ANESTHESIOLOGY

Quantitative Neuromuscular Monitoring in Clinical Practice: A Professional Practice Change Initiative

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EDITOR'S PERSPECTIVE

What We Already Know about This Topic

- Quantitative (train-of-four ratio) monitoring is the definitive standard for assessing recovery from neuromuscular block
- Residual neuromuscular block, defined as a train-of-four ratio less than 0.9, is commonly observed in patients given nondepolarizing neuromuscular blocking drugs perioperatively
- Inadequate reversal of residual neuromuscular block is associated with postoperative morbidity and mortality
- Despite guidelines from several professional societies advocating quantitative neuromuscular monitoring for neuromuscular blocking drug management, it is infrequently used

What This Article Tells Us That Is New

- A departmental professional practice initiative began with the goal of documenting a train-of-four ratio greater than or equal to 0.90 for all patients given a nondepolarizing neuromuscular blocking drug
- This retrospective assessment of the implementation of documenting train-of-four ratios greater than or equal to 0.9 before extubation improved from 1% (2 of 172) of cases in November 2016 to 93% (250 of 269) of cases in December 2020
- Attaining this endpoint required not only placing a quantitative monitor in each anesthetizing location but also ongoing educational efforts and follow-up

ABSTRACT

Background: Residual neuromuscular blockade can be avoided with quantitative neuromuscular monitoring. The authors embarked on a professional practice initiative to attain documented train-of-four ratios greater than or equal to 0.90 in all patients for improved patient outcomes through reducing residual paralysis.

Methods: The authors utilized equipment trials, educational videos, quantitative monitors in all anesthetizing locations, and electronic clinical decision support with real-time alerts, and initiated an ongoing professional practice metric. This was a retrospective assessment (2016 to 2020) of train-of-four ratios greater than or equal to 0.9 that were documented before extubation. Anesthesia records were manually reviewed for neuromuscular blockade management details. Medical charts of surgical patients who received a neuromuscular blocking drug were electronically searched for patient characteristics and outcomes.

Results: From pre- to postimplementation, more patients were assigned American Society of Anesthesiologists Physical Status III to V, fewer were inpatients, the rocuronium average dose was higher, and more patients had a prereversal train-of-four count less than 4. Manually reviewed anesthesia records (n = 2,807) had 2 of 172 (1%) cases with documentation of train-of-four ratios greater than or equal to 0.90 in November 2016, which was fewer than the cases in December 2020 (250 of 269 [93%]). Postimplementation (February 1, 2020, to December 31, 2020), sugammadex (650 of 935 [70%]), neostigmine (195 of 935 [21%]), and no reversal (90 of 935 [10%]) were used to attain train-of-four ratios greater than or equal to 0.90 in 856 of 935 (92%) of patients. In the electronically searched medical charts (n = 20,181), postimplementation inpatients had shorter postanesthesia care unit lengths of stay (7% difference; median [in min] [25th, 75th interquartile range], 73 [55, 102] to 68 [49, 95]; $P < 0.001$), pulmonary complications were less (43% difference; 94 of 4,138 [2.3%] to 23 of 1,817 [1.3%]; $P = 0.010$; –1.0% difference [95% CI, –1.7 to –0.3%]), and hospital length of stay was shorter (median [in days] [25th, 75th], 3 [2, 5] to 2 [1, 4]; $P < 0.001$).

Conclusions: In this professional practice initiative, documentation of train-of-four ratios greater than or equal to 0.90 occurred for 93% of patients in a busy clinical practice. Return-of-strength documentation is an intermediate outcome, and only one of many factors contributing to patient outcomes.

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The dangers of paralyzing a patient with neuromuscular blocking drugs are well recognized. Despite advances in anesthetic management, approximately half of all patients arriving to the postanesthesia care unit (PACU) suffer from residual blockade defined as a train-of-four ratio less than 0.9.[1]

Clinicians employ various methods, most of which have poor sensitivity, to determine if a neuromuscular blocking drug effect has regressed.[2,3] Using time from drug

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administration is unreliable because of the variable duration of blockade between patients for all neuromuscular blocking drugs. For example, a single dose of rocuronium may take more than 2 h to resolve.[4] Unfortunately, physical examination maneuvers such as head lift and hand squeeze lack the sensitivity and specificity needed to identify residual blockade.[5,6] Train-of-four peripheral nerve stimulation with subjective no-fade assessment is also limited as it only verifies that the train-of-four ratio has reached 0.4. Even when subjective monitoring was optimized in a research setting, residual blockade occurred in more than one third of patients.[7]

Residual blockade may contribute to a longer length of stay in the PACU,[8] more oxygen requirements in the PACU,[9] airway collapse,[10] airway obstruction,[11] severe hypoxia in the PACU, and lower quality of recovery.[12] Additionally, the use of neuromuscular blocking drugs and presumed inadequate reversal has been associated with postoperative hypoxia and desaturation, reintubation and unplanned admission to the intensive care unit (ICU),[13] pulmonary complications,[14,15] longer PACU and hospital lengths of stay,[16] and increased mortality.[17]

Anesthesiologists philosophically place emphasis on patient safety, which includes education and advocacy from professional societies, to fully rescue patients from their state of paralysis before awakening. The U.S. Food and Drug Administration (Silver Spring, Maryland) has approved devices to measure train-of-four ratios (quantitative monitoring) that provide reproducible and accurate measurements of paralysis. The cutoff used in clinical studies is a train-of-four ratio at the adductor pollicis of 0.9.[5] One study demonstrated marginal success in reducing residual paralysis by incorporating quantitative monitors into practice. In that study, PACU intubations were also reduced when appropriate monitoring was used.[18,19]

Our specific aim with this project was to develop a practice in which all patients given a nondepolarizing neuromuscular blocking drug were fully reversed from their state of paralysis as confirmed by a quantitative monitor measurement (*i.e.,* train-of-four ratio greater than or equal to 0.9). A train-of-four ratio greater than or equal to 0.9 could be attained spontaneously or facilitated with sugammadex or neostigmine. We embarked on a departmental professional practice initiative with the goal of documented train-of-four ratios greater than or equal to 0.90 for all patients. We aimed to improve patient outcomes through the subsequent reduction in postoperative residual paralysis.

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Materials and Methods

This project was performed as part of a professional practice initiative with a waiver from the Virginia Mason Medical Center (Seattle, Washington) Institutional Review Board. Written informed consent was not required from study participants. Virginia Mason Medical Center is a 300-bed urban hospital with 28 anesthetizing locations. The Department of Anesthesiology consists of 38 anesthesiologists, 27 anesthesia residents, 5 anesthesia fellows, 30 nurse anesthetists, and 19 anesthesia technicians. We utilized the SQUIRE 2.0 (Standards for Quality Improvement Reporting Excellence) quality improvement reporting guidelines.

Our department has a tradition of evidence-based protocol–driven anesthesia management, and neuromuscular blocking drug reversal protocols were in place throughout this process. The interventions of this project included educational efforts, formal trials of monitoring equipment, equipment cost assessments, placement of quantitative monitors in all rooms, instructional video production and distribution, performance feedback, and real-time automated anesthesia charting reminders.

Preimplementation

In 2016, every operating room contained a peripheral nerve stimulator (DigiStim II [Neuro Technologies, CCR Medical, Inc., USA] and EZ Stim II [Lifetech International, USA]). Optional neuromuscular monitors available in 2016 included uniaxial acceleromyography technology, namely the TOF-Watch SX (Organon, Ireland) and IntelliVue NMT (Philips, The Netherlands). Triaxial acceleromyography technology, the Stimpod 450× monitor (Xavant Technologies, South Africa), was introduced in July 2017. Electromyography technology, the TwitchView monitor (Blink Device Company, USA), was introduced in July 2018. Table 1 summarizes when equipment was available. Neuromuscular blocker management guidelines resided on the departmental website. The study period began in November 2016, and a 1995 guideline, updated in April 2016, was available for reference (Supplemental Digital Content 1 fig. 1, http://links.lww.com/ALN/C810). This guideline identified quantitative monitoring as the accepted standard for reversal assessment, but only provided reversal guidance using peripheral nerve stimulator–aided subjective assessment at the adductor pollicis. Clinical signs alone (*e.g.*, 5-s head lift) were identified as unreliable. Neostigmine reversal at train-of-four counts 1 and 2 was allowed using higher neostigmine doses (50 and 60 mcg/kg, respectively) but waiting for further recovery was recommended before administration of the reversal drugs. Neostigmine reversal

(50 mcg/kg) at train-of-four count 3 was allowed, but again, waiting was recommended. Reversal at train-of-four count 4 was identified as best practice, with recommendations of 40 mcg/kg neostigmine with fade and 20 mcg/kg without fade. An updated 2018 guideline differed; it offered specifics regarding quantitative monitoring and sugammadex (Supplemental Digital Content 2 fig. 2, http://links.lww.com/ALN/C811). Acceleromyography train-of-four ratios greater than or equal to 1 and electromyography train-of-four ratios greater than or equal to 0.9 were recommended before extubation. If these criteria were met spontaneously, then no reversal was recommended. Neostigmine reversal was only recommended at train-of-four count 4; at all other train-of-four counts, it was recommended to wait or use sugammadex per manufacturer dose recommendations. Choice of reversal medication was left to provider discretion for train-of-four count 4, although we encouraged neostigmine when there was sufficient time for recovery (10 to 20 min).

Implementation of Quantitative Monitoring

In 2018, new departmental leadership approved the necessary equipment purchases to initiate this project. On October 4, 2019, quantitative monitors were placed in all anesthetizing locations. Monitor selection was driven by in-house trials, formal feedback from users at our institution, informal review, and cost considerations. We originally sought a single monitor solution to streamline cost and education, but enthusiasm for both monitors changed our focus. We produced cost projections for 28 anesthetizing locations based on quotes received. Although the Stimpod ($1,250) acquisition cost was lower than the TwitchView ($1,995), our purchase decision was driven by projected disposable costs. TwitchView disposable arrays ($20 to $25 each) contrasted with readily available, low-cost electrocardiogram patches used with the Stimpod. We used historic case volume data specific to each operating room to estimate the yearly array costs when preferentially placing TwitchViews in rooms with tucked cases. We presented the department with array cost projections to support three and five TwitchViews ($28,800/yr and $48,000/yr, respectively). The department wanted these monitors preferentially for tucked cases, so we purchased four TwitchViews that were to reside in rooms with more tucked cases (*e.g.*, robotic rooms, cardiac rooms). Stimpods were placed in the other 24 locations. Extra monitors of each type were available upon request to allow for provider preference.

Education, Reminders, and Performance Feedback

Short instructional videos about the use of Stimpod and TwitchView monitors were developed and made available by December 2019. The videos explained each technology (acceleromyography and electromyography), detailed how to place the electrodes on a patient, and showed the menu items of each device. Automated alerts using Smart Anesthesia Manager (Perimatics LLC, USA) were launched on June 1, 2020. Smart Anesthesia Manager is a customizable, clinical decision support system that combines preoperative and intraoperative data to provide real-time point-of-care guidance reminders. The application provides decision support reminders for a variety of clinical areas including glycemic control, nausea prophylaxis, antibiotic delivery, blood pressure management, and neuromuscular blockade reversal. For neuromuscular blockade reversal, the reminders were triggered by the charting of reversal drug administration after a nondepolarizing neuromuscular blocker. The alerts were triggered 5 min after the reversal drug to remind the provider to chart the train-of-four ratio if none was present on the record. The alert disappeared upon recognition or after 3 min. An additional alert prompted documentation of the train-of-four ratio if a patient received a nondepolarizing neuromuscular blocker, extubation was documented, and no train-of-four ratio was recorded. Alert parameters were customized based on clinician feedback to optimize provider recognition while avoiding alarm fatigue. These alerts were only a reminder to the provider, and documentation nonadherence did not impede finalization of the anesthesia record.

Performance on departmental train-of-four ratio documentation was communicated periodically to all providers beginning in June 2019. This included department-wide emails, as well as individual emails, detailing successes and

Table 1. Equipment Available from 2016 to 2020

Year	Equipment	Location/Availability
2016	DigiStim II and EZ Stim II peripheral nerve stimulators	All operating rooms
	TOF-Watch SX neuromuscular monitor	Available
	IntelliVue NMT neuromuscular monitor	Available
2017	Stimpod 450× neuromuscular monitor	Available
2018	TwitchView neuromuscular monitor	Available
2019	Stimpod 450× and TwitchView	All operating rooms

Equipment manufacturers include Neuro Technologies, CCR Medical, Inc. (DigiStim II; USA); Lifetech International (EZ Stim II; USA); Organon (TOF-Watch SX; Ireland); Philips (IntelliVue NMT; The Netherlands), Xavant Technologies, (Stimpod 450×; South Africa), and Blink Device Company (TwitchView monitor; USA).

opportunities for improvement. In January 2020, departmental leadership announced to the department that train-of-four ratio documentation would become an Ongoing Professional Practice Evaluation metric starting in July 2020. Our hospital credentialing committee subsequently required train-of-four ratio documentation in at least 70% of cases. Two providers that fell below this threshold were informed of the need for corrective action.

Manually Reviewed Anesthesia Records: Implementation Tracking

Anesthesia records were manually reviewed to track the implementation of quantitative monitoring over time. Manual anesthesia record review was a labor-intensive effort limited by personnel availability. We estimated each record required 2 to 5 min to review. Cases with missing information required more time to check multiple monitoring and comment fields before concluding the information was not present. We initially anticipated two sets of data per year for nine time points. We balanced the time requirement with the need for sufficient data to come to the decision of assessing 2 weeks of cases—approximately 200 cases—for each time point, which would total 1,800 cases and take between 60 and 150 h for our anesthesia record data reviewers. The first records reviewed were from November 2016, starting 1 month after our adoption of electronic anesthesia charting. June and November records were reviewed in 2017 and 2018. June and October records were reviewed in 2019 because October 4, 2019, was the date at which all anesthetizing locations were outfitted with quantitative monitors. January, March, June, September, and December records were reviewed in 2020 to more closely track the rapidly changing practice after quantitative monitors were available for all cases (fig. 1). The anesthesia record review process began with electronic identification of records containing rocuronium or cisatracurium, the two nondepolarizing neuromuscular blockers used at our institution. Cases with a defasciculating dose of rocuronium (less than 10 mg) before succinylcholine were eliminated. Extubation was verified in the emergence notes. Data collected included weight, neuromuscular blocker total dose, reversal drug total dose, train-of-four count before reversal, and assessment for return of muscle strength. Return of muscle strength assessments included physical signs alone, peripheral nerve stimulation–assisted subjective evaluation, and quantitative assessment. In anesthesia records with more than one assessment technique documented, the most sensitive technique, associated with the highest train-of-four ratio, was recorded. Considered to be most sensitive was 100-Hz tetany without fade (train-of-four ratio greater than or equal to 85%), followed by double-burst stimulation without fade (train-of-four ratio greater than or equal to 60%), train-of-four without fade (train-of-four ratio greater than or equal to 40%), 50-Hz tetany without fade (train-of-four ratio greater than or equal to 40%), and train-of-four count alone.[5] Any assessment without fade was considered more sensitive than assessments recognizing fade. Only in the absence of any other assessments were physical signs alone recorded. Recorded physical signs included 5-s head lift and 5-s arm lift that occurred three times (5-s head lift in June 2017 and October 2019, and 5-s arm lift in June 2018). Our aim in this professional practice initiative was to convert from subjective measurements to quantitative measurement, so we report all subjective measurements collectively.

Electronic Medical Chart Data Set: Generalized Surgical Population Outcomes

We also electronically searched medical charts for all patients receiving a neuromuscular blocking drug from January 2016 to December 2020 to assess outcomes in this retrospective observational study. All charts from our datamart with a medication order of rocuronium, cisatracurium, neostigmine, or sugammadex were eligible. Charts were deleted for patients younger than 18 yr. Use of a nondepolarizing neuromuscular blocking drug solely for defasciculation before succinylcholine could not be determined in the electronic chart search, so rocuronium doses less than 10 mg were eliminated. Within the electronic search capabilities, there was no reliable way to differentiate between patients extubated in the operating room and transported to the ICU from those who remained intubated upon transport to the ICU. We explored search strategies (*e.g.,* PACU stay before transfer to ICU) but found we could not accurately perform that search. Therefore, patients with an ICU stay at any point during hospitalization (indicated *via* presence of an ICU note) or those undergoing a cardiac procedure were excluded from the electronic medical chart data set. For patients with two surgeries in one day, only the data from the first surgery were analyzed. PACU length of stay was determined using PACU discharge-ready as well as PACU discharge. PACU discharge-ready criteria in our institution included Aldrete score 8 to 10; patent airway; oxygen saturation greater than 92% on room air or with supplemental oxygen; hemodynamic stability without requirement of vasopressors unless transferring to ICU; temperature higher than 36°C; patient orientation or baseline mental status; block level T8 or below and receding; motor/sensory function returning; pain adequately controlled and/or returned to baseline pain level; absence of active emesis; absence of bladder retention; stable surgical site/dressing; and patency of all lines. PACU lengths of stay greater than 720 min were excluded from analysis. Postoperative pulmonary complications were defined by International Classification of Diseases, Tenth Revision discharge codes consistent with previous residual blockade research[13,20] (Supplemental Digital Content 3 table 1, http://links.lww.com/ALN/C812). Hospital length of stay, discharge disposition, and readmission data were also collected.

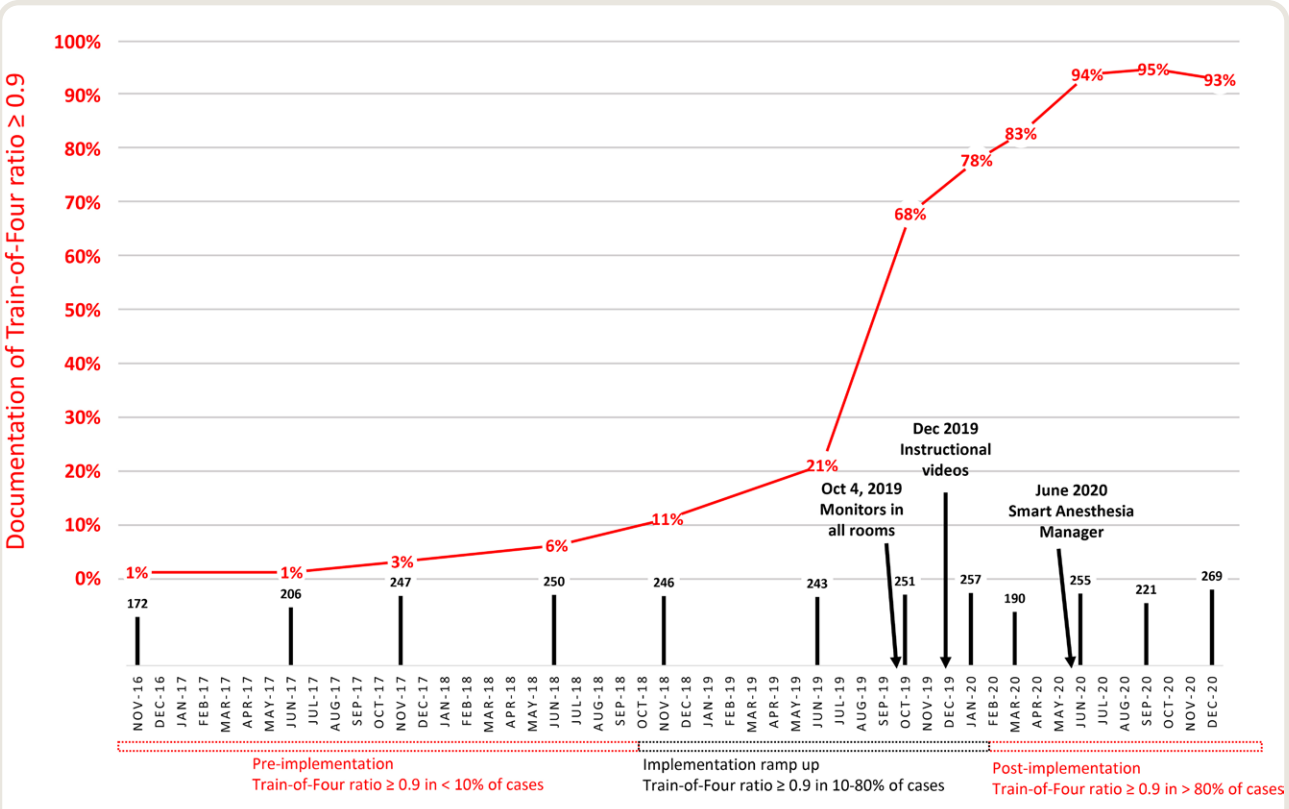

Fig. 1. Documentation trends of train-of-four ratios greater than or equal to 0.9 from 2016 to 2020 divided into three phases: preimplementation (less than 10% of cases had documentation of train-of-four ratios greater than or equal to 0.9); implementation ramp-up (10 to 80% of cases had documentation of train-of-four ratios greater than or equal to 0.9); and postimplementation (more than 80% of cases had documentation of train-of-four ratios greater than or equal to 0.9). The *red line* and numbers represent the percentage of cases documentation of train-of-four ratios greater than or equal to 0.9 on the anesthesia record. The *black bars* and numbers represent how many records were manually reviewed in each 2-week time frame.

Manual Anesthesia Record and Electronic Medical Chart Data Set Differences

The two sets of data differ fundamentally due to the ability to extract some data exclusively found in the anesthesia record. The primary purpose of the manual anesthesia record review was to track the implementation of our professional practice initiative by establishing a baseline train-of-four ratio documentation rate, and then documenting changes over time. Because of the limited number of records in this manual search strategy, we did not anticipate adequate data to assess infrequent patient outcomes (*e.g.,* pulmonary complications). To better capture patient outcomes, we conducted the electronic chart search of a larger cohort of surgical patients that were administered a neuromuscular blocker during the same period. The value of this electronic search was predicated on the assumption that train-of-four ratio documentation occurred similarly between the smaller data set of manually reviewed anesthesia records and the larger data set of electronically searched charts. An important difference between the data sets was that the manually reviewed anesthesia records included patients extubated at the end of surgery and then transferred to the ICU. Patients transferred to the ICU intubated were identifiable in the manual anesthesia records search and removed. The electronic chart data set contained no ICU patients.

Statistical Analysis

Statistical power analysis was not used to guide the sample size in this observational convenience sample. The sample size for the manually reviewed anesthesia records was limited by the availability of the anesthesiologist reviewers. The *t* test was used to compare means of continuous variables, and the chi-square to compare proportions before and after the intervention. The nonparametric Mann–Whitney U test was used to compare the medians of continuous variables that were not normally distributed. Statistical analysis was performed using StataMP 16 (Stata Corp., USA). The main analysis compared values before and after the intervention. All *P* values were two-tailed, with statistical

significance defined at $P < 0.05$. Patient and surgery characteristics were reported as number (percentage), mean ± SD, or median and interquartile range, if nonnormally distributed. The percentage change was determined by the postintervention to preintervention difference divided by the preintervention value. We acknowledge that multiple comparisons can result in falsely significant results. We provided the actual *P* values so that the reader can judge the likelihood of spurious conclusions. It is noteworthy that many of the associations would be considered significant even under conservative adjustment for multiple comparisons, such as the Bonferroni. The data analysis and statistical plan was written after the data were accessed. Ideally, we would use interrupted time series to analyze these data and adjust for known confounders. However, our intervention did not occur at a single time point, but rather was phased in, and we did not have a way to model that in a time series regression that adjusts for covariates. We chose a simple pre-/post strategy to describe the observed differences in the sample across time.

Results

The implementation graph shows the progressive increase in the percentage of cases with a documented train-of-four ratio greater than or equal to 0.9 from 2016 to 2020 (fig. 1). Manually reviewed anesthesia records (n = 2,807) showed 2 of 172 (1%) cases contained documented train-of-four ratios greater than or equal to 0.9 in November 2016 compared with 26 of 246 (11%) cases by November 2018. The introduction of quantitative monitors in all operating rooms on October 4, 2019, was associated with the greatest incremental change in documentation, from 50 of 243 (21%) in June 2019 to 170 of 251 (68%) in October 2019. In December 2020, 250 of 269 (93%) of cases contained documentation of a train-of-four ratio greater than or equal to 0.9.

Implementation of the documentation of train-of-four ratios greater than or equal to 0.9 was temporally separated into preimplementation (documentation in fewer than 10% of cases [October 1, 2016, to September 30, 2018]), implementation ramp-up (documentation in 10 to 80% of cases [October 1, 2018, to January 31, 2020]), and postimplementation (documentation in more than 80% of cases [February 1, 2020, to December 31, 2020]). This demarcation provides a comparison between subjective assessment (no quantitative monitoring, preimplementation) and quantitative monitoring (postimplementation). We manually reviewed 2,807 anesthesia records: 875 preimplementation, 997 implementation ramp-up, and 935 postimplementation. We electronically searched 20,181 medical charts: 9,034 preimplementation, 6,990 implementation ramp-up, and 4,157 postimplementation. The electronic chart search flow diagram is shown in figure 2. Our data include information unique to the manually reviewed anesthesia records data set (n = 538), information unique to the electronic chart data set (n = 17,912), and information present in both data sets (n = 2,269), for a total of 20,181 electronic charts and 2,807 manually reviewed anesthesia records.

Preimplementation to postimplementation patient demographics, surgery characteristics, neuromuscular blocker use, reversal use, and operative information from both data sets are presented in table 2. There was no difference in patient type in either data set postimplementation. In the electronic chart data set, postimplementation there were fewer inpatients: 4,138 of 9,034 (46%) preimplementation *versus* 1,817 of 4,157 (44%) postimplementation, and a longer surgical duration, mean 125 ± 88 min preimplementation *versus* 130 ± 99 min postimplementation. There were more patients with American Society of Anesthesiologists (Schaumburg, Illinois) Physical Status III to V, rocuronium use, and sugammadex use in both data sets postimplementation. Documentation of spontaneous reversal occurred in 26 of 875 (3%) cases preimplementation and 90 of 935 (10%) cases postimplementation in the anesthesia record data set. Postimplementation (February 1, 2020, to December 31, 2020), sugammadex (650 of 935 [70%]), neostigmine (195 of 935 [21%]), and no reversal (90 of 935 [10%]) were used to attain train-of-four ratios greater than or equal to 0.90 in 856 of 935 (92%) patients in the anesthesia record data set. Figure 3 demonstrates a shift over time in reversal drug use and more spontaneous reversal documentation in the anesthesia record set. A similar change in spontaneous reversal documentation occurred in the electronic chart data set: 362 of 9,034 (4%) cases preimplementation to 413 of 4,157 (10%) cases postimplementation (table 2). In postimplementation (February 1, 2020, to December 31, 2020) cases, sugammadex (2,879 of 4,157 [69%]), neostigmine (865 of 4,157 [21%]), and no reversal (413 of 4,157 [10%]) were documented in the electronic chart data set. Postimplementation patient ages were greater, there were more gynecologic and otolaryngologic cases, and there were fewer inpatients in the electronic chart data set. Importantly, the manual anesthesia record population was not a subset of the electronic chart population. There were 523 of 2,807 (19%) patients in the manual anesthesia record data set that were eliminated from the electronic chart data set. There were more inpatients (73% *vs.* 44%) in the anesthesia record data set, which included ICU patients.

Preimplementation to postimplementation data unique to the manually reviewed anesthesia records data set are presented in table 3. There was no difference in weight; average dose of cisatracurium or neostigmine; median train-of-four count before neostigmine or sugammadex administration; or average train-of-four ratio value after neostigmine, sugammadex, or spontaneous reversal. The average rocuronium dose; median overall prereversal train-of-four count; and percentages of prereversal train-of-four counts less than 4, missing pre–train-of-four count values, postreversal

train-of-four ratios greater than or equal to 0.9, and post-reversal train-of-four ratios less than 0.9 were all greater postimplementation. Documentation of train-of-four ratios greater than or equal to 0.9 occurred in 29 of 875 (3%) of cases preimplementation and 856 of 935 (92%) of cases postimplementation. Prereversal train-of-four counts equal to 4 occurred less and the average sugammadex dose was lower postimplementation. There was more frequent subjective assessment in November 2016 (146 of 172 [85%] cases) but more frequent documentation of train-of-four ratios greater than or equal to 0.9 in December 2020 (250 of 270 [93%] cases; fig. 4).

Patient outcome data from electronically searched medical charts are shown in table 4. Postimplementation, there was a shorter time from PACU arrival to ready-for-discharge (2% overall difference; median [in min] [25th, 75th], 78 [57, 110] to 76 [54, 107]; $P < 0.001$; 7% difference for inpatients; median [in min] [25th, 75th], 73 [55, 102] to 68 [49, 95]; $P < 0.001$). Time from PACU arrival to ready for discharge was not different after neostigmine, sugammadex, or no reversal. There was a shorter time from PACU arrival to discharge (4% overall difference, median [in min] [25th, 75th], 97 [72, 136] to 93 [69, 129]; $P < 0.001$). Fewer postoperative pulmonary complications occurred overall (42% difference; 104 of 9,034 [1.2%] to 28 of 4,157 [0.7%]; $P = 0.011$; −0.5% difference [95% CI, −0.8 to −0.1%]) and for inpatients (43% difference; 94 of 4,138 [2.3%] to 23 of 1,817 [1.3%]; $P = 0.010$; difference −1.0% [95% CI, −1.7 to −0.3%]). Postimplementation inpatients remained in the hospital for fewer days (hospital median length of stay [25th, 75th], 3 [2, 5] to 2 [1, 4]; $P < 0.001$). No differences were found in mortality or hospital readmissions.

Supplemental Digital Content 4 table 2 (http://links.lww.com/ALN/C813) contains patient demographic information for the implementation ramp-up period. Supplemental Digital Content 5 table 3 (http://links.lww.com/ALN/C814) contains data specific to the anesthesia records data set for the implementation ramp-up period. Supplemental Digital Content 6 table 4 (http://links.lww.com/ALN/C815) contains electronically searched medical charts outcome data for the implementation ramp-up period. Supplemental Digital Content 7 table 5 (http://links.lww.com/ALN/C816) contains the manually searched anesthesia records patient outcome data for the

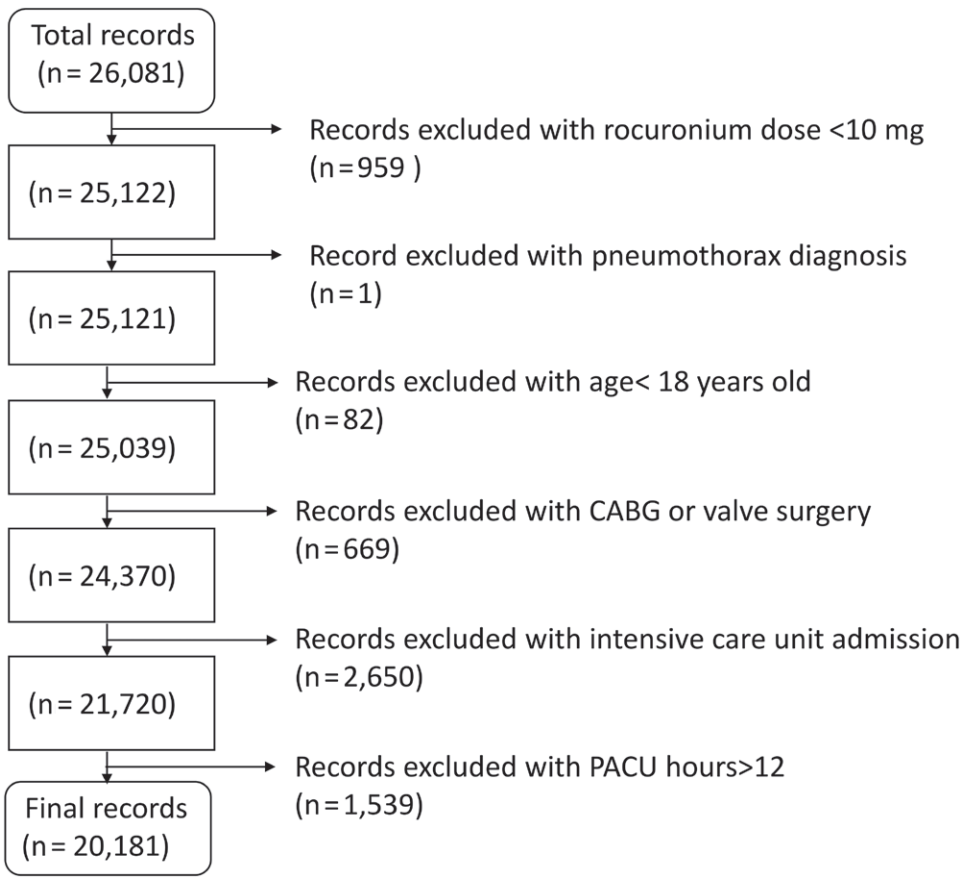

Fig. 2. Electronic chart search flow diagram showing initial surgical procedures volume, chart exclusion criteria, and final surgical procedures volume. CABG, coronary artery bypass graft; PACU, postanesthesia care unit.

Table 2. Patient Demographics, Surgery Characteristics, Neuromuscular Blocker Use, Reversal Use, and Operative Information

	Preimplementation (October 1, 2016–September 20, 2018)	Postimplementation (February 1, 2020–December 31, 2020)	*P* Value
No. patient surgeries			
Anesthesia records	875	935	
Electronic charts	9,034	4,157	
Age, yr			
Anesthesia records, mean ± SD	58.3 ± 16.1	58.0 ± 16.4	0.666
Electronic charts, median [25th, 75th]	59.3 [45.4, 69.0]	59.6 [45.4, 70.2]	0.026
Patient type, n (%)			
Anesthesia records	Female: 465 of 875 (53%); male: 410 of 875 (47%)	Female: 535 of 935 (57%); male: 400 of 935 (43%)	0.081
Electronic charts	Female: 5,176 of 9,034 (57%); male: 3,858 of 9,034 (43%)	Female: 2,428 of 4,157 (58%); male: 1,729 of 4,157 (42%)	0.228
Admit type, n (%)			
Anesthesia records			0.055
Inpatient	431 of 875 (49%)	449 of 935 (48%)	
Observation	2 of 875 (0.2%)	11 of 935 (1.2%)	
Outpatient	442 of 875 (51%)	475 of 935 (51%)	
Electronic charts			< 0.001
Inpatient	4,138 of 9,034 (46%)	1,817 of 4,157 (44%)	
Observation	25 of 9,034 (0.3%)	53 of 4,157 (1%)	
Outpatient	4,871 of 9,034 (54%)	2,287 of 4,157 (55%)	
Patient service, n (%)			
Anesthesia records			0.138
General surgery	312 of 875 (36%)	331 of 935 (35%)	
Gynecologic	74 of 875 (8%)	81 of 935 (9%)	
Otolaryngologic	94 of 875 (11%)	72 of 935 (8%)	
Other	395 of 875 (45%)	451 of 935 (48%)	
Electronic charts			< 0.001
General surgery	3,558 of 9,034 (39%)	1,620 of 4,157 (39%)	
Gynecologic	1,024 of 9,034 (11%)	361 of 4,157 (9%)	
Otolaryngologic	951 of 9,034 (11%)	342 of 4,157 (8%)	
Other	3,501 of 9,034 (39%)	1,834 of 4,157 (44%)	
ASA Physical Status class, n (%)			
Anesthesia records			< 0.001
I	90 of 875 (10%)	60 of 935 (6%)	
II	485 of 875 (55%)	457 of 935 (49%)	
III	266 of 875 (30%)	367 of 935 (39%)	
IV or V	16 of 875 (2%)	50 of 935 (5%)	
Not assigned	18 of 875 (2%)	1 of 935 (0.1%)	
Emergency	18 of 875 (2%)	35 of 935 (4%)	0.033
Electronic charts			< 0.001
I	914 of 9,034 (10%)	324 of 4,157 (8%)	
II	5,439 of 9,034 (60%)	2,190 of 4,157 (53%)	
III	2,584 of 9,034 (29%)	1,562 of 4,157 (38%)	
IV or V	97 of 9,034 (1%)	81 of 4,157 (2%)	
Not assigned	0 of 9,034 (0%)	0 of 4,157 (0%)	
Emergency	237 of 9,034 (3%)	133 of 4,157 (3%)	0.063
Admit type, n (%)			
Anesthesia records			0.936
Emergency	44 of 875 (5%)	46 of 935 (5%)	
Urgent	69 of 875 (8%)	78 of 935 (8%)	
Elective	762 of 875 (87%)	811 of 935 (87%)	
Electronic charts			0.246
Emergency	535 of 9,034 (6%)	254 of 4,157 (6%)	
Urgent	550 of 9,034 (6%)	223 of 4,157 (5%)	
Elective	7,949 of 9,034 (88%)	3,680 of 4,157 (89%)	
Neuromuscular blocking agent, n (%)			
Anesthesia records			< 0.001
Cisatracurium	93 of 875 (11%)	17 of 935 (2%)	
Rocuronium	782 of 875 (89%)	918 of 935 (98%)	
Electronic charts			< 0.001
Cisatracurium	791 of 9,034 (9%)	48 of 4,157 (1%)	
Rocuronium	8,243 of 9,034 (91%)	4,109 of 4,157 (99%)	

(*Continued*)

Table 2. (Continued)

	Preimplementation (October 1, 2016–September 20, 2018)	Postimplementation (February 1, 2020–December 31, 2020)	*P* Value
Reversal type, n (%)			
Anesthesia records			
Neostigmine	715 of 875 (82%)	195 of 935 (21%)	< 0.001
Sugammadex	134 of 875 (15%)	650 of 935 (70%)	< 0.001
No reversal	26 of 875 (3%)	90 of 935 (10%)	< 0.001
Electronic charts			
Neostigmine	7,295 of 9,034 (81%)	865 of 4,157 (21%)	< 0.001
Sugammadex	1,377 of 9,034 (15%)	2,879 of 4,157 (70%)	< 0.001
No reversal	362 of 9,034 (4%)	413 of 4,157 (10%)	< 0.001
Surgery duration, min (mean ± SD)			
Anesthesia records	141 ± 101*	139 ± 114†	0.804
Electronic charts, median [25th, 75th percentile]	125 ± 88	130 ± 99	0.004

Both data sets are presented: manual anesthesia record review (n = 2,807) and electronically searched medical charts (n = 20,181). Only the data from preimplementation and postimplementation are shown; data collected for the implementation ramp-up period are in Supplemental Digital Content 4 table 2 (http://links.lww.com/ALN/C813). Median [25th, 75th] for continuous variables; number (%) for categorical variables.

P values determined by Mann–Whitney U test for continuous variables and chi-square test for categorical variables.

*N = 843. †N = 908.

ASA, American Society of Anesthesiologists.

preimplementation, implementation ramp-up, and postimplementation periods.

Discussion

In this professional practice initiative, we accomplished documenting train-of-four ratios greater than or equal to 0.9 in the vast majority of patients. More documentation of train-of-four ratios greater than or equal to 0.90 was an intermediate outcome and one of many potential factors contributing to the observed differences in patient outcomes.

Administering sugammadex to all patients is another approach to reduce residual blockade. Sugammadex without neuromuscular monitoring appears to reduce, but not eliminate, residual blockade.[21,22] Some advocate this single-drug approach because anesthesiologists do not routinely use neuromuscular monitoring.[2,20,23,24] Sugammadex was introduced in Japan in 2010, and by 2014 was used for reversal in 95% of cases. Subsequently, concerns were raised about anaphylaxis[25] and residual blockade.[21,26] In

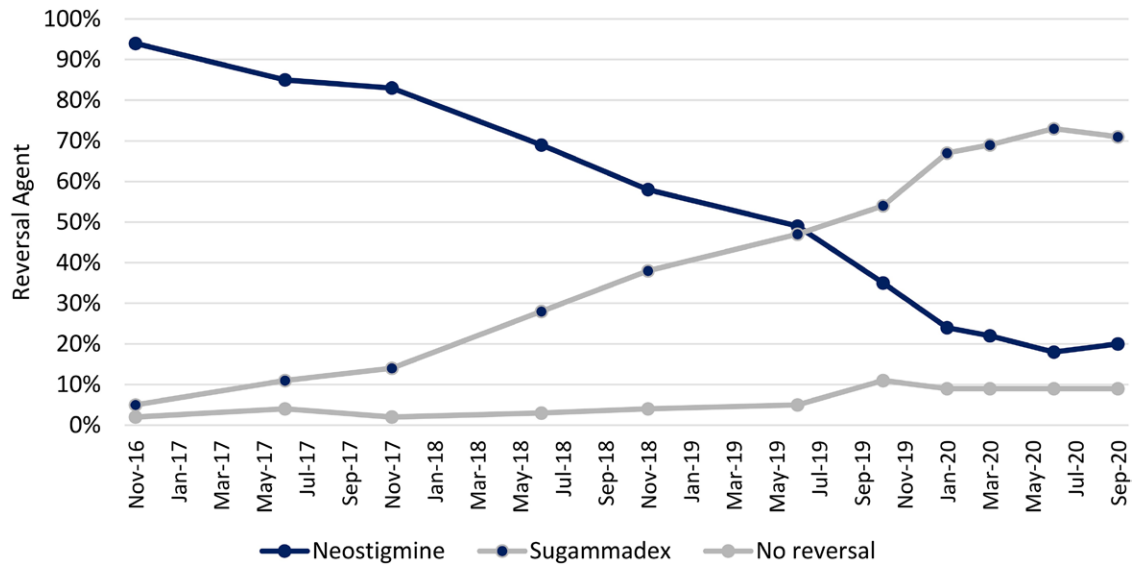

Fig. 3. Use of sugammadex, neostigmine, or no reversal drug from 2016 to 2020 in manually reviewed anesthesia records (n = 2,807).

Table 3. Neuromuscular Blocker Dose, Reversal Dose, Prereversal Assessment, and Postreversal Assessment

	Preimplementation (October 1, 2016–September 20, 2018)	Postimplementation (February 1, 2020–December 31, 2020)	*P* Value
No. patient surgeries	875	935	
Weight, kg (mean ± SD)	85 ± 23	86 ± 24	0.667
Neuromuscular blocker dose, mg (mean ± SD)			
Cisatracurium	21 ± 17	22 ± 14	0.767
Rocuronium	69 ± 41	75 ± 45	0.003
Prereversal train-of-four count, median [25th, 75th]			
Overall	4 [3, 4]*	2 [1, 4]†	< 0.001
Neostigmine	4 [4, 4]‡	4 [4, 4]§	0.118
Sugammadex	2 [1, 4]‖	2 [1, 4]#	0.542
Prereversal train-of-four count, n (%)			
Train-of-four count = 4	522 of 875 (60%)	286 of 935 (31%)	< 0.001
Train-of-four count < 4	240 of 875 (27%)	407 of 935 (44%)	< 0.001
Train-of-four count missing	113 of 875 (13%)	242 of 935 (26%)	< 0.001
Reversal dose, mg (mean ± SD)			
Neostigmine	4 ± 1	3 ± 1	0.102
Sugammadex	261 ± 123	224 ± 104	< 0.001
Operating room assessment overall, n (%)			< 0.001
Not recorded	122 of 875 (14%)	13 of 935 (1%)	
Subjective	721 of 875 (82%)	48 of 935 (5%)	
Train-of-four ratio ≥ 0.9	29 of 875 (3%)	856 of 935 (92%)	
Train-of-four ratio < 0.9	3 of 875 (0.3%)	18 of 935 (2%)	
Train-of-four ratios for train-of-four ratio ≥ 0.9 cases, mean ± SD			
Neostigmine	0.95 ± 0.14**	1.01 ± 0.15††	0.085
Sugammadex	0.95 ± 0.05‡‡	1.05 ± 0.16§§	0.059
No reversal	0.95 ± 0.07‖‖	1.07 ± 0.17##	0.328

Data are specific only to the manually collected anesthesia records data set (n = 2,807). Only preimplementation and postimplementation data are shown; data collected for the implementation ramp-up period are in Supplemental Digital Content 5 table 3 (http://links.lww.com/ALN/C814). *P* values determined by Mann–Whitney U test for continuous variables and chi-square test for categorical variables.

*N = 762. †N = 693. ‡N = 644. §N = 164. ‖N = 118. #N = 529. **N = 21. ††N = 186. ‡‡N = 9. §§N = 611. ‖‖N = 2. ##N = 77.

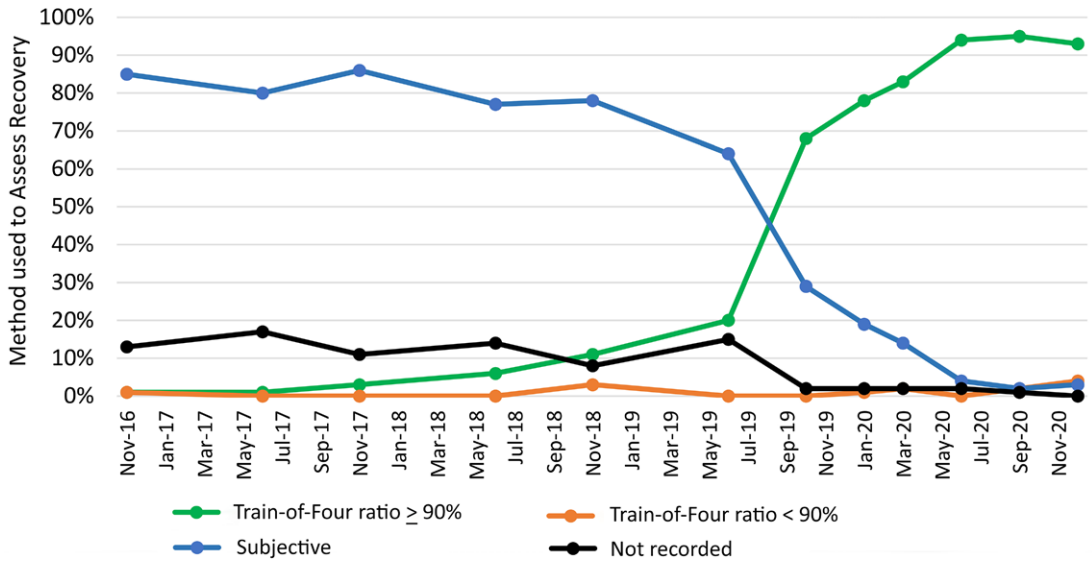

Fig. 4. Methods used to assess return of strength from 2016 to 2020 in manually reviewed anesthesia records (n = 2,807). Subjective assessment included 100-Hz tetany without fade, double-burst stimulation without fade, train-of-four without fade, 50-Hz tetany without fade, train-of-four with fade, train-of-four count 4, 5-s head lift, 5-s arm lift, and train-of-four count 0.

Table 4. Outcome Data from Electronically Searched Medical Charts (n = 20,181)

	Preimplementation (October 1, 2016–September 20, 2018)	Postimplementation (February 1, 2020–December 31, 2020)	*P* Value	Difference (95% CI)
Surgeries, n	9,034	4,157		
PACU ready for discharge by patient type, min (median [25th, 75th])				
Overall	78 [57, 110]	76 [54, 107]	< 0.001	
Inpatient	73 [55, 102]	68 [49, 95]	< 0.001	
Observation	61 [53, 83]	50 [36, 73]	0.154	
Outpatient	84 [60, 117]	85 [60, 119]	0.939	
PACU ready for discharge by reversal, min (median [25th, 75th])				
Neostigmine	79 [57, 111]	77 [56, 112]	0.438	
Sugammadex	76 [56, 107]	75 [53, 105]	0.218	
No reversal	82 [60, 117]	80 [58, 109]	0.225	
PACU to discharge, min (median [25th, 75th])	97 [72, 136]	93 [69, 129]	< 0.001	—
Postoperative pulmonary complications, n (%)				
Overall	104 of 9,034 (1.2%)	28 of 4,157 (0.7%)	0.011	–0.5% [–0.8% to –0.1%]
Inpatient	94 of 4,138 (2.3%)	23 of 1,817 (1.3%)	0.010	–1.0% [–1.7% to –0.3%]
Observation	0 of 25 (0%)	0 of 53 (0%)	—	—
Outpatient	10 of 4,871 (0.2%)	5 of 2,287 (0.2%)	0.908	0.0% [–0.2% to 0.2%]
Hospital length of stay, days (median [25th, 75th])				
Inpatient	3 [2, 5]	2 [1, 4]	< 0.001	—
Observation	1 [1, 2]	1 [1, 2]	0.545	—
Outpatient	0 [0, 1]	0 [0,1]	< 0.001	—
Discharge disposition, n (%)				
Home	8,554 of 9,034 (94.7%)	3,936 of 4,157 (94.7%)	0.994	0.0% [–0.8% to 0.8%]
Died	4 of 9,034 (0.04%)	2 of 4,157 (0.05%)	0.924	0.0% [–0.08% to 0.08%]
Inpatients readmitted to hospital, n (%)	229 of 4,137 (5.5%)	101 of 1,812 (5.6%)	0.952	0.03% [–1.30% to 1.23%]

P values determined by Mann–Whitney U test for continuous variables and chi-square test for categorical variables. Only data from preimplementation and postimplementation are shown. Median [25th, 75th] indicated for continuous variables; n (%) indicated for categorical variables.

PACU, postanesthesia care unit.

January 2019, the Japanese Society of Anesthesiologists (Kobe, Japan) warned of the dangers of using sugammadex[27] without neuromuscular monitoring, and soon afterward started recommending neuromuscular monitoring when using muscle relaxant antagonists.[28] Guidelines from the United Kingdom,[29] Canada,[30] Australia,[31] and France[32] also advocate neuromuscular monitoring for neuromuscular blocking drug management; none recommend one specific reversal drug for all patients. The reasons for avoidance of monitoring include the belief that it is not necessary, overconfidence in current practice, lack of knowledge/equipment, inability to use equipment, and/or distrust of equipment.[33,34] Contemporary quantitative monitors have been shown relatively easy to use,[35] which contributed to our department-wide adoption.

Acceleromyography yields higher train-of-four ratios compared with electromyography, leading some experts to recommend train-of-four ratios greater than or equal to 1.0 for acceleromyography and train-of-four ratios greater than or equal to 0.9 for electromyography.[1,36,37] Our documentation does not delineate monitor type, so we chose to use the lower cutoff, train-of-four ratio greater than or equal to 0.9, in the context of 24 operating rooms with acceleromyography and 4 with electromyography monitors (with extras of each monitor type also available). Normalizing and preload were not done routinely; therefore, our raw acceleromyography train-of-four ratios between 0.9 to 1.0 may represent incomplete reversal since the Stimpod shows train-of-four ratios greater than 1.0 in approximately one quarter of unparalyzed patients.[38] Numerous studies quantifying residual blockade and assessing postoperative effects have used raw acceleromyography train-of-four ratios greater than or equal to 0.9, supporting our approach.[4,7–9,11,12,39–41] Furthermore, our documentation of acceleromyography measurements before extubation represents a higher standard than PACU measurements, and it saved patients the discomfort of nerve stimulation while awake.[7,39,42]

We analyzed the time from PACU arrival to PACU ready for discharge as an estimate of patient recovery, realizing that

PACU time is affected by many variables. Longer PACU lengths of stay have been reported in the presence of residual blockade.[8,41,43,44] However, our rates of residual paralysis were unknown, so the 7% PACU stay reduction cannot be definitively linked to a reduction in residual paralysis. In 2016, when subjective assessment prevailed, we estimate that one third of our patients likely had residual blockade in the PACU.[45] In June 2019, we evaluated 22 patients arriving to our PACU, and 9% were found to have residual blockade. In December 2020, residual blockade occurred in less than 7% of our patients per operating room train-of-four ratio documentation. In short, we compared populations with inferred, but unknown, rates of residual paralysis.

Recurrent paralysis or regression of the train-of-four ratio after full return of strength was not captured in our study since train-of-four ratios were not measured in the PACU. Neuromuscular blocker duration of action surpassing reversal drug duration of action could lead to recurrent paralysis after neostigmine, but this occurrence is unlikely after a train-of-four ratio greater than or equal to 0.9.[46] Redistribution of neuromuscular blocker molecules from peripheral compartments has been postulated to explain recurrent paralysis after sugammadex.[47] This has generally occurred in the setting of antagonizing deep neuromuscular blockade with low-dose sugammadex. In our study, the average dose of sugammadex given was comparable to manufacturer recommendations, thereby reducing the potential for recurrent paralysis.

A single group before and after analysis lacks a control group, which leaves the conclusions drawn from this type of research vulnerable to confounding factors that threaten the validity of the findings. In our study, many factors exist that impact PACU length of stay, pulmonary complications, and hospital length of stay. We could not control for these factors; therefore, our results must necessarily be viewed with caution. A patient characteristic that could explain improved patient outcomes was that there were 2% fewer inpatient surgeries. Conversely, improved patient outcomes would be less likely with the 10% more ASA Physical Status III to V patients and longer surgical durations present postintervention. Additionally, the anesthesia record data show higher doses of neuromuscular blocker and deeper levels of neuromuscular blockade at the time of reversal. PACU length of stay may have been impacted by intraoperative surgical factors, PACU nursing practices, and PACU-specific quality improvement projects. The change in PACU length of stay may have been due to improved discharge efficiency over time, although this did not occur for patients in our hospital who were managed with a laryngeal mask airway and received no neuromuscular blockade during the same period. Pulmonary complications may be influenced by ventilator management and perioperative pulmonary care practices, but we are unaware of changes in this care occurring between 2016 and 2020. Hospital length of stay was influenced by many factors that were not measured or controlled.

Acceleromyography setup required free movement of the thumb but otherwise closely resembled peripheral nerve stimulator use, a technique familiar to our providers. Frequent error messages and inability to attain measurements historically impeded uniaxial acceleromyography enthusiasm. Introduction of the triaxial monitor, which measured three dimensions of movement, worked more reliably, which facilitated acceleromyography monitor use. We experienced TwitchView array failures that included failed current delivery, failed signal return, poor-quality signal, and inaccurate readings (*e.g.,* train-of-four count 0 with four visible thumb movements). Array failures demotivated providers from using the TwitchView given the cost of each array. This hesitancy was tempered by an agreement with the company to receive two arrays for each that failed (failed array return was required). Our anesthesia technicians were trained on how to place and set up both monitors, and provided reliable, timely, and important assistance. Ongoing equipment upkeep along with responsive device company service contributed immensely to our adoption of quantitative neuromuscular monitoring.

Acceptance of the new standard of train-of-four ratio documentation evolved differently among different anesthesia providers in our department. Residents, in general, were open and receptive to neuromuscular monitor teaching, though monitor utilization was hindered initially by lagging support from some teaching faculty. During supervision, identifying situations when a patient struggled to breathe and subsequently was found by quantitative measurement to have a low train-of-four ratio proved to be a powerful teaching opportunity on multiple occasions. This recognition of patient harm in real time convinced multiple anesthesia providers of the value of monitoring. Our ongoing teaching efforts occurred in departmental meetings, departmental and personal emails, and personal communication. Acceptance occurred differently among anesthesia providers, likely because of the varied preconceived notions about the prevalence of residual paralysis, value of quantitative monitoring, effort required to incorporate quantitative monitoring into practice, and impact of residual paralysis on patients.

We cultivated the mindset of attaining quantitative measurements in part through the implementation of the Ongoing Professional Practice Evaluation, which tied documentation of train-of-four ratios greater than or equal to 0.90 with hospital credentialing. This link established the importance we place on this anesthesiology performance metric. The threshold was set at 70% of cases, but a higher threshold may be warranted. Our practice believes a return-of-strength measurement should be required after every nondepolarizing neuromuscular blocking drug administration.

The improved documentation of train-of-four ratios greater than or equal to 0.9 after incorporation of automated alerts was consistent with known benefits of this technology.[48] We solicited and responded to provider feedback about the alarms to strike a balance between helpful

prompting and alarm fatigue. The optimal delivery of automated prompts will likely differ between institutions.

This work realized the goal of utilizing quantitative monitoring to guide neuromuscular blocker management, which has been advocated in studies, editorials, consensus statements, and practice guidelines. We are continuing our work with anesthesia records that are now electronically searchable to build a dashboard to track documentation of train-of-four ratios greater than or equal to 0.9 in all cases in real time. We are educating providers to document train-of-four ratio in a monitoring field to facilitate electronic searching, as opposed to writing it as a comment in the record. We are working toward automatic data entry into our anesthetic record to streamline the workflow for our providers. Our goal is to make the acquisition of this information seamlessly integrated into the anesthesia care workflow.

Our departmental experience demonstrates that, at the end of surgery in the vast majority of patients, achieving and documenting a train-of-four ratio greater than or equal to 0.9 after administration of a nondepolarizing neuromuscular blocker is not a quixotic goal. This result was achieved in a busy tertiary hospital. However, attaining this endpoint requires more than just placing a quantitative monitor at each anesthetizing location. Ongoing educational effort and follow-up are required. We think our experience provides a useful road map to this end. Anesthesia providers are solely responsible for properly rescuing patients from the states of paralyses they initiate. This should occur for all patients as verified by quantitative measurement and documentation of train-of-four ratios greater than or equal to 0.9.

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Competing Interests

The authors declare no competing interests.

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