Original Article

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Anaesthesia Section

Comparison of Sugammadex and Neostigmine on Speed and Quality of Recovery after Vecuronium Neuromuscular Blockade in Adult Patients Undergoing Spine Surgery under General Anaesthesia: A Randomised Clinical Study

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ABSTRACT

Introduction: Residual neuromuscular blockade after non depolarising muscle relaxants is an important concern during recovery from anaesthesia. Incomplete reversal may affect ventilation, airway protection, and safe extubation. This problem is more relevant in spine surgery, where prolonged anaesthesia, prone positioning, and the need for early neurological assessment make reliable recovery essential.

Aim: To compare sugammadex with neostigmine plus glycopyrrolate for reversal of vecuronium-induced neuromuscular blockade in adult patients undergoing elective spine surgery under general anaesthesia.

Materials and Methods: This single-blinded randomised clinical study was conducted in the Department of Anaesthesiology, Krishna Hospital and Medical Centre, Krishna Institute of Medical Sciences, Karad, Maharashtra, India, from July 2024 to December 2025. The study included 60 adult patients aged 18-60 years with American Society of Anaesthesiologists (ASA) physical status I or II who were posted for elective spine surgery. Eligible participants were randomly distributed into two groups of 30 patients each. Patients in Group S were administered intravenous sugammadex 2 mg/kg, whereas patients in Group N received intravenous neostigmine 0.05 mg/kg along with glycopyrrolate 0.01 mg/kg following the return of the second twitch on quantitative Train-Of-Four (TOF) monitoring. The main outcome assessed was the duration required to attain a TOF ratio of ≥0.9. Additional outcomes included extubation time, haemodynamic variables, post-anaesthesia care unit duration, total hospital stay, and treatment-related adverse events. Data were analysed using independent-samples t-test, Chi-square test, and Fisher's-exact test as appropriate, with $p<0.05$ considered statistically significant.

Results: Baseline characteristics were comparable between group S and group N: age 44.8±9.2 versus 46.1±8.7 years; gender 18/12 versus 17/13 (M/F); Body Mass Index (BMI) 24.6±2.8 versus 24.9±2.6 kg/m^2; and ASA I/II 19/11 versus 20/10. Time to TOF ratio ≥0.9 was significantly shorter in group S than group N (2.8±0.9 versus 14.6±3.8 minutes; $p<0.001$). Time to extubation was also reduced with sugammadex (5.9±1.4 versus 17.8±4.6 minutes; $p<0.001$). Post-anaesthesia care unit stay was shorter in group S (42±10 versus 58±14 minutes; $p<0.001$), while hospital stay was comparable (4.1±0.9 versus 4.4±1.0 days; $p=0.19$). Haemodynamic parameters were similar between groups. Bradycardia was significantly more frequent in group N (1/30 versus 6/30; $p=0.04$). No serious adverse event was observed.

Conclusion: In adult patients undergoing elective spine surgery, sugammadex enabled quicker and more reliable reversal of vecuronium-induced neuromuscular blockade than the conventional neostigmine–glycopyrrolate regimen. It shortened the time to extubation and post-anaesthesia care unit stay without compromising haemodynamic stability. Its main benefit was seen during immediate postoperative recovery.

Keywords: Adult, Anaesthesia recovery period, Extubation, Postoperative complications

INTRODUCTION

Non depolarising neuromuscular blocking agents are widely used during general anaesthesia to facilitate tracheal intubation, improve surgical exposure, and allow controlled ventilation. Despite their routine use, incomplete recovery from neuromuscular blockade remains an important postoperative safety concern. Residual neuromuscular blockade is commonly defined as a TOF ratio below 0.9 and may persist even when clinical signs suggest adequate recovery. It can contribute to upper airway obstruction, impaired pharyngeal coordination, reduced respiratory muscle strength, diminished response to hypoxia, postoperative atelectasis, and delayed discharge from the recovery area [1-3]. Postoperative pulmonary complications are multifactorial, but residual neuromuscular weakness is a modifiable contributor when objective monitoring and appropriate reversal are not consistently applied [4,5].

Objective assessment of neuromuscular recovery has become increasingly important because bedside clinical tests alone may fail to detect clinically relevant residual weakness. Quantitative TOF monitoring provides a more reliable estimate of neuromuscular transmission and helps guide the timing of reversal and extubation. In patients receiving non depolarising muscle relaxants, confirmation of a TOF ratio of at least 0.9 is considered a practical safety threshold before tracheal extubation. This is particularly relevant in procedures where delayed recovery, airway compromise, or inability to assess neurological status may affect immediate postoperative care. Spine surgery presents a distinct perioperative context in which neuromuscular recovery deserves special attention. These

procedures are often prolonged, are commonly performed in the prone position, and may require repeated doses of muscle relaxant to maintain immobility and adequate operating conditions. At the end of surgery, the patient must be repositioned from prone to supine, spontaneous ventilation and airway reflexes must be restored, and extubation must be performed safely. In addition, early postoperative neurological assessment is clinically important after spine surgery because timely evaluation of limb movement and neurological function can help detect new deficits at an early stage. Residual weakness may delay extubation, interfere with respiratory recovery, and reduce the reliability of early neurological examination. Therefore, a predictable and objectively confirmed reversal strategy is especially valuable in adult spine-surgery patients [2,6].

The acetylcholinesterase inhibitor neostigmine has long been used for reversal of non depolarising neuromuscular blockade. Its effect depends on the degree of spontaneous recovery present at the time of administration and is limited by a ceiling effect. Neostigmine also increases muscarinic activity and is therefore administered with an anticholinergic agent such as glycopyrrolate to reduce bradycardia, secretions, and other cholinergic adverse effects [7]. Sugammadex is a modified γ-cyclodextrin that selectively binds aminosteroidal neuromuscular blocking agents, including rocuronium and vecuronium. By encapsulating the relaxant in plasma, sugammadex reduces the free drug concentration and produces a concentration gradient that promotes diffusion of the relaxant away from the neuromuscular junction, allowing faster recovery of neuromuscular transmission [7,8].

Previous clinical trials and pooled analyses have shown that sugammadex provides more rapid recovery to a TOF ratio of ≥0.9 than neostigmine after aminosteroidal neuromuscular blockade [7-11]. The Cochrane review by Hristovska AM et al., and the meta-analysis by Carron M et al., further support the efficacy and safety of sugammadex compared with neostigmine in adult surgical patients [10,11]. However, much of the available evidence has been derived from mixed surgical populations, and fewer data are available for adult patients undergoing elective spine surgery after vecuronium-induced neuromuscular blockade. In addition, Indian tertiary-care practice requires context-specific evidence because vecuronium remains commonly used and the cost difference between sugammadex and neostigmine-glycopyrrolate is relevant to routine decision-making [7-11].

The present study was therefore conducted to compare sugammadex with neostigmine plus glycopyrrolate for reversal of vecuronium-induced neuromuscular blockade in adult patients undergoing elective spine surgery under general anaesthesia, using quantitative TOF-guided assessment. The primary objective was to compare the time required to achieve a TOF ratio of ≥0.9. The secondary objectives were to compare time to extubation, haemodynamic parameters, post-anaesthesia care unit stay, hospital stay, and adverse events.

MATERIALS AND METHODS

This single-blinded randomised clinical study was conducted in the Department of Anaesthesiology, Krishna Hospital and Medical Centre, Krishna Institute of Medical Sciences, Karad, Maharashtra, India, from July 2024 to December 2025. The study was conducted after obtaining approval from the Institutional Ethics Committee of Krishna Institute of Medical Sciences, Karad, under reference number KVV/IEC/05/2024, dated 15-04-2024, and written informed consent was obtained from all participants before enrolment.

Sample size calculation: Based on the study by Khuenl-Brady KS et al., the sample size was calculated using the mean time to achieve a TOF ratio ≥0.9 as the primary outcome parameter [7]. A clinically meaningful between-group difference of 3.0 minutes and a pooled standard deviation of 4.0 minutes were considered. Using the formula for comparison of two independent means,

$n=2(Z\alpha/2 + Z\beta)^2\ \sigma^2/d^2$,

where $Z\alpha/2=1.96$ at 95% confidence level, $Z\beta=0.84$ at 80% power, $\sigma=4.0$ minutes, and $d=3.0$ minutes:

$n=2(1.96 + 0.84)^2\times(4.0)^2/(3.0)^2$

$n=2(2.80)^2\times16/9$

$n=2\times7.84\times16/9$

$n=250.88/9$

$n=27.87$

Thus, the minimum required sample size was 28 patients per group. To account for an anticipated dropout or protocol-deviation rate of approximately 7.1%, the sample size was increased to 30 patients per group. Therefore, a total of 60 patients were enrolled, with 30 allocated to the sugammadex group and 30 allocated to the neostigmine-glycopyrrolate group.

Inclusion criteria: Adult patients aged 18-60 years of either gender, belonging to ASA physical status I or II, scheduled for elective spine surgery under general anaesthesia, and requiring vecuronium as the neuromuscular blocking agent were included in the study.

Exclusion criteria: Patients who refused consent, had known hypersensitivity to any study drug, significant cardiovascular or respiratory disease, central nervous system disorder, deranged liver function, poor cardiopulmonary reserve, uncontrolled hypertension, seizure disorder, current antidepressant or antipsychotic therapy, or BMI>30 kg/m^2 were excluded.

All allocated participants received the planned intervention, completed the follow-up period, and were included in the final statistical analysis. The flow of participants through screening, randomisation, allocation, follow-up, and analysis is shown in [Table/Fig-1] computer-generated random allocation sequence was prepared in a 1:1 ratio by an investigator/statistician not involved in patient enrolment, intraoperative management, or outcome assessment. Eligible patients were enrolled by the principal investigator. Allocation concealment was maintained using sequentially numbered, opaque, sealed envelopes, which were opened only after eligibility confirmation and immediately before administration of the reversal agent. The assigned intervention was administered by the attending anaesthesiologist, who was aware of group allocation because of differences in drug preparation and dosing.

A total of 66 patients were screened: six were excluded, of whom four did not fulfil the eligibility criteria, and two declined participation. The remaining 60 patients were included and randomised in equal numbers into the two study groups.

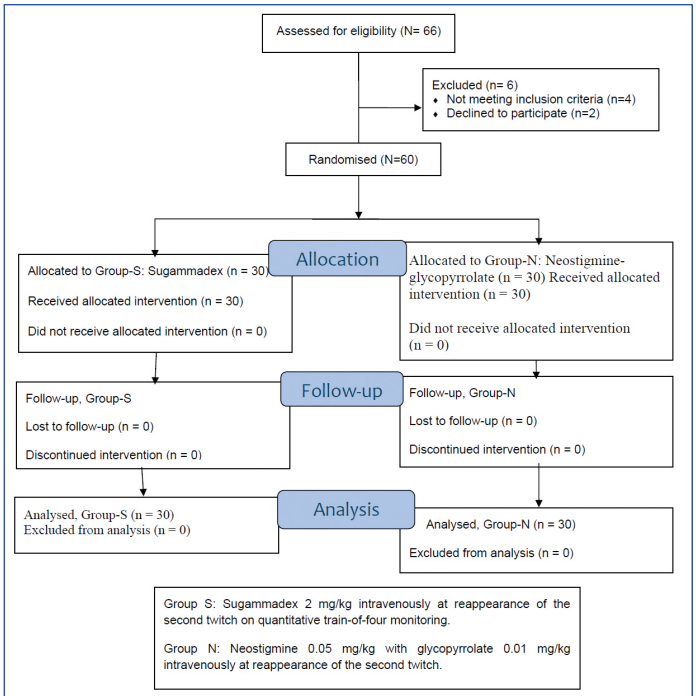
Group S (n=30): Patients who received sugammadex, administered intravenous sugammadex 2 mg/kg

Group N (n=30): Patients who received intravenous neostigmine 0.05 mg/kg along with glycopyrrolate 0.01 mg/kg following the return of the second twitch on quantitative Train-Of-Four (TOF) monitoring.

Outcome assessment was performed by an independent observer who was blinded to group allocation. Thus, the study followed a single-blind, observer-blinded design. Bias was reduced by using computer-generated randomisation, allocation concealment, uniform anaesthetic technique, standardised reversal criteria, quantitative TOF monitoring, predefined extubation criteria, and blinded assessment of recovery outcomes.

Study Procedure

All patients underwent pre-anaesthetic evaluation and were managed according to a standard institutional anaesthetic protocol. In the operating room, standard monitoring included electrocardiography, non invasive blood pressure, pulse oximetry, capnography, and



[Table/Fig-1]: CONSORT flow diagram showing enrolment, randomisation, allocation, follow-up, and analysis of study participants.

quantitative TOF monitoring. Quantitative TOF monitoring was performed at the adductor pollicis after ulnar nerve stimulation using a quantitative neuromuscular monitor. The TOF monitor was calibrated before administration of vecuronium, and supramaximal stimulation was confirmed according to the manufacturer's recommendations. Anaesthesia was induced with midazolam 0.02 mg/kg, fentanyl 2 µg/kg, propofol 2 mg/kg, and vecuronium 0.1 mg/kg to facilitate tracheal intubation. Anaesthesia was maintained with oxygen, nitrous oxide, and isoflurane, with ventilation adjusted to maintain normocapnia. Additional vecuronium boluses of 0.01-0.02 mg/kg were administered when the TOF count increased above two twitches, to maintain one to two twitches during surgery.

At the end of surgery, inhalational anaesthetic agents were discontinued, and reversal was administered after reappearance of the second twitch on quantitative TOF monitoring. Patients in group S received intravenous sugammadex 2 mg/kg, while patients in group N received intravenous neostigmine 0.05 mg/kg with glycopyrrolate 0.01 mg/kg. The selected reversal doses were based on previously published clinical studies and standard anaesthetic practice for reversal of moderate aminosteroidal neuromuscular blockade [7,8]. After reversal, the TOF ratio was recorded at regular intervals until a value ≥0.9 was achieved and confirmed on three consecutive measurements. Extubation was performed after fulfilment of standard criteria, including adequate consciousness, sustained spontaneous ventilation, stable haemodynamic parameters, acceptable oxygen saturation, airway reflex recovery, and TOF ratio ≥0.9. Time to extubation was defined as the interval from administration of the reversal agent to removal of the endotracheal tube.

After extubation, all patients were shifted to the post-anaesthesia care unit and monitored using pulse oximetry, non invasive blood pressure, heart rate, respiratory rate, and clinical assessment for residual neuromuscular weakness. Oxygen supplementation, analgesia, and antiemetic treatment were provided according to the institutional postoperative anaesthetic protocol and were applied uniformly in both groups. Patients were observed for haemodynamic instability, respiratory difficulty, postoperative nausea and vomiting, bradycardia, hypotension, and features of residual neuromuscular blockade. Discharge from the post-anaesthesia care unit was permitted after achieving stable vital parameters, adequate oxygenation, satisfactory pain control, and absence of clinically significant residual weakness.

The primary outcome was the time from administration of the reversal agent to achievement of TOF ratio ≥0.9, confirmed on three consecutive quantitative TOF measurements. A TOF ratio ≥0.9 was selected as the cutoff for adequate neuromuscular recovery based on accepted recommendations and previous literature defining residual neuromuscular blockade as TOF ratio <0.9 [1,2,6]. Secondary outcomes included time to extubation, heart rate, mean arterial pressure, peripheral oxygen saturation at extubation, post-anaesthesia care unit stay, total hospital stay, and adverse events such as bradycardia, hypotension, postoperative nausea and vomiting, and residual neuromuscular blockade.

STATISTICAL ANALYSIS

Data were analysed using SPSS version 21.0. Continuous variables were summarised as mean±standard deviation, while categorical variables were expressed as frequency and percentage. Independent-samples t-test was used to compare continuous variables between Group S and Group N, including age, body mass index, duration of surgery, total vecuronium dose, time to TOF ratio ≥0.9, extubation time, haemodynamic parameters, PACU stay, and hospital stay. The Chi-square test was applied for comparison of sex distribution and ASA physical status. Fisher's-exact test was used for adverse-event comparisons, including bradycardia, hypotension, postoperative nausea and vomiting, and residual neuromuscular blockade. All statistical tests were two-sided, and a p-value<0.05 was considered statistically significant.

RESULTS

The baseline demographic and perioperative variables were similar in both study groups, suggesting adequate comparability after randomisation. Age, sex distribution, body mass index, ASA physical status, duration of surgery, and total vecuronium dose did not differ significantly between Group S and Group N, as presented in [Table/Fig-2].

Variables	Group S (n=30)	Group N (n=30)	p-value
Age, (in years)	44.8±9.2	46.1±8.7	0.56
Gender Male/Female	18/12	17/13	0.79
BMI, (kg/m^2)	24.6±2.8	24.9±2.6	0.64
ASA I/II	19/11	20/10	0.79
Duration of surgery, (in minutes)	152±28	158±31	0.43
Total vecuronium dose, (in mg)	9.8±1.6	10.1±1.7	0.48

[Table/Fig-2]: Baseline demographic and perioperative characteristics (N=60).

Neuromuscular recovery, extubation profile, haemodynamic parameters, oxygenation, and postoperative recovery outcomes are summarised in [Table/Fig-3]. Patients who received sugammadex had a shorter post-anaesthesia care unit stay than those who received neostigmine with glycopyrrolate (42±10 versus 58±14 minutes; p<0.001). In contrast, heart rate, mean arterial pressure, peripheral oxygen saturation at extubation, and total hospital stay were comparable between the two groups.

No serious adverse event was recorded in either group. Bradycardia occurred significantly more often in group N than in group S. Other adverse events, including hypotension, postoperative nausea and vomiting, and residual neuromuscular blockade, were numerically higher in group N but did not reach statistical significance. The adverse event profile is summarised in [Table/Fig-4].

Overall, sugammadex was associated with faster neuromuscular recovery, earlier extubation, and shorter recovery-unit stay after vecuronium-induced neuromuscular blockade in adult spine surgery. The two groups remained comparable with respect to haemodynamic parameters and hospital stay, while bradycardia was significantly less frequent with sugammadex.

Parameters	Group S (n=30)	Group N (n=30)	p-value
Time to Train-Of-Four (TOF) ratio ≥0.9, (minutes)	2.8±0.9	14.6±3.8	<0.001
Time to extubation, minutes	5.9±1.4	17.8±4.6	<0.001
Heart rate at extubation, (beats/min)	89±10	85±11	0.10
Mean arterial pressure at extubation, (mmHg)	88±7	86±8	0.31
SpO_2 at extubation, %	99±1	98±1	0.12
PACU stay, (minutes)	42±10	58±14	<0.001
Hospital stay, (days)	4.1±0.9	4.4±1.0	0.19

[Table/Fig-3]: Neuromuscular, extubation, haemodynamic, oxygenation, and postoperative recovery outcomes.
Values are expressed as mean±standard deviation. Group S: sugammadex; Group N: neostigmine with glycopyrrolate; TOF: Train-of-four; SpO_2: peripheral oxygen saturation; PACU: Post-anaesthesia care unit. A p-value <0.05 was considered statistically significant.

Adverse events	Group S n (%)	Group N n (%)	p-value
Bradycardia	1 (3.3)	6 (20.0)	0.04
Hypotension	2 (6.7)	3 (10.0)	0.64
Postoperative nausea and vomiting	3 (10.0)	5 (16.7)	0.46
Residual neuromuscular blockade	0	2 (6.7)	0.15

[Table/Fig-4]: Adverse events in the study groups.

DISCUSSION

In the present study, sugammadex produced significantly faster recovery from vecuronium-induced neuromuscular blockade than neostigmine-glycopyrrolate in adult patients undergoing elective spine surgery. The mean time to achieve a TOF ratio ≥0.9 was 2.8±0.9 minutes in the sugammadex group compared with 14.6±3.8 minutes in the neostigmine-glycopyrrolate group, showing a marked reduction in objective neuromuscular recovery time. This finding is clinically relevant because spine surgery often involves prolonged anaesthesia, prone positioning, and repeated administration of neuromuscular blocking agents. Similar superiority of sugammadex for objective neuromuscular recovery has been reported in large perioperative datasets and recent evidence syntheses. Kheterpal S et al., observed that sugammadex-based reversal was associated with improved postoperative respiratory outcomes compared with neostigmine in a large multicentre cohort, supporting the clinical importance of more complete and predictable reversal [12]. Recent meta-analyses by Olesnicky BL et al., and Zhu N and Li Y also reported that sugammadex was associated with faster neuromuscular recovery and a lower risk of residual neuromuscular blockade than neostigmine-based reversal [13,14]. Thus, the primary outcome of the present study agrees with broader evidence and adds procedure-specific data in adult spine surgery after vecuronium-induced blockade.

The present study also showed significantly earlier tracheal extubation with sugammadex. Patients in the sugammadex group were extubated at 5.9±1.4 minutes, whereas those in the neostigmine-glycopyrrolate group required 17.8±4.6 minutes. This difference of nearly 12 minutes is important in spine surgery, where safe emergence after prone-to-supine repositioning and early neurological assessment are essential. Faster extubation following sugammadex has also been supported by studies evaluating early postoperative respiratory recovery. Ledowski et al. reported favourable recovery characteristics with sugammadex in relation to postoperative neuromuscular recovery and early recovery-room outcomes [15]. Murphy GS et al., compared neostigmine and sugammadex in thoracic surgical patients and found clinically relevant differences in neuromuscular and clinical recovery, highlighting that reversal choice can influence early extubation-related recovery milestones [16]. Huang C et al., further demonstrated better post-extubation respiratory muscle strength after sugammadex than after neostigmine, which supports the present finding that faster objective reversal may translate into earlier and safer extubation when standard extubation criteria are fulfilled [17].

In the present study, PACU stay was significantly shorter in the sugammadex group, whereas total hospital stay did not differ significantly between the groups. Patients receiving sugammadex had a mean PACU stay of 42±10 minutes compared with 58±14 minutes in the neostigmine-glycopyrrolate group. This indicates that sugammadex mainly improved immediate postoperative recovery-unit readiness rather than the complete hospital course. Similar patterns have been observed in published studies, where sugammadex showed benefits in early recovery markers but did not consistently shorten overall hospital stay. Kheterpal S et al., and Li G et al., reported lower postoperative pulmonary complications with sugammadex in large observational analyses, suggesting potential recovery benefits beyond TOF ratio alone [12,18]. However, Togioka BM et al., did not find a clear reduction in postoperative pulmonary complications among older adults in a randomised clinical trial, showing that benefits may vary according to patient risk profile, type of surgery, and study design [19]. In spine surgery, hospital discharge is influenced by pain control, mobilisation, neurological status, wound condition, surgical factors, and institutional discharge protocols. Therefore, the present study's lack of difference in hospital stay is reasonable, even though PACU stay was reduced.

The present study found that haemodynamic parameters and oxygenation at extubation were comparable between the two groups. Heart rate, mean arterial pressure, and SpO_2 did not differ significantly, suggesting that faster reversal with sugammadex did not compromise immediate haemodynamic stability or oxygenation. Bradycardia, however, was significantly more frequent in the neostigmine-glycopyrrolate group. This finding is pharmacologically plausible because neostigmine increases cholinergic activity and requires anticholinergic coadministration to reduce muscarinic effects. Similar safety observations have been reported in comparative studies and meta-analyses. Murphy GS et al., noted clinically relevant differences in recovery profiles between sugammadex and neostigmine in surgical patients requiring neuromuscular reversal [16]. Olesnicky BL et al., and Zhu N and Li Y also reported that sugammadex was associated with a lower incidence of residual blockade and fewer recovery-related adverse events than neostigmine in pooled analyses [13,14]. In the present study, hypotension, postoperative nausea and vomiting, and residual neuromuscular blockade were numerically more frequent in the neostigmine-glycopyrrolate group but did not reach statistical significance, probably because the study was not powered for uncommon adverse events.

The present study should be interpreted within the specific clinical context of adult elective spine surgery. Sugammadex improved objective TOF recovery, shortened extubation time, reduced PACU stay, and lowered bradycardia without affecting hospital stay or causing major haemodynamic instability. These findings are relevant because early postoperative neurological assessment is a key concern after spine surgery, and residual weakness may delay assessment or reduce its reliability. At the same time, recovery after anaesthesia is broader than TOF recovery alone. Han J et al., evaluated the quality of recovery after reversal of neuromuscular blockade and emphasised that patient-centred recovery outcomes require validated tools rather than reliance only on physiological recovery markers [20]. Therefore, the present study supports the benefit of sugammadex for speed and early safety-related recovery parameters, but it should not be interpreted as evidence of improved validated quality of recovery. In Indian tertiary-care practice, the higher acquisition cost of sugammadex also needs consideration. Its use may be most justified in selected spine-surgery patients in whom rapid extubation, early neurological assessment, avoidance of residual blockade, or efficient recovery-room turnover is clinically important [14,15,20].

Limitation(s)

The study was conducted in a single centre and the number of patients was 60, which restricts applicability to other anaesthesia techniques and spine surgery. Double blinding could not be maintained because the anaesthesiologist administering the reversal agent was aware of group allocation; however, outcome assessment was performed by an observer blinded to the treatment group. Long-term pulmonary outcomes, cost analysis and validated patient-reported quality-of-recovery scores were not reported. The study only involved ASA I-II patients and may not be directly applied to high-risk patients or obese or selected elderly patients.

CONCLUSION(S)

Sugammadex in generally anaesthetised adult patients undergoing elective spine surgery induced significantly faster reversal of vecuronium-induced neuromuscular blockade compared to neostigmine and glycopyrrolate. It reduced the time required to achieve a TOF ratio ≥0.9. No significant difference in hospital stay was seen, suggesting the main benefit was seen during the immediate recovery period. Bradycardia was less common with sugammadex, and there were no serious adverse events. Quantitative monitoring-guided sugammadex reversal may be a valuable approach to ensure a timely, safe and reliable emergence after spine surgery, particularly when rapid neurologic assessment and quick turnaround of the recovery room is a critical clinical need.

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