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ORIGINAL ARTICLE

A novel stimulating electrode attachment method designed to maintain electromyography-based neuromuscular monitoring detectability during laparoscopic surgery: a single-center randomized, double-blind, controlled pilot study

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Abstract

Purpose We evaluated the electromyography (EMG)-based neuromuscular monitoring detectability of our novel stimulating electrode attachment method compared to the original Nihon–Kohden (Tokyo, Japan) attachment method.

Methods This single-center randomized, double-blind, controlled pilot study enrolled 32 patients aged ≥ 18 years, undergoing scheduled laparoscopic surgery. The EMG electrode NM-345Y™ was attached to one forearm using the Nihon–Kohden method (Pattern N–K) and the other forearm using our novel method (Pattern Cross). The allocation to each attachment method was determined post-randomization. In Pattern Cross, the NM-345Y™ was attached such that the line connecting the anode and cathode crosses the ulnar nerve. Patients received 0.9 mg/kg rocuronium after calibration with the forearm in 90-degree supination. Following tracheal intubation, the forearm was positioned in 0-degree pronation. Intraoperatively, 0.2 mg/kg rocuronium was administered if the train-of-four (TOF) count one persisted for 1 min on either side. Post-surgery, the forearm position was returned to 90-degree supination, and rocuronium was antagonized with sugammadex. TOF and post-tetanic count (PTC) were simultaneously measured bilaterally every 15 s and 5 min, respectively, from post-calibration to tracheal extubation.

Results The time to first PTC appearance was significantly shorter by 33 min in the Pattern Cross group than in the Pattern N–K group (95% Confidence interval: 1–66, $p = 0.043$). Following sugammadex administration, TOF ratios ≥ 0.9 were achieved in 72% of patients in the Pattern N–K group and 97% of those in the Pattern Cross group ($p = 0.025$).

Conclusions Crossing the line connecting the anode and cathode with the ulnar nerve stabilizes EMG-based neuromuscular monitoring detectability.

Keywords Electromyography · Forearm position · Neuromuscular monitoring detectability · Neuromuscular blocking agents · Stimulating electrode attachment

Introduction

The pharmacokinetics of neuromuscular blocking agents administered during general anesthesia are influenced by various factors, such as age and hepatic and renal functions; their efficacy varies among individuals [1]. Therefore, neuromuscular monitoring is essential to prevent adverse events due to underdosing and/or overdosing of neuromuscular blocking agents [2–6]. In electromyography (EMG)-based neuromuscular monitoring using an EMG electrode (NM-345Y™, Nihon–Kohden Corporation, Tokyo, Japan), it is recommended that the EMG electrode should be attached

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such that the distal ulnar corner of the stimulating electrode is aligned with the bottom of the pisiform bone and the stimulating electrode itself is aligned with the ulnar nerve [7, 8]. However, there have been cases in which the EMG-based neuromuscular monitoring detectability deteriorated when the forearm position changed from the calibrated position using the original method recommended by Nihon–Kohden Corporation as described above [8]. As a clue to the deterioration of monitoring detectability, a previous study reported that the ulnar nerve may be separated from the skin at the stimulating electrode site and out of the electrode's stimulation range when the forearm is supinated or pronated during ulnar nerve stimulation in EMG measurements [9].

In our previous study on healthy adult participants, we devised a method for attaching an EMG electrode where the line connecting the centers of the anode and cathode of the stimulating electrode crosses the ulnar nerve to improve the detectability of EMG-based neuromuscular monitoring [8, 10]. The results suggest that the detectability of EMG-based neuromuscular monitoring may be less affected by changes in the forearm position with our novel attachment method. However, the clinical implications of our novel attachment method need to be validated in patients undergoing general anesthesia and neuromuscular blockade. This study aimed to evaluate the monitoring detectability of our novel stimulating electrode attachment method compared to the original attachment method recommended by Nihon–Kohden concerning the recovery process of the muscle response after rocuronium administration during general anesthesia.

Methods

This single-center randomized, double-blind, controlled pilot study was conducted at Nagasaki University Hospital (Nagasaki, Japan). This study was approved by the Institutional Review Board of Nagasaki University Hospital, Nagasaki, Japan (approval number: 23082102) on August 29th, 2023, and followed the principles of the Declaration of Helsinki. The study was registered with the UMIN Clinical Trials Registry (trial registry number; UMIN000051981, registration date: August 23rd, 2023) before participant enrollment. Written informed consent was obtained from each participant before participation in the study. This study adheres to the guidelines of the Consolidated Standards of Reporting Trials.

Participant selection

The recruitment period for the study participants was from August 30th, 2023, to November 13th, 2023. The study participants were patients aged 18 years or older with lower gastrointestinal, hepatobiliary, or gynecologic diseases undergoing scheduled laparoscopic surgery with 0-degree pronation in both upper limb positions (Fig. 1A). Patients with neuropathy or neuromuscular disease, those with pacemakers or implantable cardioverter–defibrillators, pregnant women, patients with fragile skin at the measurement site, those with a history of surgery on the measurement limb, those with a history of allergy to rocuronium or sugammadex, and those undergoing hemodialysis were excluded.

Methods of electrode attachment and intervention

The study participants were placed in a horizontal supine position on the operating table with their elbows extended and forearms in 90-degree supination (Fig. 1B). Both forearms were wiped clean with alcohol cotton swabs before the EMG electrode seal was attached. The NM-345Y™ was attached to one forearm of the study participants using the attachment method originally recommended by Nihon–Kohden (Pattern N–K), as described in the Instruction Manual of the electromyographic module (AF201-P™, Nihon–Kohden Corporation, revised on June 6, 2022) (Fig. 2A). In Pattern N–K, the distal ulnar corner of the stimulating electrode was aligned with the bottom of the pisiform bone as identified by palpation, and the stimulating electrode itself was attached along the ulnar nerve. On the other forearm, the center of the distal edge of the stimulating electrode was aligned with the bottom of the pisiform bone. Subsequently, the stimulating electrode was attached such that the line connecting the center of the electrode's distal edge and its proximal radial corner was parallel to the central axis of the forearm. Consequently, the anode of the stimulating electrode deviated approximately 10 degrees to the ulnar side (Fig. 2B). In this attachment method, we observed that the line connecting the centers of the anode and cathode of the stimulating electrode crossed the ulnar nerve in all study participants examined in a previous study [10]. Therefore, we named this group "Pattern Cross." In both patterns, the reference and active electrodes were attached according to the recommendations of the Nihon–Kohden Corporation, targeting the abductor

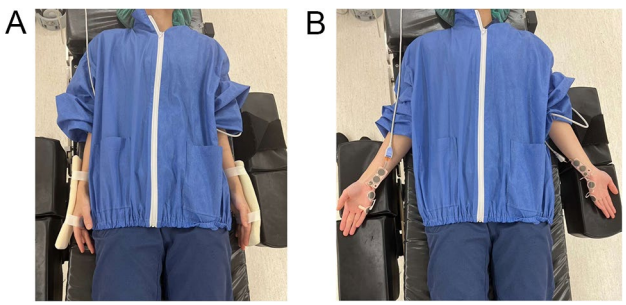

Fig. 1 Two forearm limb positions. **A** Forearms in 0-degree pronation. **B** Forearms in 90-degree supination

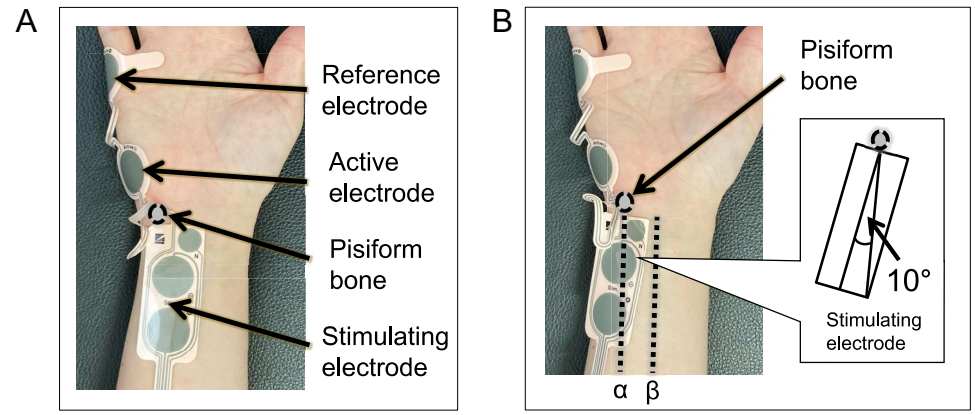

Fig. 2 Electromyography electrode NM-345Y™ and the two attachment patterns. **A** Pattern N–K. **B** Pattern Cross. Line α represents the line connecting the center of the stimulating electrode's distal edge and its proximal radial corner, and Line β represents the central axis of the forearm. The stimulating electrode is attached so that Line α and Line β are parallel

digiti minimi muscle, and no ultrasound device was used to identify the ulnar nerve in the forearm while attaching the NM-345Y™. Each NM-345Y™ was connected to the muscle relaxation display unit (VA-201R™, Nihon–Kohden Corporation, Tokyo, Japan) via an individual EMG-based muscle relaxation module AF-201P™.

Anesthesia management and neuromuscular monitoring

Upon arrival in the operating room, all study participants were monitored with electrocardiogram, noninvasive blood pressure, and pulse oximetry. Propofol 0.5–2.0 mg/kg and remifentanil 0.25–1.0 μg/kg/min were administered, and calibration was performed when the study participants lost consciousness to measure stimulus current values and sensitivity. After calibration, rocuronium 0.9 mg/kg was administered while train-of-four (TOF) measurements were initiated. Subsequently, TOF measurements were repeated every 15 s, and post-tetanic count (PTC) measurements were performed every 5 min if the TOF count was zero. The timing of the calibration, TOF, and PTC measurements were matched between the left and right forearms. After the first dose of rocuronium, tracheal intubation was performed after confirming that the TOF count was zero for both the N–K and Cross Patterns. After the anesthesia induction, the bilateral forearm positions were changed to 0-degree pronation. Splints were used on both forearms to fix their positions (Fig. 1A).

Total intravenous anesthesia was maintained using propofol, remifentanil, and rocuronium. Intraoperatively, rocuronium was administered at an additional bolus dose of 0.2 mg/kg if TOF count one was sustained for 1 min by the EMG-based neuromuscular monitoring on either side. No additional rocuronium dose was administered after the start of wound closure. After completing the surgery, the bilateral forearm positions were changed to 90-degree supination. Sugammadex was administered in accordance with the greater PTC or TOF counts measured on the bilateral forearms at the end of continuous doses of propofol and remifentanil. Sugammadex was administered at 2 mg/kg if the TOF counts were two or greater and 4 mg/kg if they were less than two.

Randomization and blinding

The attachment method was applied to each forearm was determined after randomization and assignment of study participants according to whether the Pattern Cross was attached to the dominant or non-dominant hand. The envelope method was used for randomization in this study. Because 32 participants were assumed to be eligible for the study, one opaque envelope was filled with a sheet of paper labeled with either the dominant or non-dominant hand, making 16 envelopes with the dominant hand paper and 16 envelopes with the non-dominant hand paper. The assignment of the study participants was determined by selecting one of the 32 envelopes, opening it, and checking the paper marked as the dominant or non-dominant hand. The study participants and responsible anesthesiologists were not notified of the determined combinations to ensure double-blinding. Therefore, another anesthesiologist with knowledge of the combination attached the NM-345Y™ electrodes and removed them when the study participants left the operating room.

Data collection and study endpoints

Baseline participant demographics and surgery-related and neuromuscular monitoring-related data were obtained from all study participants. Data on all study participants were retrieved through our electronic medical record system (MegaOakHR; NEC Co. Ltd., Tokyo, Japan), anesthesia records (Prescient® OR; FUJIFILM Medical Co. Ltd., Tokyo, Japan), and the respective muscle relaxation display unit VA-201R™.

The primary endpoint of this study was the time to the first PTC appearance after the first dose of rocuronium

(0.9 mg/kg). We defined the time until the PTC became measurable as an index of reduced sensitivity due to the location of the stimulating electrode when assessing the state of muscle relaxation. By measuring the time until the PTC became measurable on both forearms, we aimed to clarify the differences in monitoring results between different attachment patterns applied to the same patient simultaneously.

The secondary endpoints included the stimulus current value and sensitivity at calibration, total PTC every 1 h after forearm position change to 0-degree pronation, time to the TOF counts of one, two, three, and four appearances after the last rocuronium administration, the TOF ratio and the values of the first twitch response (T1) amplitude before and after sugammadex administration, and the proportion of study participants with TOF ratios greater than 0.9 after sugammadex administration. We also investigated the attachment patterns in which TOF count one was observed when an additional bolus dose of rocuronium 0.2 mg/kg was administered intraoperatively. Furthermore, we evaluated the detectability of the EMG-based neuromuscular monitoring with each attachment pattern throughout the intraoperative period for each patient by a Japanese Medical Specialty Board Certified Doctor of Anesthesiology who was not involved in the planning, data collection, or statistical analysis of this study. Specifically, graphs describing the timing of rocuronium and sugammadex administration, and the time course of TOF counts and PTC were presented to assess whether the detectability of the EMG-based neuromuscular monitoring in each attachment pattern was "adequate" or "inadequate" (Fig. 3).

The presence of perioperative adverse events associated with overdosing and underdosing of neuromuscular blocking agents was also investigated. Perioperative adverse events include intraoperative body movements, formation of subcutaneous emphysema, and neuromuscular blockade symptoms following sugammadex antagonism.

Statistical analyses

For the purpose of sample size calculations, the time to the first PTC appearance after the first dose of rocuronium was investigated using clinical data from 10 patients with stimulating electrodes attached in Pattern N–K and 10 patients with stimulating electrodes attached in Pattern Cross. All 20 patients underwent laparoscopic surgery with the forearm in 0-degree pronation. The results showed that the mean difference in the time to the first PTC appearance after the first dose of rocuronium between the Pattern N–K and Pattern Cross groups was 13 min (standard deviation, 24 min). These were paired data, and the number of required participants was calculated using a one-sample *t* test with a significance level of 0.05 and a power of 80%, resulting in 29 participants. Considering a dropout rate of 10%, the target number of study participants was set at 32. The sample size was calculated using SAS version 9.4 (SAS Institute Inc., Cary, NC, USA).

Data are presented as the mean (standard deviation [SD]) or number of participants (%). For the primary endpoint, "time to first PTC appearance after the first dose of rocuronium" in Pattern N–K and Pattern Cross, the distribution of each attachment pattern for all study participants is shown in box plots and the cumulative probability of the first PTC as the event was illustrated using the Kaplan–Meier method. A paired *t* test was employed to compare the patterns. This test was two-tailed, and p-values < 0.05 indicated statistical significance. Secondary endpoints were compared between the patterns using the same method as the primary endpoint. These p-values should be interpreted exploratorily. The difference and ratio of the number of PTC per hour between the attachment methods were estimated using linear and Poisson regression models with the number of PTC per hour as the outcome variable. Preliminary studies have shown that outliers occur in Pattern N–K. However, a paired *t*-test, which assumes a normal distribution, was employed to analyze the primary endpoint. This is because it is meaningful to compare the distributions among the patterns, including outliers. Nonetheless, considering that the *t*-test may not be valid and to ascertain the usefulness of the Pattern Cross even when outliers are excluded, a supplementary paired *t*-test was conducted, excluding outliers up to the initial occurrence of PTC. Outliers were defined as observed values that satisfy the following criteria: $Q3 + (Q3 - Q1) \times 1.5 \leq value$, $Q1 - (Q3 - Q1) \times 1.5 \geq value$, where the first quartile (25th percentile) is Q1 and the third quartile (75th percentile) is Q3. Statistical analyses were performed using JMP® Pro 16.0.0 (SAS Institute Inc., Cary, NC, USA) and R version 4.2.2 (R Foundation for Statistical Computing, Vienna, Austria).

Results

A total of 32 participants were evaluated for eligibility, and no participants were excluded. Of the 32 participants enrolled, 29 were finally evaluated, because the data for three participants were lost owing measurement errors at calibration. A summary of participant demographics and surgery-related data is presented in Table 1. Patterns N–K and Cross were applied to the dominant hand in 15 (52%) and 14 (48%) study participants, respectively. The cuffs for the noninvasive blood pressure measurement were placed on the forearms of 14 patients (48%) in the Pattern N–K group and 15 patients (52%) in the Pattern Cross group.

The results of the primary and secondary endpoints are presented in Table 2. For the primary endpoint, the mean

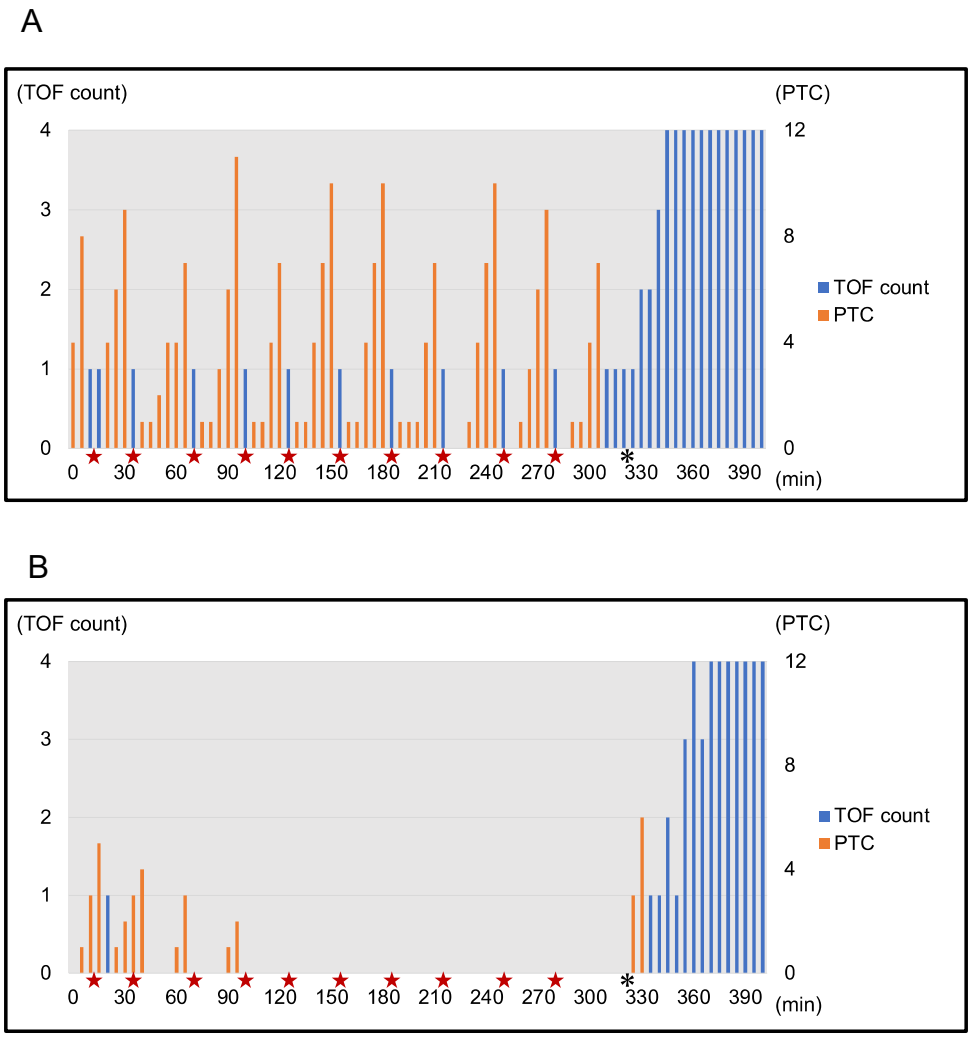

Fig. 3 Graphs to assess whether the detectability of EMG-based neuromuscular monitoring in each attachment pattern is "adequate" or "inadequate". The bars in each graph indicate TOF count and PTC. The horizontal axis indicates the time course every 5 min after the forearm position was changed to 0-degree pronation. Star symbols indicate when rocuronium 0.2 mg/kg was administered. The asterisk indicates when the forearm position was changed to 90-degree supination after surgery. **A** Example of "adequate" neuromuscular monitoring detectability: the TOF counts and PTC disappear after rocuronium bolus administration and recover over time, even after the forearm position change. **B** Example of "inadequate" neuromuscular monitoring detectability; the TOF counts and PTC are difficult to measure when the forearm position changes. Furthermore, although the TOF and PTC appear after the forearm position is returned to 90-degree supination postoperatively, the trend in their appearance does not fully reflect recovery from the state of muscle relaxation. For example, the TOF counts increased from one to two without additional neuromuscular blocking agent administration but then returned to one. *TOF* train-of-four, *PTC* post-tetanic count

time to the first PTC appearance was 62 min (SD: 87 min) in Pattern N–K and 29 min (SD: 16 min) in Pattern Cross. Pattern Cross was significantly shorter by 33 min than Pattern N–K (95% confidence interval [CI] 1–66, $p = 0.043$). In addition, the boxplot and cumulative probability by the Kaplan–Meier method also showed a shorter time to the first PTC in Pattern Cross than in Pattern N–K (Fig. 4). In Pattern N–K, the PTC never appeared after the forearm position was changed to 0-degree pronation in two study participants.

Secondary endpoints were categorized into two parts: one for neuromuscular monitoring during calibration and surgery, and the other for neuromuscular monitoring from the final dose of rocuronium until 5 min after sugammadex administration (Table 2). Pattern Cross had significantly lower stimulus current values ($p < 0.001$) and significantly greater sensitivity at calibration ($p = 0.001$) than Pattern N–K. The total PTC every 1 h after changing the forearm position to 0-degree pronation was significantly greater in Pattern Cross than in Pattern N–K in each period. Furthermore, Pattern Cross showed a higher frequency of PTC events per 1 h compared to Pattern N–K, with an average increase of 19 events per hour (95% CI 8.2–30) and a 2.05

Table 1 Summary of participant demographics and surgery-related data

Characteristics	$N=29$
Age (years)	55 (16)
Height (cm)	159 (8)
Weight (kg)	61 (11)
BMI (kg/m^2)	24 (5)
ASA physical status	
Class 1	7 (24%)
Class 2	21 (73%)
Class 3	1 (3%)
Preoperative body temperature (°C)	36.5 (0.3)
Preoperative blood test data	
AST (IU/L)	20 (8)
ALT (IU/L)	18 (12)
eGFR (mL/min/m^2)	71 (17)
Diabetes mellitus	3 (10%)
Liver disease	0 (0%)
Chronic kidney disease	1 (3%)
Cerebrovascular disease	2 (7%)
Surgical organ	
Lower gastrointestinal tract	13 (45%)
Uterus and appendages	14 (48%)
Liver and biliary tract	2 (7%)
Surgical position	
Supine position	2 (7%)
Open-leg position	13 (45%)
Lithotomy position	14 (48%)
Surgery time (minutes)	220 (92)
Anesthesia time (minutes)	331 (102)
Laparoscopic time (minutes)	190 (106)
Intraoperative fluid volume	
Crystalline solution (mL)	1722 (611)
Colloidal liquid (mL)	222 (326)
Intraoperative urine volume (mL)	687 (711)
Intraoperative blood loss (mL)	80 (156)
Intraoperative fluid balance (mL)	1178 (568)

Data are presented as mean (standard deviation) or the number of participants (%)

BMI body mass index, *ASA* American Society of Anesthesiologist, *AST* aspartate aminotransferase, *ALT* alanine aminotransferase, *IU* international unit, *eGFR* estimated glomerular filtration rate

times higher frequency (95% CI 1.97–2.15). The total number of additional bolus doses of rocuronium (0.2 mg/kg) for all study participants was 211. During these additional bolus doses of rocuronium, TOF counts one was observed 16 times (8%) in Pattern N–K alone, 119 times (56%) in Pattern Cross alone, and 76 times (36%) in both patterns.

The time to the TOF counts of one, two, three, and four appearances after the last rocuronium administration was shorter in Pattern Cross than in Pattern N–K. The TOF ratio and T1 amplitude at 1, 3, and 5 min after sugammadex administration were greater in Pattern Cross than in Pattern N–K. Twenty-one participants (72%) in Patterns N–K and 28 participants (97%) in Pattern Cross recovered to a TOF ratio of 0.9 or higher after sugammadex administration ($p=0.025$). Furthermore, the number of study participants evaluated by the Japanese Medical Specialty Board Certified Doctors of Anesthesiology as having adequate neuromuscular monitoring detectability was 15 participants (52%) in Patterns N–K and 28 participants (97%) in Pattern Cross ($p<0.001$). None of the study participants developed intraoperative body movements, formation of subcutaneous emphysema, or neuromuscular blockade symptoms after sugammadex antagonism.

Three cases were excluded from the supplementary analysis because they were outliers. The results showed that Pattern N–K was 35 min (SD: 18 min) and Pattern Cross was 26 min (SD: 13 min), indicating that Pattern Cross was 9.6 min shorter than Pattern N–K (95% CI 5.2–14.1, $p<0.001$) (Supplementary material 1).

Discussion

In this study, we evaluated the clinical implications of the NM-345Y™ attachment method in which the anode of the stimulating electrode deviated approximately 10 degrees to the ulnar side, with the line connecting the centers of the stimulating electrode's anode and cathode crossing the ulnar nerve, using the pisiform bone as a landmark. The results showed that the detectability of the EMG-based neuromuscular monitoring after changing the forearm position to 0-degree pronation was higher with our novel attachment method than with the original method recommended by Nihon–Kohden. In addition, the detectability of neuromuscular monitoring after returning the forearm position to 90-degree supination postoperatively was also superior for Pattern Cross compared to Pattern N–K. Therefore, these results suggest that Pattern Cross is a stimulating electrode attachment method that can maintain sufficient neuromuscular monitoring detectability throughout the perioperative period.

In a previous experimental study on healthy volunteers, we investigated the stimulus current values at calibration in the 90-degree supination and 0-degree pronation forearm positions [8]. The results showed that in Pattern N–K, the stimulus current values at calibration increased significantly with forearm pronation, whereas in Pattern Cross, there was no significant difference between these values before and after the forearm position change. These findings may reflect the shorter distance between the central axis of the stimulating electrode and the ulnar nerve in Pattern Cross than in Pattern N–K after forearm pronation. In the present study

Table 2 Primary and secondary endpoints

Endpoint	Pattern N–K ($N=29$)	Pattern Cross ($N=29$)	p-value
Primary endpoint			
Time to first PTC appearance (minutes)	62 (87)	29 (16)	0.043
Difference (95%CI)[a]		33 (1 to 66)	
Secondary endpoint			
Summary of neuromuscular monitoring-related data at calibration and during surgery			
Stimulus current value at calibration (mA)	45 (15)	33 (13)	< 0.001
Sensitivity at calibration (mV)	8.7 (3.5)	10.8 (3.6)	0.001
Total PTC every 1 h after forearm position change to 0-degree pronation (counts)			
Within the first hour	22 (24) [$n=29$]	35 (22) [$n=29$]	< 0.001
Within the second hour	27 (25) [$n=29$]	52 (26) [$n=29$]	< 0.001
Within the third hour	19 (19) [$n=25$]	46 (26) [$n=25$]	< 0.001
Within the fourth hour	21 (24) [$n=19$]	42 (22) [$n=19$]	0.003
Within the fifth hour	19 (23) [$n=13$]	44 (30) [$n=13$]	0.010
Total number of PTC per hour			
Difference (95%CI)[b]		19 (8.2 to 30)	< 0.001
Ratio (95%CI)[c]		2.05 (1.97–2.15)	< 0.001
Summary of neuromuscular monitoring-related data during the period from the last dose of rocuronium to 5 min after sugammadex administration			
Time from last dose of rocuronium to TOF appearance (minutes)			
TOF one appearance	45 (28)	32 (17)	0.001
TOF two appearance	57 (27)	49 (23)	0.004
TOF three appearance	61 (25)	56 (25)	0.014
TOF four appearance	63 (25)	57 (24)	0.010
TOF ratio before and after sugammadex administration (%)			
Just before sugammadex	21 (30)	30 (31)	0.057
1 min after sugammadex	38 (38)	59 (33)	0.005
3 min after sugammadex	64 (46)	88 (23)	0.005
5 min after sugammadex	68 (47)	95 (19)	0.003
T1 amplitude before and after sugammadex administration (%)			
Just before sugammadex	31 (35)	52 (37)	0.002
1 min after sugammadex	44 (37)	67 (31)	0.002
3 min after sugammadex	58 (41)	82 (22)	0.002
5 min after sugammadex	58 (43)	86 (21)	0.001
Recovered to TOF ratio of 0.9 or higher after sugammadex	15 (52%)	28 (97%)	< 0.001

Data are presented as mean (standard deviation) or the number of participants (%)

CI confidence interval, *PTC* post-tetanic count, *TOF* train-of-four, *T1* first twitch response

[a]Crude Estimates

[b]Estimate with linear regression model

[c]Estimate with Poisson regression model. The offset term is logarithm of total PTC observation time

of patients undergoing laparoscopic surgery under general anesthesia, Pattern Cross had a significantly shorter time to first PTC appearance and a higher frequency of PTC events per 1 h after the forearm position changed to 0-degree pronation compared to Pattern N–K. Furthermore, Pattern Cross captured the TOF response after the last dose of rocuronium more sensitively than Pattern N–K, despite the lower stimulus current value and greater sensitivity at calibration. Thus, EMG-based neuromuscular monitoring with Pattern Cross may have captured muscle response recovery more sensitively after neuromuscular blockade because the distance between the stimulating electrode and the ulnar nerve did not increase even after the forearm was pronated.

Inaccurate neuromuscular monitoring is dangerous because it can result in the development of adverse events due to overdosing and/or underdosing of neuromuscular blocking agents. In the present study, most of the additional intraoperative administrations of rocuronium were triggered

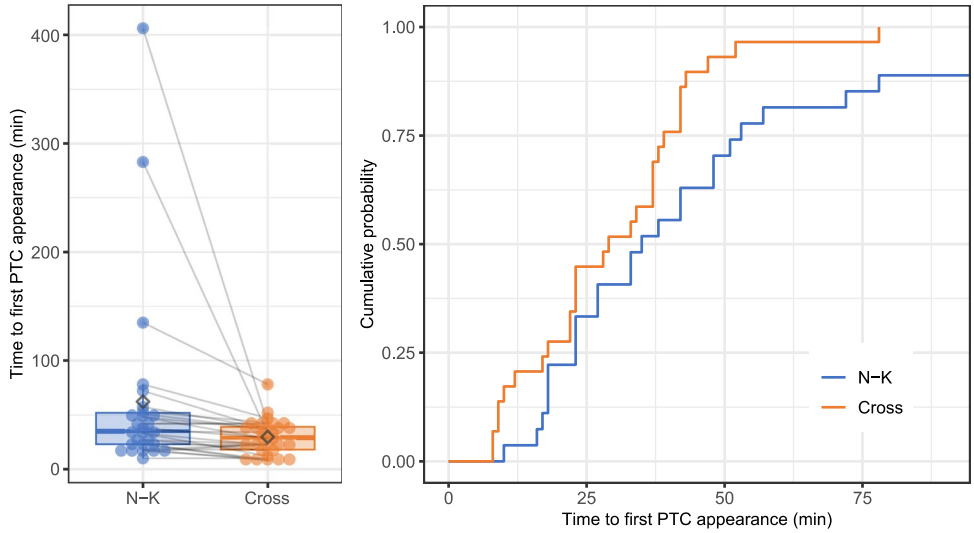

Fig. 4 Time to first PTC appearance in Pattern N–K and Pattern cross. **A** Graph visualizing the time to the first PTC appearance for all study participants. Boxplots show the median (horizontal bar) with 25th–75th percentiles (box) of the time to the first PTC appearance. Dots indicate individual values. Gray lines connect data from the same study participants. Gray diamonds indicate the mean value in each attachment pattern. **B** The cumulative probability of the first PTC as an event by attachment pattern was illustrated using the Kaplan–Meier method. *PTC* post-tetanic count

by the appearance of TOF count one in Pattern Cross. As a result, none of the study participants developed intraoperative body movements, formation of subcutaneous emphysema, or neuromuscular blockade symptoms after sugammadex administration. In addition, Pattern Cross was evaluated by the Japanese Medical Specialty Board Certified Doctors of Anesthesiology as having adequate monitoring detectability in 97% of the study participants. Based on these results, the Pattern Cross adequately monitored the neuromuscular blocking status caused by intermittent rocuronium boluses even when the forearm was in 0-degree pronation. By contrast, neuromuscular monitoring using Pattern N–K during surgery involving forearm pronation may incorrectly assess the depth of the neuromuscular blockade. Surprisingly, with Patterns N–K, the PTC never appeared after changing the forearm position to 0-degree pronation in the two study participants. This suggests that the ulnar nerve left the skin at the stimulating electrode site after forearm pronation and was outside the stimulation range of the electrode. If this situation occurs intraoperatively, anesthesiologists would lose their index to administer neuromuscular blocking agents. Furthermore, in Pattern N–K, although only 72% of patients recovered to a TOF ratio of 0.9 or higher, which is considered the standard for extubation, none of the study participants had residual neuromuscular blockade symptoms. Therefore, Pattern N–K demonstrated less accurate neuromuscular monitoring compared with Pattern Cross, not only during forearm pronation but also after returning to the initial forearm position. In recent years, reports of residual or recurrent postoperative neuromuscular blocks have increased [11–13]. These adverse events might have been caused by the inappropriate administration of rocuronium or sugammadex, sometimes due to inadequate neuromuscular monitoring [14].

As a matter of fact, the January 2023 revised Instruction Manual for the Nihon–Kohden AF-201P™ updated the attachment position of the NM-345Y™ stimulating electrode (Supplementary material 2, provided by Nihon–Kohden Corporation). Nihon–Kohden Corporation recommends a modified attachment method in which the distal radial corner of the stimulating electrode is aligned with the bottom of the pisiform bone, and the stimulating electrode is attached along the forearm axis. As a result, the stimulating electrode would be attached with greater ulnar deviation than with the original manufacturer-recommended attachment method. This revision was made in response to feedback from the anesthesiologists, who were concerned that the original attachment method would result in less accurate measurements during forearm pronation. However, to the best of our knowledge, no study has examined the clinical implications of this modified stimulating electrode attachment method. Additional research should be conducted to compare the detectability of neuromuscular monitoring during forearm pronation using three different attachment methods: the original manufacturer-recommended attachment method (Pattern N–K in this study), the modified manufacturer-recommended attachment method, and Pattern Cross.

This study had a few limitations. First, we have yet to investigate how the relationship between the central axis of the stimulating electrode and the position of the ulnar

nerve actually changes with forearm pronation in Pattern Cross. Judging from the previous study [10], it seems most likely that the central axis of the stimulating electrode crossed the ulnar nerve at least in the initial forearm position in the present study. However, it is unclear whether the central axis of the stimulating electrode really crossed the ulnar nerve after pronation or supination. The results of the present study might imply that the central axis of the stimulating electrode was minimally displaced from the ulnar nerve. Second, the neuromuscular monitoring detectability in this study was validated only in 90-degree supination and 0-degree pronation forearm positions. Therefore, the detectability of neuromuscular monitoring in other forearm pronation positions should be evaluated in future studies. Third, while observation of the EMG waveform itself is considered important to assess the detectability of EMG-based neuromuscular monitoring [15], the EMG waveform information during neuromuscular monitoring was not an endpoint in the present study. However, patients in this study received an additional bolus dose of rocuronium at 0.2 mg/kg if the TOF count one was sustained for 1 min by the EMG-based neuromuscular monitoring on either side. Consequently, the amplitude of the EMG waveform was minimal for a long time during the forearm pronation period, making it difficult to evaluate the changes in the EMG waveform compared to the time of calibration.

In conclusion, a novel attachment method in which the line connecting the centers of the anode and cathode of the NM-345Y™ stimulating electrode likely crosses the ulnar nerve stabilizes the detectability of EMG-based neuromuscular monitoring, regardless of forearm position changes. This novel attachment method enables the maintenance of stable neuromuscular monitoring detectability throughout the perioperative period and may prevent adverse events due to the underdosing and/or overdosing of neuromuscular blocking agents. However, further studies are required to evaluate the clinical implications and versatility of this attachment method.

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Declarations

Conflict of interest The authors have no conflicts of interest to declare.

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