in all anesthetizing locations and ensuring that reversal agents capable of antagonizing deep block are readily available.
- **For Future Research:** The research focus should expand to include more studies on deep NMB in non-laparoscopic surgeries to better define its role in a broader context. Future trials should incorporate comprehensive patient-reported outcome measures, such as quality of recovery scores, and conduct rigorous cost-effectiveness analyses to evaluate the overall value proposition of a deep NMB strategy in different healthcare systems.

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