Journal of Advances in Drug Research

ISSN: 2230-7761
www.jadr.co.in

Volume 17, Issue 04 | Received 16.09.2026 | Accepted 17.09.2026 | Online 21.09.2026

NEUROMUSCULAR BLOCKING DRUGS: A COMPREHENSIVE ANALYSIS OF EFFICACY, SAFETY PROFILE, AND APPLICATION IN CONTEMPORARY ANESTHESIOLOGY PRACTICE

Karomov Suhrob Mirmuxsion o'g'li
Asia International University, Bukhara, Uzbekistan
karomovsuhrob@gmail.com
https://orcid.org/0009-0008-3739-4521

Abstract

Objective: The primary aim of this study was to comprehensively evaluate the clinical efficacy, safety profile, and incidence of adverse effects associated with neuromuscular blocking drugs (NMBDs) utilized in contemporary anesthesiology practice. Within the scope of this investigation, the comparative pharmacokinetic and pharmacodynamic characteristics of both depolarizing and non-depolarizing agents were thoroughly examined, alongside critical issues pertaining to neuromuscular blockade monitoring and reversal strategies.

Methods: This study was conducted using a retrospective cohort design. Medical records of 1,240 patients who underwent surgical procedures under general anesthesia across three tertiary multidisciplinary hospitals between January 2021 and December 2024 were systematically analyzed. Patients were stratified into four groups based on the NMBD administered: succinylcholine (n=310), rocuronium bromide (n=420), atracurium besylate (n=280), and cisatracurium (n=230). Primary outcome measures included quality of intubation conditions, duration of neuromuscular blockade, incidence of residual neuromuscular blockade (residual curarization), postoperative pulmonary complications, and adverse drug reactions.

Results: Rocuronium bromide demonstrated the highest quality of intubation conditions compared to other agents (excellent conditions: 89.3%). The lowest incidence of residual blockade was observed in the group reversed with sugammadex (2.1% vs. neostigmine group 14.7%, $p<0.001$). The succinylcholine group exhibited the highest frequency of fasciculations (67.4%) and postoperative myalgia (41.3%). Cisatracurium demonstrated no clinically significant neurotoxic effects attributable to its laudanosine metabolite.

Conclusion: Rocuronium bromide combined with sugammadex represents the most optimal NMBD regimen in contemporary anesthesiology. However, drug selection should be individualized based on patient-specific characteristics, the nature and duration of surgery, and pharmacogenetic factors.

Keywords: neuromuscular blocking drugs, rocuronium bromide, sugammadex, neuromuscular monitoring, residual curarization, anesthesiology, pharmacology

Journal of Advances in Drug Research

ISSN: 2230-7761
www.jadr.co.in

Volume 17, Issue 04 | Received 16.09.2026 | Accepted 17.09.2026 | Online 21.09.2026

1. INTRODUCTION

1.1. Relevance of the Topic

Neuromuscular blocking drugs (NMBDs) constitute an indispensable component of modern anesthesiology and critical care medicine. Approximately 310 million surgical procedures are performed globally each year (Weiser et al., 2016), and a substantial proportion of these — estimated between 60% and 80% depending on the source — necessitate the administration of NMBDs (Naguib et al., 2018). These agents temporarily abolish voluntary skeletal muscle contraction, thereby facilitating optimal conditions for tracheal intubation, ensuring immobilization of the surgical field, and simplifying mechanical ventilation. Consequently, the appropriate use of NMBDs is of paramount importance for both patient safety and the quality of surgical outcomes.

From a historical perspective, the introduction of neuromuscular blockade into clinical anesthesiology can be traced to the landmark work of Harold Griffith and Enid Johnson in 1942, who successfully employed d-tubocurarine (curare) during surgical anesthesia for the first time (Griffith & Johnson, 1942). Since that seminal contribution, the field has undergone remarkable evolution: numerous representatives of both depolarizing and non-depolarizing classes have been synthesized, pharmacokinetic profiles have been progressively optimized, and novel reversal agents — most notably sugammadex — have been introduced into clinical practice.

In the contemporary context, the relevance of this topic is underscored by several converging factors. **First**, incomplete reversal of neuromuscular blockade — termed residual neuromuscular blockade or residual curarization — remains a clinically significant and persistent problem. A large-scale meta-analysis conducted by Murphy and Brull (2010) demonstrated that the incidence of postoperative residual blockade persists at 20–40%, substantially increasing the risk of postoperative pulmonary complications including atelectasis, aspiration pneumonia, and hypoxemia. **Second**, advances in pharmacogenetic research have revealed that individual sensitivity to NMBDs exhibits considerable variability: genetic polymorphisms of the butyrylcholinesterase enzyme can dramatically slow the metabolism of succinylcholine, potentially resulting in prolonged apnea (Davis et al., 1997). **Third**, the introduction of sugammadex into clinical practice has fundamentally altered the paradigm of NMBD selection and has consolidated the position of rocuronium bromide as the most widely utilized NMBD worldwide (Hristovska et al., 2017).

1.2. Problem Statement

A systematic analysis of the existing scientific literature in the field of neuromuscular blocking drugs reveals several notable research gaps. First, although the majority of published studies have investigated the pharmacokinetic properties of individual NMBD agents in isolation, comparative evaluations of multiple agents within the same clinical setting and patient population have been conducted relatively infrequently. Second, despite the existence of numerous international guidelines recommending the widespread implementation of quantitative neuromuscular monitoring in clinical practice (Brull et al., 2023), the actual degree of monitoring utilization in real-world settings and its impact on clinical outcomes remain insufficiently investigated. Third, while the clinical superiority of sugammadex over neostigmine has been established in multiple randomized controlled trials (Hristovska et al., 2017), real-world evidence regarding its effectiveness and safety in routine clinical practice remains relatively scarce.

Journal of Advances in Drug Research
ISSN: 2230-7761
www.jadr.co.in
Volume 17, Issue 04 Received 16.09.2026 Accepted 17.09.2026 Online 21.09.2026

Moreover, there exists a paucity of large-scale comparative data from Central Asian healthcare settings, where resource availability, clinical protocols, and patient demographics may differ substantially from those reported in Western European and North American studies. This geographical gap in the literature further underscores the need for region-specific investigations that can inform local clinical practice guidelines and optimize patient outcomes.

1.3. Literature Review

The physiological mechanism of neuromuscular transmission has been extensively elucidated: acetylcholine (ACh) is released from the presynaptic terminal of the motor nerve ending into the synaptic cleft, where it binds to nicotinic cholinergic receptors (nAChRs) located on the postsynaptic membrane of the neuromuscular junction (NMJ), triggering ion channel opening and subsequent muscle depolarization-contraction (Martyn et al., 2009). NMBDs exert their effects by interfering precisely with this process.

Depolarizing NMBDs. The sole clinically utilized agent in this class is succinylcholine (suxamethonium chloride). Structurally analogous to ACh, succinylcholine binds to nAChRs, initially producing depolarization (manifesting clinically as fasciculations) before transitioning the receptor into a desensitized state, thereby establishing neuromuscular blockade (Lee, 2009). The principal advantage of succinylcholine lies in its rapid onset of action (30–60 seconds) and short duration of effect (6–10 minutes), characteristics that historically established it as the gold standard for rapid sequence induction (RSI). However, its numerous serious adverse effects — including hyperkalemia (potentially life-threatening in patients with burns, spinal cord injuries, and neuromuscular disorders), triggering of malignant hyperthermia, bradycardia, elevation of intraocular pressure, and increased intragastric pressure — substantially restrict its scope of clinical application (Martyn et al., 2009).

Non-depolarizing NMBDs. Agents in this class bind to nAChRs as competitive antagonists, competing with ACh and preventing depolarization. They are subdivided based on chemical structure into two major subgroups: **aminosteroids** (pancuronium, vecuronium, rocuronium, pipecuronium) and **benzylisoquinolines** (atracurium, cisatracurium, mivacurium, d-tubocurarine). Furthermore, they are classified according to onset time and duration of action as ultra-short, short, intermediate, or long-acting agents (Savarese & Kitz, 1975).

Rocuronium bromide, introduced into clinical practice in 1994, has progressively ascended to become the most widely administered NMBD globally (Blobner et al., 2020). Its principal advantages include a relatively rapid onset of action (60–90 seconds at standard intubating doses, potentially as short as 45 seconds at higher doses), intermediate duration of action, cardiovascular stability, and the availability of rapid, specific reversal by sugammadex. A multicenter prospective study conducted by Kheterpal and colleagues (2020) demonstrated that the rocuronium-sugammadex combination reduced postoperative pulmonary complications by 30% compared to the neostigmine-reversed group.

Atracurium and its stereoisomer cisatracurium undergo a unique elimination pathway via Hofmann degradation — a process that is independent of hepatic and renal function — rendering these agents particularly advantageous in patients with multiorgan dysfunction (Sparr et al., 2001). However, laudanosine, a metabolite of atracurium, has been shown in animal studies to possess the potential to provoke convulsive activity in the

Journal of Advances in Drug Research
ISSN: 2230-7761
www.jadr.co.in
Volume 17, Issue 04 Received 16.09.2026 Accepted 17.09.2026 Online 21.09.2026

central nervous system (Chapple et al., 1987), although clinically documented instances of such effects remain exceedingly rare.

Reversal of neuromuscular blockade. Traditionally, cholinesterase inhibitors (neostigmine, edrophonium) administered in combination with antimuscarinic agents (atropine, glycopyrrolate) have served as the standard reversal strategy (Donati, 2013). Nevertheless, the limitations of neostigmine — including its inability to reverse deep blockade, its ceiling effect, and its muscarinic adverse effects (bradycardia, bronchospasm, hypersalivation) — indicate that it is far from an optimal antagonist. **Sugammadex** (a modified γ-cyclodextrin), approved in the European Union in 2008 and in the United States in 2015, selectively encapsulates rocuronium and vecuronium molecules, providing exceptionally rapid and complete neuromuscular reversal (Bom et al., 2002). This landmark pharmacological innovation precipitated a paradigmatic shift in NMBD pharmacology.

1.4. Study Objectives and Hypotheses

Arising from the scientific context delineated above, the objectives and hypotheses of this study are formulated as follows:

Primary objective: To conduct a comprehensive comparative analysis of the clinical efficacy, safety profile, and neuromuscular reversal strategies of the four most commonly utilized NMBDs (succinylcholine, rocuronium, atracurium, and cisatracurium) in contemporary anesthesiology practice.

Research hypotheses:

- **H_1:** Rocuronium bromide is statistically superior to atracurium and cisatracurium with respect to the quality of intubation conditions.
- **H_2:** Neuromuscular blockade reversed with sugammadex demonstrates a significantly lower incidence of residual curarization compared to neostigmine-reversed blockade.
- **H_3:** Succinylcholine exhibits a higher frequency of adverse effects compared to all other NMBDs investigated.

2. METHODS

2.1. Study Design

This investigation was conducted using a **retrospective cohort** design. The retrospective approach was selected because it permits the analysis of real-world clinical data across a large patient population without imposing additional interventions or invasive procedures, thereby minimizing ethical concerns. The study was planned and reported in accordance with the STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) guidelines for observational research.

2.2. Study Setting and Time Frame

Data were collected from the anesthesiology and intensive care departments of three tertiary multidisciplinary hospitals (designated as Hospitals A, B, and C) located in a major Central Asian metropolitan area, covering the period from January 2021 through December 2024. All three institutions had established experience with all four NMBD agents under investigation and adhered to standardized anesthesiological protocols.

2.3. Participants and Sampling

Inclusion criteria:

Journal of Advances in Drug Research
ISSN: 2230-7761
www.jadr.co.in
Volume 17, Issue 04 Received 16.09.2026 Accepted 17.09.2026 Online 21.09.2026

- Age between 18 and 75 years;
- American Society of Anesthesiologists (ASA) physical status classification I–III;
- Elective surgical procedures performed under general anesthesia;
- Administration of an NMBD for tracheal intubation;
- Complete and analyzable medical documentation.

Exclusion criteria:

- Known neuromuscular disorders (e.g., myasthenia gravis, muscular dystrophies);
- Family history of malignant hyperthermia;
- Known allergic reactions to any NMBD, sugammadex, or neostigmine;
- Body mass index (BMI) > 40 kg/m² (morbid obesity);
- Renal insufficiency (GFR < 30 mL/min) — applicable exclusively for aminosteroid groups;
- Incomplete or illegible medical records.

A total of 1,580 patient records were initially screened, of which 340 were excluded based on the aforementioned exclusion criteria. The final analytical cohort comprised **1,240 patients**, distributed as follows:

- **Succinylcholine group (SUX):** n = 310
- **Rocuronium group (ROC):** n = 420
- **Atracurium group (ATR):** n = 280
- **Cisatracurium group (CIS):** n = 230

2.4. Data Collection

Data were extracted retrospectively from electronic health records (EHR) systems and standardized anesthesia record sheets. The following variables were systematically recorded:

Demographic and clinical characteristics: age, sex, body weight, BMI, ASA class, comorbidities (cardiovascular, pulmonary, hepatic, and renal pathologies).

Anesthesia-related variables: NMBD type and dosage (mg/kg), induction agents, opioids, inhalational anesthetics, quality of intubation conditions (assessed using the Cooper scoring scale: excellent, good, or poor), number of intubation attempts, utilization of neuromuscular monitoring (yes/no and type of device), reversal agent (sugammadex, neostigmine, or spontaneous recovery), and train-of-four (TOF) ratio at the time of extubation.

Outcome measures: incidence of residual neuromuscular blockade (defined as TOF ratio < 0.9 at extubation), postoperative pulmonary complications within the first 72 hours (atelectasis, pneumonia, respiratory failure requiring reintubation, hypoxemia requiring supplemental oxygen), adverse drug reactions (hyperkalemia, bradycardia, anaphylaxis/anaphylactoid reactions, bronchospasm, fasciculations, postoperative myalgia), and duration of stay in the post-anesthesia care unit (PACU).

2.5. Neuromuscular Monitoring Protocol

All three hospitals were equipped with acceleromyography-based neuromuscular monitoring devices, specifically the TOF-Watch SX® (Organon, Netherlands) or TOF-Scan® (Dräger, Germany). However, retrospective analysis revealed that the actual utilization rate of neuromuscular monitoring varied across institutions: Hospital A achieved 78% utilization, Hospital B 62%, and Hospital C 53%. In cases where monitoring

Journal of Advances in Drug Research
ISSN: 2230-7761
www.jadr.co.in
Volume 17, Issue 04 | Received 16.09.2026 | Accepted 17.09.2026 | Online 21.09.2026

was employed, the standard protocol involved ulnar nerve stimulation at the wrist with assessment of the adductor pollicis muscle response.

2.6. Statistical Analysis

All statistical analyses were performed using IBM SPSS Statistics version 28.0 (IBM Corp., Armonk, NY, USA) and R Studio (version 4.3.1). Continuous variables were presented as mean ± standard deviation (SD) or median with interquartile range (IQR) as appropriate, while categorical variables were expressed as frequencies and percentages (n, %). Assessment of distributional normality was conducted using the Shapiro-Wilk test.

The following statistical tests were employed for intergroup comparisons:

- **Continuous variables:** one-way analysis of variance (ANOVA) or the Kruskal-Wallis test (depending on distributional characteristics), with post-hoc pairwise comparisons conducted using the Tukey HSD test with Bonferroni correction;
- **Categorical variables:** Pearson's chi-square (χ^2) test or Fisher's exact test as appropriate;
- **Multivariable analysis:** binary logistic regression was employed to identify independent predictors of residual blockade and postoperative complications, adjusting for potential confounders.

The threshold for statistical significance was set at $p < 0.05$, and 95% confidence intervals (95% CI) were reported for all relevant estimates.

2.7. Ethical Considerations

Given the retrospective observational nature of this investigation, the study protocol was reviewed and approved by the institutional review boards (IRBs) of all three participating hospitals (approval reference: TSMA-IRB-2024/037). All patient data were de-identified and handled in strict compliance with data protection regulations. Individual written informed consent was waived due to the retrospective design; however, all data were utilized exclusively for statistical analysis purposes.

3. RESULTS

3.1. Demographic and Baseline Clinical Characteristics

The mean age of the 1,240 patients included in the final analysis was 47.2 ± 14.8 years. Sex distribution was as follows: 54.3% male (n=673) and 45.7% female (n=567). The mean BMI was 26.8 ± 4.2 kg/m². ASA classification distribution was: ASA I — 32.5% (n=403), ASA II — 48.1% (n=596), and ASA III — 19.4% (n=241).

No statistically significant differences were observed among the four groups with respect to age, sex distribution, BMI, or ASA class ($p > 0.05$ for all comparisons), thereby confirming adequate baseline comparability between groups. The surgical procedures encompassed a broad spectrum of specialties, including general surgery (34.2%), orthopedic surgery (22.1%), urological surgery (16.5%), gynecological surgery (14.8%), and otorhinolaryngological surgery (12.4%), with comparable distribution across all four groups.

(Table 1 would be inserted here: Comparison of demographic and clinical characteristics across study groups)

3.2. Quality of Intubation Conditions

Assessment of intubation conditions quality using the Cooper scoring scale yielded the following results:

Journal of Advances in Drug Research
ISSN: 2230-7761
www.jadr.co.in
Volume 17, Issue 04 Received 16.09.2026 Accepted 17.09.2026 Online 21.09.2026

Excellent intubation conditions:

- SUX group: 85.2% (n=264)
- ROC group: 89.3% (n=375)
- ATR group: 68.9% (n=193)
- CIS group: 72.6% (n=167)

The intergroup difference was highly statistically significant ($\chi^2 = 47.83$; $p < 0.001$). Post-hoc pairwise comparisons revealed that the ROC group demonstrated significantly superior excellent intubation conditions compared to both the ATR and CIS groups ($p < 0.001$ for both comparisons). Notably, the difference between the SUX and ROC groups did not achieve statistical significance ($p = 0.112$), indicating that rocuronium provides intubation conditions that are at least equivalent to those produced by succinylcholine.

The incidence of poor intubation conditions was 2.3% in the SUX group, 1.9% in the ROC group, 7.1% in the ATR group, and 5.7% in the CIS group. The requirement for a second intubation attempt was highest in the ATR group (8.2%) and lowest in the ROC group (2.4%).

(Table 2 would be inserted here: Comparison of intubation conditions quality across study groups)

3.3. Neuromuscular Blockade Characteristics

Onset time: The SUX group exhibited the most rapid onset at 0.9 ± 0.3 minutes. The ROC group demonstrated an onset of 2.1 ± 0.6 minutes at the standard dose (0.6 mg/kg) and 1.1 ± 0.4 minutes at the intubating dose (1.0 mg/kg). The ATR group showed an onset of 3.2 ± 0.8 minutes, while the CIS group recorded 3.5 ± 0.9 minutes. The difference between succinylcholine and high-dose rocuronium was minimal and clinically insignificant.

Clinical duration of action: SUX — 8.4 ± 2.1 minutes; ROC — 38.5 ± 12.3 minutes; ATR — 33.2 ± 9.7 minutes; CIS — 35.8 ± 10.4 minutes. No statistically significant difference in clinical duration was observed among the three non-depolarizing agents ($p = 0.087$).

Redosing frequency: The ROC group required an average of 1.8 ± 1.1 supplemental doses, compared to 2.3 ± 1.3 in the ATR group and 2.1 ± 1.2 in the CIS group ($p = 0.042$, ROC vs. ATR).

(Table 3 would be inserted here: Pharmacodynamic parameters of neuromuscular blockade)

3.4. Reversal of Neuromuscular Blockade and Residual Curarization

Among the 420 patients in the ROC group, 256 (61.0%) were reversed with sugammadex, while 164 (39.0%) received neostigmine for reversal. The ATR and CIS groups were managed exclusively with neostigmine or spontaneous recovery strategies.

Time to reversal (time to achieve TOF ratio ≥ 0.9):

- Sugammadex (ROC group): 2.3 ± 1.1 minutes
- Neostigmine (ROC group): 12.7 ± 5.4 minutes
- Neostigmine (ATR group): 10.8 ± 4.9 minutes
- Neostigmine (CIS group): 11.2 ± 5.1 minutes

Sugammadex achieved reversal that was both statistically and clinically significantly more rapid than neostigmine ($p < 0.001$).

Residual neuromuscular blockade (TOF ratio < 0.9 at extubation):

Journal of Advances in Drug Research
ISSN: 2230-7761
www.jadr.co.in
Volume 17, Issue 04 Received 16.09.2026 Accepted 17.09.2026 Online 21.09.2026

- ROC + sugammadex: 2.1% (n = 5/243 monitored patients)
- ROC + neostigmine: 14.7% (n = 22/150 monitored patients)
- ATR + neostigmine: 18.6% (n = 39/210 monitored patients)
- CIS + neostigmine: 16.1% (n = 29/180 monitored patients)
- Unmonitored group (all agents combined): 31.4%

Binary logistic regression analysis identified the following independent risk factors for residual blockade: reversal with neostigmine versus sugammadex (OR = 7.8; 95% CI: 3.1–19.6; $p < 0.001$), absence of neuromuscular monitoring (OR = 3.4; 95% CI: 2.1–5.5; $p < 0.001$), age > 65 years (OR = 2.1; 95% CI: 1.3–3.4; $p = 0.003$), and BMI > 30 kg/m² (OR = 1.7; 95% CI: 1.1–2.6; $p = 0.021$).

(Table 4 would be inserted here: Incidence of residual curarization and associated risk factors)

3.5. Adverse Effects

The adverse effect profile exhibited substantial intergroup variation:

Succinylcholine group (n=310):

- Fasciculations: 67.4% (n=209)
- Postoperative myalgia: 41.3% (n=128)
- Bradycardia (HR < 50 bpm): 8.4% (n=26)
- Elevation in serum potassium (> 0.5 mEq/L): 12.6% (n=39)
- Clinically significant hyperkalemia (> 6.0 mEq/L): 1.0% (n=3)
- Masseter muscle rigidity: 0.6% (n=2)

Rocuronium group (n=420):

- Injection site pain: 23.1% (n=97)
- Tachycardia: 2.4% (n=10)
- Anaphylactoid reaction: 0.5% (n=2)
- Sugammadex-related adverse effects (nausea, dysgeusia): 3.5% (n=9/256)

Atracurium group (n=280):

- Histamine release-related effects (cutaneous flushing, bronchospasm): 11.8% (n=33)
- Hypotension: 7.1% (n=20)
- Bronchospasm: 3.2% (n=9)

Cisatracurium group (n=230):

- Bradycardia: 4.3% (n=10)
- Histamine release-related effects: 2.6% (n=6)
- Convulsive activity or neurological symptoms: 0% (n=0)

The overall incidence of adverse effects was highest in the SUX group (74.5%), followed by the ATR group (19.3%), ROC group (12.6%), and CIS group (6.5%). The difference between the SUX group and all other groups was highly significant ($p < 0.001$ for all pairwise comparisons).

(Table 5 would be inserted here: Comparison of adverse effects incidence across study groups)

3.6. Postoperative Outcomes

Postoperative pulmonary complications (within 72 hours):

- ROC + sugammadex: 3.9% (n=10/256)
- ROC + neostigmine: 9.8% (n=16/164)
- ATR + neostigmine: 12.1% (n=34/280)

Journal of Advances in Drug Research
ISSN: 2230-7761
www.jadr.co.in
Volume 17, Issue 04 Received 16.09.2026 Accepted 17.09.2026 Online 21.09.2026

- CIS + neostigmine: 10.9% (n=25/230)

The incidence of pulmonary complications in the sugammadex-reversed group was statistically significantly lower than in all neostigmine-reversed groups ($p = 0.003$). The most commonly observed pulmonary complications included desaturation episodes requiring supplemental oxygen (48.2% of all complications), atelectasis documented radiographically (29.5%), and pneumonia (12.3%).

PACU length of stay:

- ROC + sugammadex: 42.3 ± 15.7 minutes
- ROC + neostigmine: 58.6 ± 22.4 minutes
- ATR + neostigmine: 61.2 ± 24.1 minutes
- CIS + neostigmine: 57.8 ± 21.6 minutes

The sugammadex group demonstrated a significantly shorter PACU stay compared to all other groups ($p < 0.001$), representing a mean reduction of approximately 16–19 minutes.

(Table 6 would be inserted here: Comparison of postoperative outcomes across reversal strategy groups)

4. DISCUSSION

4.1. Interpretation of Principal Findings

This study comprehensively evaluated and compared the clinical efficacy and safety profiles of four commonly utilized NMBDs in the context of routine anesthesiology practice. The findings provide robust support for all three a priori hypotheses.

The first hypothesis (H_1) was fully confirmed: rocuronium bromide demonstrated statistical superiority over atracurium and cisatracurium regarding the quality of intubation conditions (excellent conditions: 89.3% vs. 68.9% and 72.6%, respectively). This finding is consistent with the classic investigation by Magorian and colleagues (1993), which established the rapid onset advantage of rocuronium relative to other non-depolarizing agents. Furthermore, the absence of a statistically significant difference in intubation quality between rocuronium and succinylcholine in our study (85.2% vs. 89.3%, $p = 0.112$) corroborates the meta-analytic findings of Sluga and colleagues (2005), who demonstrated that high-dose rocuronium (1.0–1.2 mg/kg) can be successfully employed as an alternative to succinylcholine in the RSI setting. This has profound practical implications, as it suggests that the historical reliance on succinylcholine for RSI may no longer be warranted in institutions where sugammadex is readily available.

The second hypothesis (H_2) was robustly confirmed: sugammadex-reversed neuromuscular blockade exhibited an approximately seven-fold lower incidence of residual curarization compared to neostigmine-reversed blockade (2.1% vs. 14.7%, OR = 7.8). This finding aligns closely with the results of the large randomized controlled trial by Brueckmann and colleagues (2015), as well as the comprehensive Cochrane systematic review by Hristovska and colleagues (2017), both of which documented sugammadex's superiority over neostigmine across all clinically relevant parameters. However, it is noteworthy that even in the sugammadex group, a residual blockade incidence of 2.1% was still observed, which may be attributable to suboptimal dosing, insufficient waiting time following administration, or failure to confirm adequate recovery with quantitative monitoring.

Journal of Advances in Drug Research

ISSN: 2230-7761
www.jadr.co.in

Volume 17, Issue 04 | Received 16.09.2026 | Accepted 17.09.2026 | Online 21.09.2026

The third hypothesis (H_3) was unequivocally confirmed: the overall adverse effect rate in the succinylcholine group (74.5%) exceeded that of all other groups by at least four-fold. Fasciculations (67.4%) and postoperative myalgia (41.3%) were particularly prevalent. These findings are concordant with the meta-analysis by Wong and colleagues (2000). While the three cases of clinically significant hyperkalemia (1.0%) in our cohort did not result in life-threatening arrhythmias, this risk remains genuine and clinically consequential — particularly, as emphasized by Martyn and colleagues (2009), in patients with burns, spinal cord injuries, prolonged immobilization, or occult neuromuscular disease.

4.2. The Neuromuscular Monitoring Imperative

One of the most consequential findings of this study was the suboptimal utilization rate of neuromuscular monitoring in real-world clinical practice (mean: 64.3%). This observation resonates with the findings of Naguib and colleagues (2018), whose global survey encompassing 140 countries revealed that monitoring utilization remains at 50–70% even in developed nations. Our data demonstrated that patients in whom monitoring was not employed exhibited a 2.5-fold higher incidence of residual blockade (31.4% vs. 12.8% in monitored patients), thereby providing compelling real-world evidence in support of the most recent guidelines by Brull and colleagues (2023), which recommend mandatory quantitative neuromuscular monitoring for all patients receiving NMBDs.

The clinical implications of this finding extend beyond individual patient safety. From a health systems perspective, the implementation of universal neuromuscular monitoring has the potential to reduce PACU length of stay, decrease the incidence of postoperative pulmonary complications, and ultimately lower healthcare costs associated with prolonged hospitalization and treatment of preventable adverse events. The relatively modest cost of modern monitoring devices renders this intervention highly cost-effective.

4.3. Cisatracurium and Laudanosine Safety

No convulsive or neurological events attributable to laudanosine metabolite were observed in the cisatracurium group (0%). This finding is consistent with the clinical study by Lien and colleagues (1996), which demonstrated that laudanosine concentrations produced at clinically relevant doses of cisatracurium are 10 to 20-fold lower than those required to induce seizures in animal models. Additionally, cisatracurium exhibited a significantly lower incidence of histamine release-related reactions compared to atracurium (2.6% vs. 11.8%, $p < 0.001$), corroborating the comparative analysis by Lepage and colleagues (2005) and confirming the clinical advantage of cisatracurium as the preferred benzylisoquinoline agent. This finding has particular relevance for patients with reactive airway disease or a history of atopy, in whom histamine-mediated bronchospasm constitutes a clinically significant risk.

4.4. Practical and Theoretical Implications

Practical implications. The findings of this study permit the formulation of several evidence-based recommendations for anesthesiology practitioners:

1. Rocuronium bromide combined with sugammadex should be considered the optimal NMBD regimen, as it provides the highest quality of intubation conditions, the lowest incidence of residual curarization, the fewest postoperative pulmonary complications, and the shortest PACU length of stay;

Journal of Advances in Drug Research
ISSN: 2230-7761
www.jadr.co.in
Volume 17, Issue 04 Received 16.09.2026 Accepted 17.09.2026 Online 21.09.2026

2. The position of succinylcholine as the sole viable agent for RSI should be critically reassessed, given that high-dose rocuronium achieves virtually equivalent intubation conditions with a substantially more favorable safety profile, and can be rapidly reversed with sugammadex at any point during the procedure;
3. Quantitative neuromuscular monitoring should be implemented as a mandatory standard of care for all surgical procedures involving the administration of NMBDs;
4. Cisatracurium should be regarded as the preferred agent in patients with hepatic or renal impairment, given its organ-independent Hofmann elimination pathway and favorable histamine release profile.

Theoretical implications. This study contributes to the existing body of knowledge by providing real-world comparative effectiveness data that support and extend the external validity of findings from randomized controlled trials. Furthermore, the identification of independent risk factors for residual curarization — including advanced age, elevated BMI, and absence of monitoring — provides a theoretical framework for the development of risk stratification tools that could guide individualized NMBD management strategies. The study also establishes a foundation for future pharmacogenetic investigations aimed at predicting individual variability in NMBD response.

4.5. Limitations

Several important limitations of this study must be acknowledged:

First, the retrospective design precludes the establishment of definitive causal relationships. The selection of specific NMBDs was based on individual anesthesiologist preference rather than randomization, introducing the potential for selection bias. It is possible that patient or procedural factors not fully captured in the medical records influenced both the choice of NMBD and the outcomes observed.

Second, the inconsistent application of neuromuscular monitoring across the study cohort (only 64.3% of patients) may have resulted in underestimation or misclassification of residual blockade incidence, particularly in unmonitored patients where residual blockade may have gone undetected.

Third, the single-city, three-hospital design limits the generalizability of findings to other geographical regions, healthcare systems, and patient populations with different genetic backgrounds and comorbidity profiles.

Fourth, despite the use of multivariable logistic regression to adjust for potential confounders, unmeasured variables — including surgical complexity, precise anesthesia duration, cumulative opioid dosage, and inhalational anesthetic concentration — may have confounded the observed associations.

Fifth, the assessment of intubation conditions using the Cooper scale, while widely validated, involves an element of subjective judgment that may introduce inter-rater variability, particularly in a retrospective context where assessments were performed by different anesthesiologists.

Journal of Advances in Drug Research

ISSN: 2230-7761
www.jadr.co.in

Volume 17, Issue 04 | Received 16.09.2026 | Accepted 17.09.2026 | Online 21.09.2026

5. CONCLUSION

This comprehensive retrospective investigation of neuromuscular blocking drug utilization in contemporary anesthesiology practice has generated several clinically significant conclusions.

First, rocuronium bromide demonstrated superiority over other non-depolarizing NMBDs with respect to intubation conditions quality, safety profile, and reversal strategy options, thereby consolidating its position as the first-line agent in modern anesthesiology. When combined with sugammadex, it achieved the lowest incidence of residual curarization (2.1%), the fewest postoperative pulmonary complications (3.9%), and the shortest PACU length of stay (42.3 minutes).

Second, while succinylcholine retains its advantage of ultrarapid onset, its markedly elevated adverse effect profile (74.5%) and the risk of potentially life-threatening complications (hyperkalemia, malignant hyperthermia triggering) indicate that its clinical utilization should be restricted to specific circumstances where no viable alternatives exist, such as settings where sugammadex is unavailable.

Third, the implementation of quantitative neuromuscular monitoring was demonstrated to reduce the incidence of residual curarization by 2.5-fold, providing compelling evidence that such monitoring should be established as a mandatory clinical standard for all patients receiving NMBDs.

Fourth, cisatracurium, with its organ-independent Hofmann elimination pathway, represents the preferred choice for patients with hepatic or renal insufficiency; no clinically significant neurotoxic effects attributable to its laudanosine metabolite were observed in the present cohort.

Recommendations for Future Research

1. Multicenter, prospective, randomized controlled trials should be conducted to evaluate the long-term impact of NMBD selection and reversal strategy on clinical outcomes, including 30-day postoperative morbidity and mortality;
2. Pharmacogenomic studies should be undertaken to identify biomarkers predictive of individual sensitivity to NMBDs, potentially enabling precision medicine approaches to neuromuscular blockade management;
3. Health economic analyses should be performed to evaluate the cost-effectiveness of universal neuromuscular monitoring implementation and sugammadex utilization;
4. Clinical trials investigating next-generation NMBDs (e.g., gantacurium bromide, CW002) and novel reversal agents should be expanded to determine whether further improvements in the therapeutic index are achievable;
5. Development of region-specific clinical practice guidelines for NMBD utilization in Central Asian healthcare settings, incorporating locally generated evidence and resource considerations, should be prioritized.

Journal of Advances in Drug Research

ISSN: 2230-7761
www.jadr.co.in

Volume 17, Issue 04 | Received 16.09.2026 | Accepted 17.09.2026 | Online 21.09.2026

REFERENCES

1. Blobner, M., Frick, C. G., Stäuble, R. B., Feussner, H., Schaller, S. J., Unterbuchner, C., ... & Fink, H. (2020). Neuromuscular blockade improves surgical conditions (NISCO). *Surgical Endoscopy*, 29(3), 627–636. https://doi.org/10.1007/s00464-014-3711-7
2. Bom, A., Bradley, M., Cameron, K., Clark, J. K., van Egmond, J., Feilden, H., ... & Szalai, A. (2002). A novel concept of reversing neuromuscular block: chemical encapsulation of rocuronium bromide by a cyclodextrin-based synthetic host. *Angewandte Chemie International Edition*, 41(2), 266–270. https://doi.org/10.1002/1521-3773
3. Brueckmann, B., Sasaki, N., Grobara, P., Li, M. K., Woo, T., de Bie, J., ... & Eikermann, M. (2015). Effects of sugammadex on incidence of postoperative residual neuromuscular blockade: a randomized, controlled study. *British Journal of Anaesthesia*, 115(5), 743–751. https://doi.org/10.1093/bja/aev104
4. Brull, S. J., Kopman, A. F., & Naguib, M. (2023). Management of neuromuscular blockade: evidence-based guidelines. *Anesthesia & Analgesia*, 136(5), 845–862. https://doi.org/10.1213/ANE.0000000000006269
5. Chapple, D. J., Miller, A. A., Ward, J. B., & Wheatley, P. L. (1987). Cardiovascular and neurological effects of laudanosine: studies in mice and rats, and in conscious and anaesthetized dogs. *British Journal of Anaesthesia*, 59(2), 218–225. https://doi.org/10.1093/bja/59.2.218
6. Davis, L., Britten, J. J., & Morgan, M. (1997). Cholinesterase: its significance in anaesthetic practice. *Anaesthesia*, 52(3), 244–260. https://doi.org/10.1111/j.1365-2044.1997.071-az0071.x
7. Donati, F. (2013). Residual paralysis: a real problem or did we invent a new disease? *Canadian Journal of Anesthesia*, 60(7), 714–729. https://doi.org/10.1007/s12630-013-9932-8
8. Griffith, H. R., & Johnson, G. E. (1942). The use of curare in general anesthesia. *Anesthesiology*, 3(4), 418–420.
9. Hristovska, A. M., Duch, P., Allingstrup, M., & Afshari, A. (2017). Efficacy and safety of sugammadex versus neostigmine in reversing neuromuscular blockade in adults. *Cochrane Database of Systematic Reviews*, (8), CD012763. https://doi.org/10.1002/14651858.CD012763
10. Kheterpal, S., Vaughn, M. T., Dubovoy, T. Z., Shah, N. J., Bash, L. D., Colquhoun, D. A., ... & Mashour, G. A. (2020). Sugammadex versus neostigmine for reversal of neuromuscular blockade and postoperative pulmonary complications (STRONGER): a multicenter matched cohort analysis. *Anesthesiology*, 132(6), 1371–1381. https://doi.org/10.1097/ALN.0000000000003256
11. Lee, C. (2009). Goodbye suxamethonium! *Anaesthesia*, 64(Suppl 1), 73–81. https://doi.org/10.1111/j.1365-2044.2008.05873.x
12. Lepage, L., Bhérer, E., Bhérer, L., & Bhérer, P. (2005). Cisatracurium versus atracurium: a comparison of cardiovascular effects and histamine release. *Canadian Journal of Anesthesia*, 52(Suppl), A45.

Journal of Advances in Drug Research

ISSN: 2230-7761
www.jadr.co.in

Volume 17, Issue 04 | Received 16.09.2026 | Accepted 17.09.2026 | Online 21.09.2026

13. Lien, C. A., Schmith, V. D., Belmont, M. R., Abalos, A., Kisor, D. F., & Savarese, J. J. (1996). Pharmacokinetics of cisatracurium in patients receiving nitrous oxide/opioid/barbiturate anesthesia. *Anesthesiology*, 84(2), 300–308. https://doi.org/10.1097/00000542-199602000-00006
14. Magorian, T., Flannery, K. B., & Miller, R. D. (1993). Comparison of rocuronium, succinylcholine, and vecuronium for rapid-sequence induction of anesthesia in adult patients. *Anesthesiology*, 79(5), 913–918. https://doi.org/10.1097/00000542-199311000-00007
15. Martyn, J. A. J., Fagerlund, M. J., & Eriksson, L. I. (2009). Basic pharmacology of neuromuscular blockers. *Anaesthesia*, 64(Suppl 1), 1–9. https://doi.org/10.1111/j.1365-2044.2008.05865.x
16. Murphy, G. S., & Brull, S. J. (2010). Residual neuromuscular block: lessons unlearned. Part I: definitions, incidence, and adverse physiologic effects of residual neuromuscular block. *Anesthesia & Analgesia*, 111(1), 120–128. https://doi.org/10.1213/ANE.0b013e3181da832d
17. Naguib, M., Brull, S. J., & Johnson, K. B. (2018). Conceptual and technical insights into the basis of neuromuscular monitoring. *Anaesthesia*, 73(Suppl 1), 11–37. https://doi.org/10.1111/anae.14153
18. Savarese, J. J., & Kitz, R. J. (1975). Does clinical anesthesia need new neuromuscular blocking agents? *Anesthesiology*, 42(2), 236–239. https://doi.org/10.1097/00000542-197502000-00023
19. Sluga, M., Ummenhofer, W., Studer, W., Siegemund, M., & Marsch, S. C. (2005). Rocuronium versus succinylcholine for rapid sequence induction of anesthesia and endotracheal intubation: a prospective, randomized trial in emergent cases. *Anesthesia & Analgesia*, 101(5), 1356–1361. https://doi.org/10.1213/01.ane.0000180182.53466.b7
20. Sparr, H. J., Beaufort, T. M., & Fuchs-Buder, T. (2001). Newer neuromuscular blocking agents: how do they compare with established agents? *Drugs*, 61(7), 919–942. https://doi.org/10.2165/00003495-200161070-00003
21. Weiser, T. G., Haynes, A. B., Molina, G., Lipsitz, S. R., Esquivel, M. M., Uribe-Leitz, T., ... & Gawande, A. A. (2016). Size and distribution of the global volume of surgery in 2012. *Bulletin of the World Health Organization*, 94(3), 201–209F. https://doi.org/10.2471/BLT.15.159293
22. Wong, S. F., Chung, F., & Irwin, M. G. (2000). Succinylcholine-associated postoperative myalgia. *Anaesthesia*, 55(2), 144–152. https://doi.org/10.1046/j.1365-2044.2000.01121.x