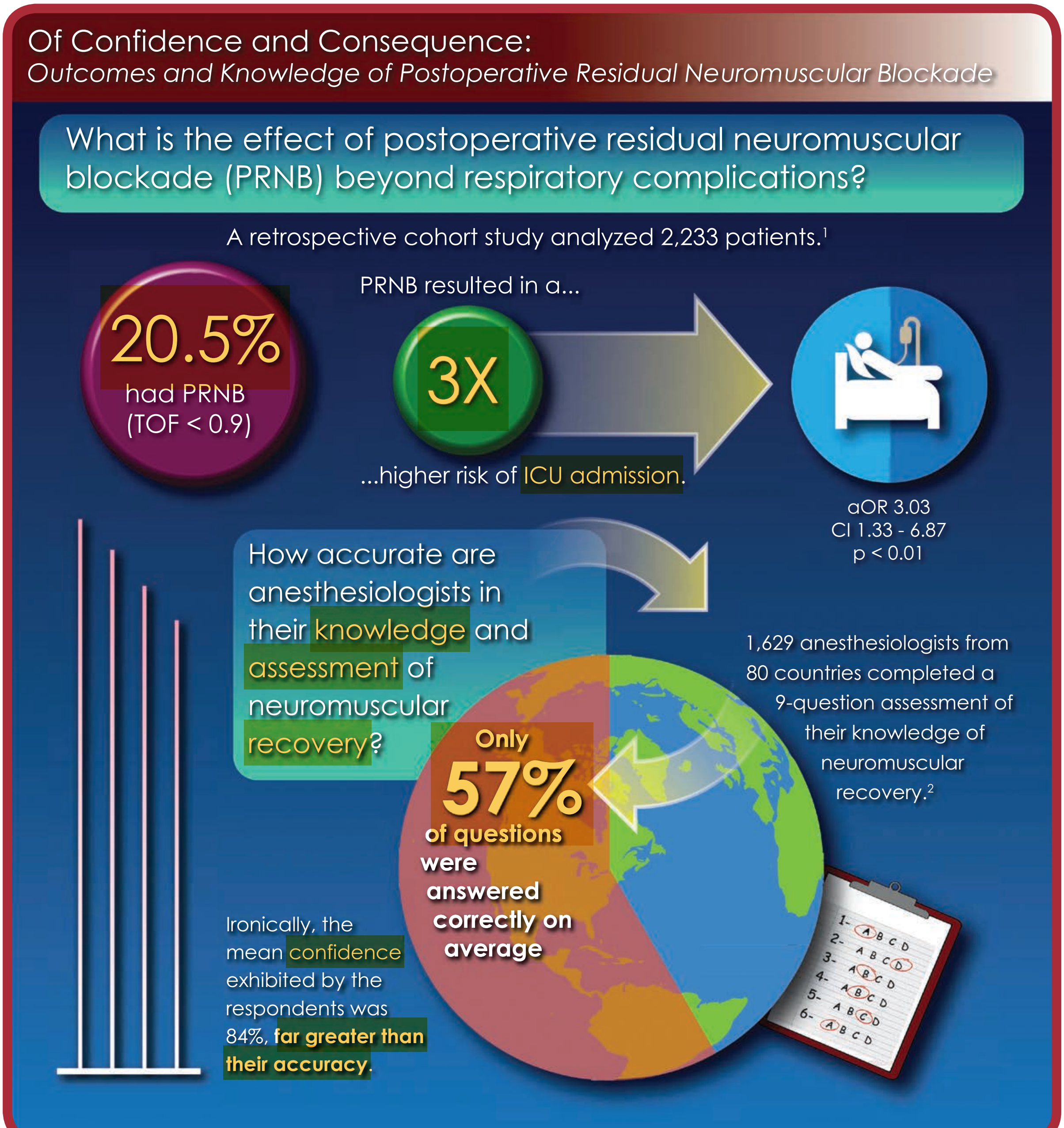
ANESTHESIA & ANALGESIA® *Infographic*



Postoperative residual neuromuscular blockade (PRNB) continues to place patients at risk for adverse respiratory events. More than 2000 patients were analyzed in a retrospective cohort study by Grabitz et al[1] for the presence of PRNB in the postoperative recovery unit. One-fifth of these patients demonstrated PRNB as defined by a train of four (TOF) ratio of <0.9. These patients sustained a 3-fold higher risk of intensive care unit (ICU) admission compared to those without PRNB. The investigation did not clearly show an increase in hospital costs associated with PRNB; however, this parameter was particularly challenging to ascertain as a direct effect of PRNB. Despite the continued presence of measurable PRNB in the postoperative care unit, anesthesiologists are seemingly overconfident in their knowledge of the problem and the fundamental management of reversal intraoperatively. Using a 9-question multinational survey, Naguib et al[2] present only a 57% accuracy rate of respondents on this topic, while their solicited confidence level was far in excess of this value. For further depth of understanding on this important component of anesthetic practice, readers are strongly encouraged to review these articles and their accompanying editorials.

ICU indicates intensive care unit; PRNB, postoperative residual neuromuscular blockade; TOF, train of four.

The Infographic is composed by Naveen Nathan, MD, Northwestern University Feinberg School of Medicine (n-nathan@northwestern.edu). Illustration by Naveen Nathan, MD.

The author declares no conflicts of interest.

REFERENCES

1. Grabitz SD, Rajaratnam N, Changani K, et al. The effects of postoperative residual neuromuscular blockade on hospital costs and intensive care unit admission: a population-based cohort study. *Anesth Analg*. 2019;128:1129–1136.
2. Naguib M, Brull SJ, Hunter JM, et al. Anesthesiologists' overconfidence in their perceived knowledge of neuromuscular monitoring and its relevance to all aspects of medical practice: an international survey. *Anesth Analg*. 2019;128:1118–1126.
3. Naguib M, Kopman AF. Neuromuscular monitoring: keep it simple! *Anesth Analg*. 2019;128:1063–1064.
4. Harman A, Tung A, Fox C, Lien CA. Heuristics, overconfidence, and experience: impact on monitoring depth of neuromuscular blockade. *Anesth Analg*. 2019;128:1057–1059.

IARS International Anesthesia Research Society

Anesthesiologists' Overconfidence in Their Perceived Knowledge of Neuromuscular Monitoring and Its Relevance to All Aspects of Medical Practice: An International Survey

Mohamed Naguib, MD, MSc, FCARCSI,* Sorin J. Brull, MD, FCARCSI (Hon),†
Jennifer M. Hunter, MBE, MBChB, PhD, FRCA, FCARCSI (Hon),‡ Aaron F. Kopman, MD,§
Béla Fülesdi, MD, PhD, DSci,‖ Ken B. Johnson, MD,¶ and Hal R. Arkes, BA, PhD#

See Editorial, p 1057

BACKGROUND: In patients who receive a nondepolarizing neuromuscular blocking drug (NMBD) during anesthesia, undetected postoperative residual neuromuscular block is a common occurrence that carries a risk of potentially serious adverse events, particularly postoperative pulmonary complications. There is abundant evidence that residual block can be prevented when real-time (quantitative) neuromuscular monitoring with measurement of the train-of-four ratio is used to guide NMBD administration and reversal. Nevertheless, a significant percentage of anesthesiologists fail to use quantitative devices or even conventional peripheral nerve stimulators routinely. Our hypothesis was that a contributing factor to the nonutilization of neuromuscular monitoring was anesthesiologists' overconfidence in their knowledge and ability to manage the use of NMBDs without such guidance.

METHODS: We conducted an Internet-based multilingual survey among anesthesiologists worldwide. We asked respondents to answer 9 true/false questions related to the use of neuromuscular blocking drugs. Participants were also asked to rate their confidence in the accuracy of each of their answers on a scale of 50% (pure guess) to 100% (certain of answer).

RESULTS: Two thousand five hundred sixty persons accessed the website; of these, 1629 anesthesiologists from 80 countries completed the 9-question survey. The respondents correctly answered only 57% of the questions. In contrast, the mean confidence exhibited by the respondents was 84%, which was significantly greater than their accuracy. Of the 1629 respondents, 1496 (92%) were overconfident.

CONCLUSIONS: The anesthesiologists surveyed expressed overconfidence in their knowledge and ability to manage the use of NMBDs. This overconfidence may be partially responsible for the failure to adopt routine perioperative neuromuscular monitoring. When clinicians are highly confident in their knowledge about a procedure, they are less likely to modify their clinical practice or seek further guidance on its use. (Anesth Analg 2019;128:1118–26)

KEY POINTS

- **Question:** What is the confidence level among anesthesiologists in their personal knowledge of how to manage the administration of neuromuscular blocking drugs and reversal agents?
- **Findings:** Anesthesiologists surveyed are overconfident in their knowledge of how to monitor neuromuscular blockade.
- **Meaning:** Anesthesiologists' overconfidence may contribute to their belief that they can intuitively manage neuromuscular blockade without neuromuscular monitoring.

All you need in this life is ignorance and confidence, and then success is sure.

—Samuel Langhorne Clemens
(known as Mark Twain) (1835–1910)

A 2010 survey found that almost 20% of European and 10% of American anesthesiologists never use neuromuscular monitors of any kind.[1] Most respondents reported that neither conventional peripheral nerve

From the *Department of General Anesthesia, Cleveland Clinic Lerner College of Medicine of Case Western Reserve University, Cleveland Clinic, Cleveland, Ohio; †Department of Anesthesiology and Perioperative Medicine, Mayo Clinic College of Medicine, Jacksonville, Florida; ‡Department of Musculoskeletal Biology, University of Liverpool, Liverpool, United Kingdom; §Weill Cornell Medical College, New York City, New York; ‖Department of Anesthesiology and Intensive Care, University of Debrecen Faculty of Medicine, Debrecen, Hungary; ¶Department of Anesthesiology, University of Utah, Salt Lake City, Utah; and #Department of Psychology, The Ohio State University, Columbus, Ohio.

Accepted for publication July 3, 2018.

DOI: 10.1213/ANE.0000000000003714

Funding: S.J.B. has received research funding from Merck & Co, Inc (Kenilworth, NJ) (funds to Mayo Clinic).

Conflicts of Interest: See Disclosures at the end of the article.

Supplemental digital content is available for this article. Direct URL citations appear in the printed text and are provided in the HTML and PDF versions of this article on the journal's website (www.anesthesia-analgesia.org).

M. Naguib and S. J. Brull contributed equally to this work and share first authorship.

A. F. Kopman is now retired.

Reprints will not be available from the authors.

Address correspondence to Mohamed Naguib, MD, MSc, FCARCSI, Department of General Anesthesia, Anesthesiology Institute, Cleveland Clinic, 9500 Euclid Ave, NE6-306, Cleveland, OH 44195. Address e-mail to naguibm@ccf.org.

stimulators (PNSs) nor quantitative train-of-four monitors should be part of minimum monitoring standards.[1] Thus, neuromuscular blockers and their antagonists are often administered without proper guidance.[1–3] The incidence of residual paralysis in the immediate postoperative period (defined as a train-of-four ratio, <0.90) remains around 40%.[2,4–6] It is estimated that as many as 112,000 patients annually in the United States are at risk of critical respiratory events associated with undetected residual neuromuscular blockade.[7] Residual neuromuscular weakness may result in tracheal reintubation in the postanesthesia care unit (PACU), postoperative pulmonary complications, and delays in hospital discharge.[8–10] The incidence of tracheal reintubation in the PACU directly attributed to inadequate recovery of neuromuscular function is not known. However, different studies from large medical centers report reintubation rates of 0.05%–0.19% in this context.[11–14]

Despite a plethora of publications that stress the need for routine neuromuscular monitoring,[15–18] many anesthesiologists feel sufficiently confident about their medical knowledge and clinical expertise to believe that they can safely manage neuromuscular blockade without quantitative monitoring or even the use of a PNS.[1] Evidence contradicts these beliefs.[2,5,19,20]

The aim of our study was to explore anesthesiologists' confidence in their knowledge of the core concepts in neuromuscular monitoring. Overconfidence in this clinical domain may contribute to the persistence of inadequate detection of residual neuromuscular blockade by well-trained anesthesiologists. In the presence of overconfidence, the perceived need to confirm clinical assessments with quantitative monitoring tools is probably considered superfluous.[21,22]

We hypothesized that many anesthesiologists are overconfident in their knowledge of the intraoperative management of neuromuscular monitoring. To explore this hypothesis, we conducted a survey of anesthesiologists that consisted of 9 questions relevant to the clinical management of neuromuscular blockade and assessed their confidence in their response to each question. Inappropriately high confidence in their (incorrect) answers would be consistent with our hypothesis.

Confidence

The assessment of confidence has a long history in psychology and decision sciences. Such assessment is usually couched in terms of "calibration." To the extent that one's confidence is appropriate for one's level of accuracy, the person is said to be well calibrated. Assume that you have been presented with one hundred 2-option forced-choice questions such as "What is the capital of Arizona? A. Tucson. B. Phoenix." If you have assigned a confidence level of 70% to 10 of your 100 answers to such questions, you should correctly answer exactly 7 of those 10 questions to be perfectly calibrated; your accuracy and confidence level for that subset of questions would be identical, 70%. If you have assigned a confidence level of 100% to 27 of the 100 questions, every one of those 27 questions must be answered correctly for you to be perfectly calibrated for that subset of questions. Figure 1 contains 3 curves. The 45° line represents perfect calibration of confidence; each confidence level is appropriate for each level of accuracy. Over- and underconfidence are also indicated. Note that the abscissa cannot go <50% for the confidence one has in one's answers to 2-option questions because if one were <50% confident that the correct answer was chosen, she/he would have selected the other answer. Also note that under- and overconfidence are both examples of poor calibration; both diverge from the perfect calibration, 45° line in Figure 1.

It is important to understand what the calibration of confidence does not represent: it is not a measure of accuracy. People who answer a small number of questions correctly can be very well calibrated if they assign appropriately low confidence levels to their answers. Our hypothesis is that anesthesiologists answering questions about neuromuscular monitoring will provide data similar to the curve labeled "overconfident" in Figure 1. We offer no hypothesis as to what their accuracy data will be.

Calibration in the Medical Decision-Making Literature

Calibration is an important aspect of judgment performance, but the medical decision-making literature suggests that calibration is often deficient. For example, Dawson et al[23] asked 198 physicians to estimate values of pulmonary capillary wedge pressure, cardiac index, and systemic vascular resistance before right heart catheterization in 846 patients. The physicians also provided confidence in each of their estimates. The estimates' deviation from the actual measurements was unrelated to physician confidence in the estimates. The lack of relationship between accuracy and confidence signifies extremely poor calibration. Similarly, Stiegler et al[24] noted the presence of overconfidence among over half of resident physicians' management of a simulated anesthesia emergency.

Why Appropriate Confidence Is Important

Arkes et al[21] asked baseball experts and nonexperts to examine the batting statistics for each of 3 players who might have won the National League Most Valuable Player Award for each of 19 years. The participants were given the following helpful decision rule: "If you choose the player whose team finished highest in the standings that year, you will choose

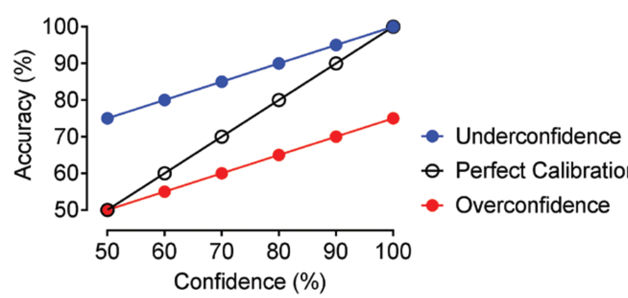


Figure 1. The black line with open circles represents perfect calibration of confidence; each confidence level is appropriate for each level of accuracy. The red and blue lines with filled circles represent over- and underconfidence, respectively. For 2-option questions (eg, true/false), the abscissa starts at 50%. Respondents would not indicate that their confidence was <50%, because to do so would indicate that they preferred the other answer. Under- and overconfidence are both examples of poor calibration; both diverge from the perfect calibration, 45° line.

correctly 75% of the time." The experts were seriously overconfident in their selection of the most valuable player for each of the 19 years. The nonexperts actually made significantly more correct choices than did the experts, due to the fact that the nonexperts used the very helpful decision rule more. We propose that an inappropriately high degree of confidence might also be responsible for anesthesiologists' reluctance to utilize quantitative assessment of perioperative neuromuscular monitoring; this hypothesis is consistent with a conjecture by Stiegler and Tung[25] that overconfidence would diminish a physician's likelihood to seek assistance.

Slope As an Additional Dependent Variable

Not only does the assessment of accuracy and confidence allow us to measure calibration, it also allows us to examine an index called "slope,"[26] which is defined as the difference between the confidence assigned to correct answers and the confidence assigned to incorrect answers. Slope is not a measure of under- or overconfidence. It is a measure of discrimination; can the respondent discriminate between correct and incorrect answers by assigning different confidence levels to these 2 categories of answers? People can be overconfident, underconfident, or perfectly calibrated and yet manifest the exact same slope. Whereas calibration pertains to the overall relationship between confidence and accuracy, slope is an important index of "meta-knowledge"—knowledge about what one knows and what one does not know. True experts can have good slope even if they are not well calibrated. Slope and calibration are not controversial concepts: no one would accept weak calibration and poor slope. We sought to address these issues by administering a 9-item test on neuromuscular monitoring to anesthesiologists and assessing the calibration and slope of the confidence ratings of their answers.

METHODS

After obtaining institutional approvals from Cleveland Clinic (Cleveland, OH) and Mayo Clinic (Jacksonville, FL), we conducted an Internet-based survey among anesthesiologists worldwide. Respondents gave their informed consent online before completing the survey. The International Anesthesia Research Society (United States), the Royal College of Anaesthetists (United Kingdom), The European Society of Anaesthesiology, the São Paulo State Society of Anesthesiologists (Brazil), the Hungarian Society of Anesthesiology and Intensive Therapy, the Swiss Society of Anesthesiology, and the Society of Anaesthetists of Hong Kong e-mailed all of their active members on the authors' behalf, inviting them to complete a 9-question survey anonymously (Supplemental Digital Content, Document, http://links.lww.com/AA/C535).

The survey questions were developed and critiqued by all investigators and were validated in a pilot study. The surveys were piloted twice. Our aim was to select 8–9 questions (with indisputable answers) and to omit any question that was not answered correctly (or any question that was answered correctly) by a large majority of respondents. Three questions were deleted after the first pilot, and 1 was deleted after the second pilot. We aimed to exclude nondiscriminatory questions in the pilot study. A question was deemed to be nondiscriminatory if it did not discriminate well between anesthesiologists who answered most of the questions correctly and those who did not. For instance, if there were a question for which almost no pilot subject knew the answer, the question would have been removed from the questionnaire. Also, if 99% of respondents had answered correctly, the question would have been removed from the questionnaire. Survey face validity was deemed adequate. Each survey question was developed based on previously published findings related to neuromuscular blockade monitoring. (See References Supporting Survey Questions in the Supplemental Digital Content, Document, http://links.lww.com/AA/C535.)

We provided additional separate unique links to the survey in different languages (German, French, Spanish, Portuguese, and Hungarian). To ensure accurate translation of the survey from English to other languages, a 2-step process was used. First, anesthesiologists who were native speakers of these languages translated the survey from English into their native language. Second, different anesthesiologists who were native speakers of these languages back-translated the surveys into English. The original and the back-translated versions were compared independently by 2 investigators (M.N. and S.J.B.) to assess translation accuracy.

The survey was stored on a dedicated website (https://www.surveymonkey.com/r/neuromuscularsurvey) accessed via computer. The survey was designed to be completed in <10 minutes, and all questions were formatted into a Hypertext Markup Language interface. Responses were stored electronically in separate customized databases. The survey was available online for 90 days (August 1, 2017 to October 31, 2017). An electronic link to the survey was provided within the body of the e-mail invitation and was also published on the Royal College of Anaesthetists (United Kingdom) website. Reminder e-mails were sent 30 days after the initial invitations.

All questions were in a true/false format. After each question, we asked the respondent to indicate his/her level of confidence in the answer using a scale from 50% to 100% in 5% increments using a drop-down menu. Participants were orientated to the confidence scale using the following definition: 50% indicated complete uncertainty; and 100% indicated complete certainty.[27,28]

This combination of 2-option questions and a 50%–100% confidence rating scale is extremely common in the judgment/decision-making literature.[29] As the scales of the 2 factors—accuracy and confidence—align perfectly, no respondent would ever give a confidence rating <50% because if a person were <50% confident in 1 of the 2 possible answers, he or she would choose the other answer, whose confidence level would therefore be >50%. If a person were totally ignorant about the 2 possible options for any question, then respondent would answer correctly with a probability of 50%. Thus, a perfectly calibrated but ignorant person would assign a confidence level of 50% to a question that had an accuracy probability of 50%. Confidence and accuracy would align perfectly. Analogously, a perfectly calibrated person who was fully informed about a domain would assign confidence levels of 100% to answers that were 100% likely to be accurate. Thus, the use of 2-option questions with a 50%–100% confidence scale describes a straightforward interaction between accuracy and confidence, which is the definition of calibration.

Respondents were also asked the number of years in practice (0–5, 6–10, 11–15, 16–20, >20), their degree, and the country in which they practiced.

The raw data (excluding the country of each respondent) are deposited in the Open Science Framework (https://osf.io/rn2mv).

STATISTICAL CONSIDERATIONS

Calibration is a measure of the correspondence between accuracy and confidence. To calculate calibration, we subtracted the average proportion of the questions answered correctly from the average confidence assigned to the answers to the questions. For example, if a person answered 5 of the 9 questions correctly, the proportion of correct answers is 0.556. If the average confidence one assigns to the answers to these 9 questions is 95%, then overconfidence is 0.950–0.556 = 0.394 or 39.4%. We estimated that a total sample size of 272 respondents will be needed for a t test to have a 95% power to detect an effect size (Cohen's d) of 0.2 to test whether the mean overall calibration is >0 (1-tailed test).[30] Although both over- and underconfidence signify poor calibration, we use overconfidence in this example because underconfidence is extraordinarily rare and therefore was unanticipated in our data.

We performed two 1-way analyses of variance to ascertain whether the number of years of professional experience was related either to the magnitude of overconfidence or to the percentage of questions answered correctly.

Slope was indexed by subtracting the confidence assigned to the incorrect answers from the confidence assigned to the correct answers. We calculated overall slope, and because of the heterogeneity of the questions, we also calculated the slope separately for each question using a Bonferroni correction thereby making $\alpha = .0056$ (.05/9). A P value <.05 was considered statistically significant for all other analyses.

RESULTS

A total of 2560 persons accessed the website and provided demographic information; of these, 1629 anesthesiologists from 80 different countries completed the 9-question survey. Supplemental Digital Content, Table 1, http://links.lww.com/AA/C535, contains the number of respondents from each country who completed the survey. It is impossible to determine the number of society members who received or viewed the survey. This number would be needed to calculate the response rate. Lacking that number, we only can assert that the number of respondents who completed the survey was large (1629) and geographically diverse. Supplemental Digital Content, Table 2, http://links.lww.com/AA/C535, contains information about the number of respondents at each level of experience.

The 1629 respondents correctly answered an average of 57.1% of the 9 questions. The mean confidence assigned by the respondents was 83.5% (95% confidence interval [CI], 83%–84%), which was greater than their accuracy of 57.1% (95% CI, 56.2%–58.0%) ($t_{(1628)} = 55.48$, $P < .001$). The magnitude of overconfidence was thus 26.4% (95% CI, 25.48%–27.34%) (Figure 2). Of the 1629 respondents, 1496 (91.8%) were overconfident, 119 (7.3%) were underconfident, and 14 (0.9%) were perfectly calibrated. Supplemental Digital Content, Table 3, http://links.lww.com/AA/C535, presents the proportion of correct responses for each question at each level of confidence and overall accuracy at each level of confidence. Figure 3 presents the calibration curves for each question and an overall calibration curve for all questions combined. For the purpose of constructing the graphs, we noted the accuracy of each individual answer which was assigned a confidence level within each of the 5 deciles (50%–59%, 60%–69%, 70%–79%, 80%–89%, 90%–99%) and 100% and plotted the mean accuracy of those answers in the middle of the appropriate decile and for 100% on the x-axis.[a]

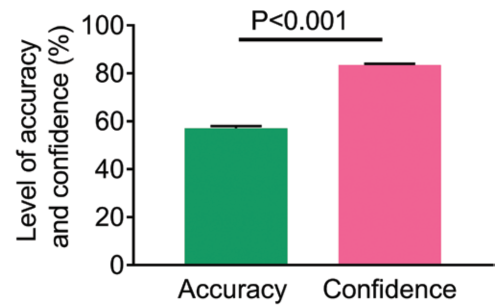


Figure 2. The level of accuracy and the level of confidence among the surveyed anesthesiologists. The mean confidence assigned by the respondents was 83.5% (95% CI, 83%–84%), which was greater than their accuracy of 57.1% (95% CI, 56.2%–58.0%) ($t_{(1628)} = 55.48$, $P < .001$). The magnitude of overconfidence was thus 26.4% (95% CI, 25.48%–27.34%). Data represent mean and 95% CI. CI indicates confidence interval.

Survey respondents manifested overconfidence on every question. When survey respondents were certain that they answered the question correctly (100% confidence), their accuracy was only 66.2%. When the respondents expressed a confidence of 50%, they were correct 46.4% of the time.

We also calculated the slope for the respondents' confidence ratings. Slope is indexed by the difference between the confidence assigned to the correct and incorrect answers. The average confidence for the correct answers was 85.6, and the average confidence for the incorrect answers was 79.7, yielding a slope of 5.8 (note the rounding error; 95% CI, 5.18–6.40) ($t_{(1611)} = 18.53$, $P < .001$). The lower degrees of freedom are due to the fact that for respondents who answered all of the questions correctly (n = 14) or all of the questions incorrectly (n = 3), the slope was not calculable. In terms of each question, for all but questions 7 and 8, the slope was positive and significant (each of 7 $ts_{(1627)} > 4.3$, each $P < .001$). The slope for question 8 was significant and negative (−13.8), $t_{(1627)} = 12.79$, $P < .001$, which means that when anesthesiologists answered incorrectly they were more confident of the correctness of their answer than when they responded correctly. The slope for question 7 was not significantly different from zero. Experience was not significantly related to either calibration or slope (both Fs < 1.0).

[a]Because the graphs have 6 decile subdivisions for confidence, a large number of respondents did not use all of the deciles in his or her answers. The accuracy level for such deciles is therefore undefined for many respondents. Many other respondents used a decile (eg, 70%) only once. The accuracy level for such deciles must be either 0% or 100%. These complications render error bars inappropriate. This is the reason that calibration graphs contain no error bars.

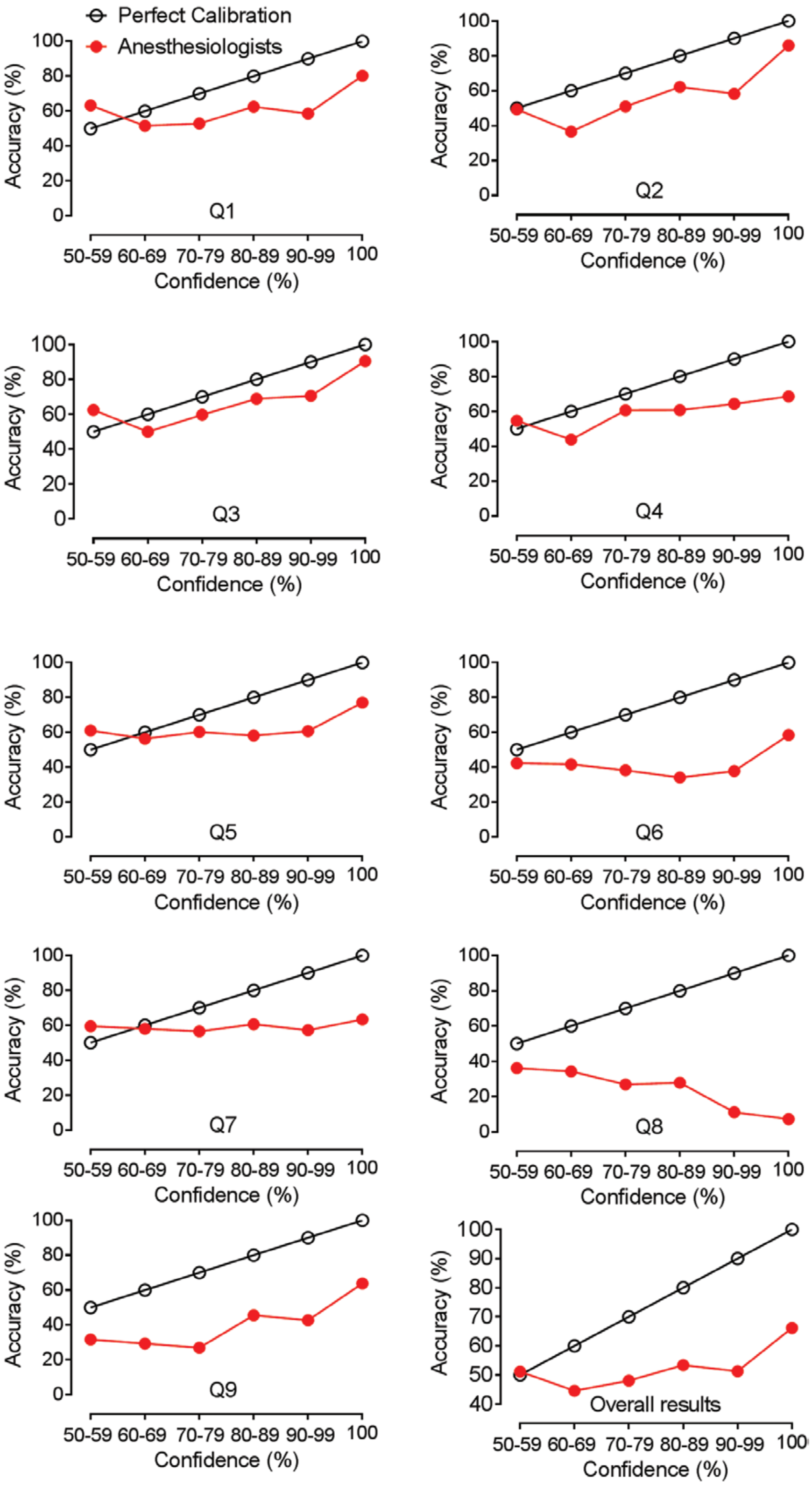


Figure 3. Calibration curves for each of the 9 questions and for the overall results summed over 9 questions. The black lines with open circles represent perfect calibration of confidence; each confidence level is appropriate for each level of accuracy. The red lines with filled circles represent overconfidence.

DISCUSSION

The results confirmed our primary study hypothesis: the findings of this survey of substantial statistical power suggested that the anesthesiologists we sampled are overconfident regarding their knowledge of intraoperative neuromuscular blockade management and monitoring. The most important results of this investigation were that the respondents were overconfident in their knowledge (26.4%), while their slope was only 5.8%. The mean overconfidence of 26.4% is larger than that generally found in the current judgment/decision-making literature.[28,29]

We attempted to characterize the magnitude of overconfidence and slope by considering previous research on these 2 factors. There are no prior studies using anesthesia professionals as respondents to 2-option, half-scale (50%–100%) true-false questions. Given this lack of prior comparable data, what level of calibration might we have expected from our respondents?

Juslin et al[29] summarized the data from numerous studies involving 29 samples of 2-option half-scale questions. They reported a mean proportion correct of 0.65. This is slightly above the accuracy level observed in our respondents. The mean magnitude of overconfidence in these studies was 10% (95% CI, ±2%). By comparison, our observed level of overconfidence in surveyed anesthesiologists (26.4%) is much greater than we might have expected.[b]

There are numerous studies in which physicians and medical students of various specialties plus other health professionals were asked to assign confidence ratings to their performance on factual questions, various clinical skills, and diagnoses. (These studies do not utilize 2-option half-scale response scales.) Such studies regularly document poor calibration between confidence and the level of performance with overconfidence being the usual finding.[26,31–37] The results of these studies support the conclusion that our result of significant overconfidence is representative and that our findings are not anomalous. In addition, we used vastly more participants (from many different countries) than these earlier studies, thus increasing our confidence in the results.

A second consideration that might have guided our expectations concerning the calibration of our respondents is known as the "hard-easy effect."[29] Figure 1 presents an idealized depiction of this effect. For hard questions with a low probability of being answered correctly, they are often found to be associated with overconfidence. As the questions become easier, the curve rises, even to the level that on extremely easy questions, underconfidence is occasionally observed.[28] The anesthesiologists' relatively modest accuracy on the true/false test pertaining to perioperative neuromuscular monitoring was 1 factor contributing to their acute overconfidence. The "hard-easy" effect is the reason why question 8 manifested the most overconfidence; it was the question with the lowest proportion of correct answers.

A third consideration pertains to the feedback environment in which confidence judgments are rendered. Horserace handicappers,[38] expert bridge players,[39] and weather forecasters[40] exhibit outstanding calibration. These 3 groups obtain prompt, incontrovertible feedback after they make an estimate. A weather forecaster who estimates 100% chance of rain might need to seek alternative employment if such estimates occur frequently for days without any rain. Do anesthesiologists receive prompt, incontrovertible feedback about adverse outcomes every time they make a subjective estimate pertaining to neuromuscular function? Probably not, and so their calibration will be deficient compared to the excellent calibration of those professionals who do receive such feedback.

A fourth factor to consider is the role of expertise. Expertise should certainly help the test taker to answer more questions correctly, but would it confer some advantage in calibration? Lichtenstein and Fischhoff[41] attempted to answer this question by asking graduate students in psychology to answer questions both on that topic and general-knowledge questions pertaining to a wide variety of other domains. The 2 sets of questions were matched in proportion answered correctly. The investigators found no difference in the calibration of the 2 sets of questions even though 1 was in the participants' field of expertise. Thus, expertise in a domain conferred no calibration advantage, so by analogy we might not have expected the anesthesiologists' superior domain knowledge to bolster their calibration.

Might medical expertise foster better—that is, larger—slope on questions of a medical context? Prior research has examined the ability of medical personnel to assign higher confidence levels to correct answers than incorrect ones.[26,42] Unfortunately, these studies involve predicting the occurrence of an external event. Such studies therefore involve a task that is not analogous to the prediction of the correctness of one's own answers, which was the task in our study. Nevertheless, such studies might guide our expectations to some extent. Physicians predicting the 6-month survival of seriously ill patients had a mean slope of 26%.[26] The patients themselves, possessing more subjective knowledge but much less medical knowledge than their physicians, had a mean slope of only 13%. In a separate study of physicians' predictions of the 6-month survival of lung cancer patients, the most accurate physician had a slope of 13%; the least accurate physician had a slope of 2%.[42] The slope we obtained was 5.8%, which does not compare favorably with prior data. Slope reflects the judge's ability to discriminate correct answers from incorrect ones; not surprisingly, such discrimination ability fosters better calibration.[42]

Why Would Anesthesiologists Not Utilize Perioperative Neuromuscular Monitoring?

We suggest that 1 reason why anesthesiologists might eschew the use of perioperative neuromuscular monitoring and especially the use of quantitative/objective monitoring of neuromuscular function is that those who believe that they have high levels of expertise think they do not need such assistance.[21,22] Closely related to this reason is the "better-than-average effect."[43] For example, Svenson[44] reported that 46% of Americans placed themselves in the top 20% in driving skills, and 82% placed themselves in the top 30% in automotive safety. Thus, many anesthesiologists might agree that the average anesthesiologist should use quantitative monitoring, but as above-average clinicians, they may think, "I certainly don't need to use it." Those who are grossly overconfident would seem to be particularly vulnerable to the "better-than-average effect."

Psychologists[45] and operations researchers[46] have long been frustrated by the fact that practitioners are highly reluctant to use quantitative actuarial formulae and decision aids that are more accurate than subjective intuitive

[b]Different levels of overconfidence occur depending on the type of task and dependent variable.[29] Those summarized by Juslin et al[29] on their page 390 are the studies most comparable to ours.

estimates. This has been documented previously in medical contexts.[47,48]

The reasons for the low adoption rate of quantitative neuromuscular monitoring are no doubt multifactorial. Overconfidence is likely to be only 1 cause of this reality[22]; other possible causes include overperception by practitioners of reasons why the quantitative technique might not be appropriate in a particular instance.[49] In addition, reticence to use monitors to guide management of neuromuscular block may be compounded by the relative paucity of easy-to-use, reliable objective monitors. One of the most frequently used such monitors (TOF-Watch; Organon, Cork, Ireland) is no longer manufactured or available commercially. However, new and improved free-standing objective monitors have recently been introduced into clinical use in the United States (StimPod NMS450; Xavant Technology Ltd, Pretoria, South Africa, and the TOFscan; IDMed, Marseilles, France), while others (TOFcuff; RGB Medical, Madrid, Spain, and TetraGraph; Senzime, Uppsala, Sweden) have been Conformité Européene (CE) Mark certified and are available for clinical use outside the United States. Despite this availability, however, their use in the routine clinical setting remains limited. Clinicians who have never used quantitative monitors (erroneously) believe that clinically significant postoperative residual neuromuscular block is a rare event[1] and that such adverse outcomes do not occur in their own practice. Psychologists have long been investigating the reluctance of people to take precautions to protect against low-probability, high-impact negative events.[50,51] For example, until the advent of mandatory seat belts in American automobiles, many people refused to wear such belts due to the low probability of a serious accident in any individual trip. Only when the lifetime risk of not wearing a seat belt was made prominent were people more likely to "buckle up."[50] Analogously, anesthesiologists might be reluctant to use objective monitoring due to the low perceived probability of residual block in any 1 patient. In fact, the majority of clinicians feel that the incidence of residual block is <1%. However, 15% of clinicians admit that they have seen a patient who had inadequately recovered from neuromuscular block in the PACU.[1]

Other factors contributing to the nonuse of neuromuscular monitoring might include the cost of providing monitors in every operating room, their maintenance, and practitioner resistance to change.

Our observations regarding overconfidence are perhaps even more applicable to the use of conventional PNS devices. There may be mitigating circumstances (eg, availability) for not using an objective monitor. But there are no reasonable excuses for not routinely using a PNS device when managing intraoperative neuromuscular block.

LIMITATIONS

As we are unable to provide a precise response rate, the question may arise as to whether our respondents comprise a representative sample of anesthesiologists. Perhaps only those who were confident in the accuracy of their answers or interested in neuromuscular monitoring would attempt the survey. Would this "self-selection" foster the large magnitude of overconfidence we found? We think not, for a couple of reasons. A calibration analysis does not in any way penalize respondents who are highly confident if their confidence is warranted by a high level of accuracy. What we do know from our analysis is that the confidence expressed by this large group of anesthesiologists was not warranted. We also know that their amount of clinical experience had no influence on calibration, which suggests that if either novice or highly experienced anesthesiologists selectively refrained from participating in our survey the results would likely not have been different.

A similar argument pertains to slope. An analysis of slope will not necessarily be unfavorable if that person had a high overall confidence level. One can still manifest a large difference between confidence levels assigned to correct versus incorrect answers despite being overconfident. We suggest that even if our survey had been differentially attractive to confident respondents, this would not explain their very poor calibration and slope.

This survey could also be criticized by the low response rate. Perhaps the biggest surveys of anesthesiologists are the annual surveys on salary and related issues (www.LocumTenens.com; www.medscape.com). Although these 2 surveys are not research experiments and do not ask the respondents to take a quiz in which their knowledge and confidence are being assessed, the 2017 response rate of these 2 surveys among American anesthesiologists was only 2% and 6%, respectively. We suspect that anesthesiologists are reticent about volunteering to have their professional knowledge assessed; we were gratified that 1629 anesthesiologists graciously did so. In fact, our study had a sample size far in excess of the number of participants (n = 24–144) in other studies that assessed confidence.[31–33,35–37] Furthermore, Dawson et al[23] and Arkes et al[26] found very poor calibration among physicians in a range of specialties. Therefore, we think that the overconfidence we documented is not an anomalous finding caused by a nonrepresentative sampling procedure.

However, we do acknowledge that the number of our respondents from each country represents only a very small fraction of anesthesiologists practicing in that country. Although our sample size greatly exceeded that employed in other studies of calibration of medical knowledge, we have not tested the vast majority of anesthesiologists in any 1 country, and the survey results may not be an accurate representation of practicing anesthesiologists worldwide.

Another limitation of the current survey may be considered to be that many of the survey questions did not ask specifically how to monitor neuromuscular function or how to dose the reversal agents based on the results of monitoring. While this may seem a relevant limitation, it would be insufficient to simply ask clinicians about monitoring. For without knowledge of the neuromuscular blocking drugs and antagonists whose effects they are monitoring, would one expect the clinician to monitor appropriately, or even monitor at all? We think not. We therefore suggest that our questions were all appropriate.

Finally, another criticism might be that our survey did not specifically ask the respondents whether they were using neuromuscular (objective) monitoring in their practice, and perhaps those who do use such monitoring would have provided different data than those who do not. Thus, the more users of neuromuscular monitoring there were among our survey participants, the more surprising would be the substantial overconfidence we did find among our respondents. However, our survey design does not allow us to ascertain if users and nonusers would have provided different data.

IMPLICATIONS

The respondents to our survey answered an average of only 57% of the questions correctly. This was only slightly better than that might be achieved by pure guesswork. Even when respondents were absolutely certain of the correctness of their answer (100% confidence), they were correct only 66% of the time. Only 14 respondents (0.9%) were perfectly calibrated. Thus, the clinicians surveyed were considerably less knowledgeable regarding perioperative neuromuscular monitoring than they believed. Almost 2 decades ago, 2 social scientists described a similar phenomenon, which has subsequently become known as the Kruger–Dunning Effect.[52] This is a cognitive bias wherein unskilled individuals suffer from illusory superiority, mistakenly rating their ability much higher than warranted; this was attributed to a metacognitive inability of the unskilled to recognize deficits in their competence or knowledge. Our results are more remarkable than those of Kruger and Dunning[52] in that our subjects were, in contrast, very highly skilled professionals answering questions in their domain of expertise, not undergraduates rating such domains as the funniness of jokes and the grammatical quality of sentences. We suggest that the anesthesiologists' overconfidence and the inability to discriminate correct from incorrect answers are at least partially responsible for the widespread failure to adopt quantitative perioperative neuromuscular monitoring. In addition, the findings could have more general clinical relevance. When clinicians are highly confident that they are knowledgeable about a procedure, they are less likely to modify their clinical practice or seek further guidance or knowledge. It is hoped that the results of this survey and the discussion generated by the discrepancy between clinicians' knowledge and confidence will serve as an impetus for a new evaluation of the role of neuromuscular and specifically quantitative monitoring in routine anesthetic practice.

ACKNOWLEDGMENTS

The authors thank Francois Donati, MD, Anke Bellinger, MD, Klaus D. Torp, MD, Mauricio Perilla, MD, Jose L. Diaz-Gomez, MD, Daniela Ionescu, MD, PhD, and Ricardo Carlos Vieira, MD, for their help with language translations.

DISCLOSURES

Name: Mohamed Naguib, MD, MSc, FCARCSI.
Contribution: This author helped design the study, analyze the data, and write the manuscript.
Conflicts of Interest: M. Naguib has served as a consultant for GE Healthcare in 2018.
Name: Sorin J. Brull, MD, FCARCSI (Hon).
Contribution: This author helped design the study and write the manuscript.
Conflicts of Interest: S. J. Brull is a principal and shareholder in Senzime AB (publ) (Uppsala, Sweden); and a member of the Scientific Advisory Boards for ClearLine MD (Woburn, MA), The Doctors Company (Napa, CA), and NMD Pharma (Aarhus, Denmark).
Name: Jennifer M. Hunter, MBE, MBChB, PhD, FRCA, FCARCSI (Hon).
Contribution: This author helped design the study and write the manuscript.
Conflicts of Interest: None.
Name: Aaron F. Kopman, MD.
Contribution: This author helped design the study and write the manuscript.
Conflicts of Interest: None.
Name: Béla Fülesdi, MD, PhD, DSci.
Contribution: This author helped design the study and write the manuscript.
Conflicts of Interest: None.
Name: Ken B. Johnson, MD.
Contribution: This author helped design the study and write the manuscript.
Conflicts of Interest: None.
Name: Hal R. Arkes, BA, PhD.
Contribution: This author helped design the study, analyze the data, and write the manuscript.
Conflicts of Interest: None.
This manuscript was handled by: Tong J. Gan, MD.

REFERENCES

1. Naguib M, Kopman AF, Lien CA, Hunter JM, Lopez A, Brull SJ. A survey of current management of neuromuscular block in the United States and Europe. *Anesth Analg*. 2010;111:110–119.
2. Naguib M, Kopman AF, Ensor JE. Neuromuscular monitoring and postoperative residual curarisation: a meta-analysis. *Br J Anaesth*. 2007;98:302–316.
3. Brull SJ, Murphy GS. Residual neuromuscular block: lessons unlearned. Part II: methods to reduce the risk of residual weakness. *Anesth Analg*. 2010;111:129–140.
4. Kopman AF, Yee PS, Neuman GG. Relationship of the train-of-four fade ratio to clinical signs and symptoms of residual paralysis in awake volunteers. *Anesthesiology*. 1997;86:765–771.
5. Todd MM, Hindman BJ, King BJ. The implementation of quantitative electromyographic neuromuscular monitoring in an academic anesthesia department. *Anesth Analg*. 2014;119:323–331.
6. Fortier LP, McKeen D, Turner K, et al. The RECITE study: a Canadian prospective, multicenter study of the incidence and severity of residual neuromuscular blockade. *Anesth Analg*. 2015;121:366–372.
7. Brull SJ, Naguib M, Miller RD. Residual neuromuscular block: rediscovering the obvious. *Anesth Analg*. 2008;107:11–14.
8. Murphy GS, Szokol JW, Marymont JH, Greenberg SB, Avram MJ, Vender JS. Residual neuromuscular blockade and critical respiratory events in the postanesthesia care unit. *Anesth Analg*. 2008;107:130–137.
9. Bulka CM, Terekhov MA, Martin BJ, Dmochowski RR, Hayes RM, Ehrenfeld JM. Nondepolarizing neuromuscular blocking agents, reversal, and risk of postoperative pneumonia. *Anesthesiology*. 2016;125:647–655.
10. Bronsert MR, Henderson WG, Monk TG, et al. Intermediate-acting nondepolarizing neuromuscular blocking agents and risk of postoperative 30-day morbidity and mortality, and long-term survival. *Anesth Analg*. 2017;124:1476–1483.
11. Mathew JP, Rosenbaum SH, O'Connor T, Barash PG. Emergency tracheal intubation in the postanesthesia care unit: physician error or patient disease? *Anesth Analg*. 1990;71:691–697.
12. Rose DK, Cohen MM, Wigglesworth DF, DeBoer DP. Critical respiratory events in the postanesthesia care unit. Patient, surgical, and anesthetic factors. *Anesthesiology*. 1994;81:410–418.
13. Lee PJ, MacLennan A, Naughton NN, O'Reilly M. An analysis of reintubations from a quality assurance database of 152,000 cases. *J Clin Anesth*. 2003;15:575–581.
14. Epstein RH, Dexter F, Lopez MG, Ehrenfeld JM. Anesthesiologist staffing considerations consequent to the temporal distribution of hypoxemic episodes in the postanesthesia care unit. *Anesth Analg*. 2014;119:1322–1333.
15. Kopman AF. Managing neuromuscular block: where are the guidelines? *Anesth Analg*. 2010;111:9–10.

16. Miller RD, Ward TA. Monitoring and pharmacologic reversal of a nondepolarizing neuromuscular blockade should be routine. *Anesth Analg*. 2010;111:3–5.
17. Donati F. Neuromuscular monitoring: what evidence do we need to be convinced? *Anesth Analg*. 2010;111:6–8.
18. Brull SJ, Kopman AF. Current status of neuromuscular reversal and monitoring: challenges and opportunities. *Anesthesiology*. 2017;126:173–190.
19. Baillard C, Gehan G, Reboul-Marty J, Larmignat P, Samama CM, Cupa M. Residual curarization in the recovery room after vecuronium. *Br J Anaesth*. 2000;84:394–395.
20. Kotake Y, Ochiai R, Suzuki T, et al. Reversal with sugammadex in the absence of monitoring did not preclude residual neuromuscular block. *Anesth Analg*. 2013;117:345–351.
21. Arkes HR, Dawes RM, Christensen C. Factors influencing the use of a decision rule in a probabilistic task. *Organ Behav Hum Decis Process*. 1986;37:93–110.
22. Sieck WR, Arkes HR. The recalcitrance of overconfidence and its contribution to decision aid neglect. *J Behav Decis Mak*. 2005;18:29–53.
23. Dawson NV, Connors AF Jr, Speroff T, Kemka A, Shaw P, Arkes HR. Hemodynamic assessment in managing the critically ill: is physician confidence warranted? *Med Decis Making*. 1993;13:258–266.
24. Stiegler MP, Neelankavil JP, Canales C, Dhillon A. Cognitive errors detected in anaesthesiology: a literature review and pilot study. *Br J Anaesth*. 2012;108:229–235.
25. Stiegler MP, Tung A. Cognitive processes in anesthesiology decision making. *Anesthesiology*. 2014;120:204–217.
26. Arkes HR, Dawson NV, Speroff T, et al. The covariance decomposition of the probability score and its use in evaluating prognostic estimates. SUPPORT Investigators. *Med Decis Making*. 1995;15:120–131.
27. Koriat A, Lichtenstein S, Fischhoff B. Reasons for confidence. *J Exp Psychol Hum Learn*. 1980;6:107–118.
28. Lichtenstein S, Fischhoff B, Phillips LD. Calibration of probabilities: the state of the art to 1980. In: Kahneman D, Slovic P, Tversky A, eds. *Judgment Under Uncertainty: Heuristics and Biases*. Cambridge, United Kingdom: Cambridge University Press, 1982:306–334.
29. Juslin P, Winman A, Olsson H. Naive empiricism and dogmatism in confidence research: a critical examination of the hard-easy effect. *Psychol Rev*. 2000;107:384–396.
30. Cohen J. *Statistical Power Analysis for the Behavioral Sciences*. 2nd ed. Hillsdale, NJ: Lawrence Erlbaum Associates; 1988.
31. Barnsley L, Lyon PM, Ralston SJ, et al. Clinical skills in junior medical officers: a comparison of self-reported confidence and observed competence. *Med Educ*. 2004;38:358–367.
32. Hodges B, Regehr G, Martin D. Difficulties in recognizing one's own incompetence: novice physicians who are unskilled and unaware of it. *Acad Med*. 2001;76:S87–S89.
33. Davis DA, Mazmanian PE, Fordis M, Van Harrison R, Thorpe KE, Perrier L. Accuracy of physician self-assessment compared with observed measures of competence: a systematic review. *JAMA*. 2006;296:1094–1102.
34. Gordon MJ. A review of the validity and accuracy of self-assessments in health professions training. *Acad Med*. 1991;66:762–769.
35. Meyer AN, Payne VL, Meeks DW, Rao R, Singh H. Physicians' diagnostic accuracy, confidence, and resource requests: a vignette study. *JAMA Intern Med*. 2013;173:1952–1958.
36. Morgan PJ, Cleave-Hogg D. Comparison between medical students' experience, confidence and competence. *Med Educ*. 2002;36:534–539.
37. Risucci DA, Tortolani AJ, Ward RJ. Ratings of surgical residents by self, supervisors and peers. *Surg Gynecol Obstet*. 1989;169:519–526.
38. Hoerl AE, Fallin HK. Reliability of subjective evaluations in a high incentive situation. *J Roy Stat Soc A*. 1974;137:227–230.
39. Keren G. Facing uncertainty in the game of bridge: a calibration study. *Organ Behav Hum Dec*. 1987;39:98–114.
40. Murphy AH, Winkler RL. Subjective probability forecasting experiments in meteorology: some preliminary results. *Am Meteorol Soc*. 1995;15:120–131.
41. Lichtenstein S, Fischhoff B. Do those who know more also know more about how much they know? *Organ Behav Hum Perform*. 1977;20:159–183.
42. Kee F, Owen T, Leathem R. Offering a prognosis in lung cancer: when is a team of experts an expert team? *J Epidemiol Community Health*. 2007;61:308–313.
43. Alicke MD, Klotz ML, Breitenbecher DL, Yurak TJ, Vredenburg DS. Personal contact, individuation, and the better-than-average effect. *J Pers Soc Psychol*. 1995;68:804–825.
44. Svenson O. Are we all less risk and more skillful than our fellow drivers? *Acta Psychol*. 1981;94:143–148.
45. Grove WM, Zald DH, Lebow BS, Snitz BE, Nelson C. Clinical versus mechanical prediction: a meta-analysis. *Psychol Assess*. 2000;12:19–30.
46. Dalrymple DJ. Sales forecasting practices: results of a United States survey. *Int J Forecast*. 1987;3:379–392.
47. Corey GA, Merenstein JH. Applying the acute ischemic heart disease predictive instrument. *J Fam Pract*. 1987;25:127–133.
48. Ridderikhoff J, van Herk B. Who is afraid of the system? Doctors' attitude towards diagnostic systems. *Int J Med Inform*. 1999;53:91–100.
49. Dawes RM, Faust D, Meehl PE. Clinical versus actuarial judgment. *Science*. 1989;243:1668–1674.
50. Slovic P, Fischhoff B, Lichtenstein S. Accident probabilities and seat belt usage: a psychological perspective. *Accid Anal Prev*. 1978;10:281–285.
51. Henrich L, McClure J, Crozier M. Effects of risk framing on earthquake risk perception: life-time frequencies enhance recognition of the risk. *Int J Disaster Risk Reduct*. 2015;13:145–150.
52. Kruger J, Dunning D. Unskilled and unaware of it: how difficulties in recognizing one's own incompetence lead to inflated self-assessments. *J Pers Soc Psychol*. 1999;77:1121–1134.

Anesthetic Clinical Pharmacology Section Editor: **Ken B. Johnson**
Preclinical Pharmacology Section Editor: **Markus W. Hollmann**

The Effects of Postoperative Residual Neuromuscular Blockade on Hospital Costs and Intensive Care Unit Admission: A Population-Based Cohort Study

Stephanie D. Grabitz, MD,* Nishan Rajaratnam, MD,* Khushi Chhagani, BS,* Tharusan Thevathasan, Cand Med,* Bijan J. Teja, MD, MBA,† Hao Deng, MD, MPH,* Matthias Eikermann, MD, PhD,†‡ and Barry J. Kelly, MD, MSc†

See Editorial, p 1065

BACKGROUND: Postoperative residual neuromuscular blockade continues to be a frequent occurrence with a reported incidence rate of up to 64%. However, the effect of postoperative residual neuromuscular blockade on health care utilization remains unclear. We conducted a retrospective cohort study to investigate the effects of postoperative residual neuromuscular blockade on hospital costs (primary outcome), intensive care unit admission rate, and hospital length of stay (secondary outcomes).

METHODS: We performed a prespecified secondary analysis of data obtained in 2233 adult patients undergoing surgery under general anesthesia. Postoperative residual neuromuscular blockade was defined as a train-of-four ratio <0.9 in the postanesthesia care unit (PACU). Our confounder model adjusted for a variety of patient, surgical, and anesthesia-related factors. We fitted truncated negative binomial regression models for hospital cost and hospital length of stay analyses and a logistic regression model for our intensive care unit admission analysis.

RESULTS: Overall, 457 (20.5%) patients in our cohort had residual neuromuscular blockade on admission to the PACU. Postoperative residual neuromuscular blockade was not independently associated with increased hospital costs (adjusted incidence rate ratio, 1.04, CI, 0.98–1.11; *P* = .22). There were significantly higher odds of intensive care unit admission in those with postoperative residual neuromuscular blockade compared to those without (adjusted odds ratio, 3.03, CI, 1.33–6.87; *P* < .01). Further, we found a trend toward increased hospital length of stay in patients with postoperative residual neuromuscular blockade (adjusted incidence rate ratio, 1.09; *P* = .06). Sensitivity analysis using the same model in the day of surgery admissions and ambulatory surgery confirmed our findings.

CONCLUSIONS: Postoperative residual neuromuscular blockade at PACU admission was not significantly associated with increased hospital costs, but was associated with higher rates of intensive care unit admission. These findings support the view that clinicians should continue to work to reduce the rate of postoperative residual neuromuscular blockade. (Anesth Analg 2019;128:1129–36)

KEY POINTS

- **Question:** Is there an association between postoperative residual neuromuscular blockade in postanesthesia care unit and hospital costs?
- **Findings:** Postoperative residual neuromuscular blockade in postanesthesia care unit was not associated with increased hospital costs but there was a significant increase in the odds of intensive care unit admission.
- **Meaning:** Postoperative residual neuromuscular blockade is prevalent and its association with an increased odds of intensive care unit admission should alert clinicians to screen for its presence.

From the *Department of Anesthesia, Critical Care, and Pain Medicine, Massachusetts General Hospital and Harvard Medical School, Boston, Massachusetts; †Department of Anesthesia, Critical Care, and Pain Medicine, Harvard Medical School, Beth Israel Deaconess Medical Center, Boston, Massachusetts; and ‡Klinik für Anästhesiologie und Intensivmedizin, Universität Duisburg-Essen, Essen, Germany.

Accepted for publication December 12, 2018.

Funding: Dr Eikermann reports receipt of grants from Merck; personal fees (honoraria) from Merck; funding from Jeffrey and Judith Buzen; holds equity in Calabash Bioscience and an investigator-initiated grant (IISP# 39442) was provided by Schering-Plough Research Institute, Kenilworth, NJ, a Division of Schering Corporation, to the Massachusetts General Hospital.

DOI: 10.1213/ANE.0000000000004028

The authors declare no conflicts of interest.

Supplemental digital content is available for this article. Direct URL citations appear in the printed text and are provided in the HTML and PDF versions of this article on the journal's website (www.anesthesia-analgesia.org).

S. D. Grabitz and N. Rajaratnam contributed equally and share first authorship.

Clinical trial number and registry URL: clinicaltrials.gov (NCT01718860).

Reprints will not be available from the authors.

Address correspondence to Barry J. Kelly, MD, MSc, Department of Anesthesia, Critical Care and Pain Medicine, Harvard Medical School, Beth Israel Deaconess Medical Center, 330 Brookline Ave, Boston, MA 02215. Address e-mail to bjkelly@bidmc.harvard.edu.

Recent data suggest that nondepolarizing neuromuscular blocking agents are associated with increased rates of postoperative respiratory complications.[1] In addition, nondepolarizing neuromuscular blocking agent dose dependability increases the odds of hospital readmission and the hospital length of stay.[2] However, it is unclear whether the observed association between nondepolarizing neuromuscular blocking agent and adverse patient outcomes in these studies was related to impaired neuromuscular transmission, given that objective evidence of postoperative residual neuromuscular blockade by train-of-four ratio was not evaluated. Postoperative residual neuromuscular blockade continues to be a frequent occurrence with reported incidences ranging from 4% to 64%.[3–8]

Rationale

The effect of residual neuromuscular blockade on health care utilization and cost remains unclear. We hypothesized that postoperative residual neuromuscular blockade at admission to the postanesthesia care unit (PACU) is associated with increased hospital costs. We also hypothesized that postoperative residual neuromuscular blockade would be associated with increased odds of intensive care unit admission and hospital length of stay.

Study Objectives

The aim of this retrospective observational study was to evaluate the effects of postoperative residual neuromuscular blockade on our primary outcome, hospital costs. Secondary analyses were conducted to evaluate the effects of postoperative residual neuromuscular blockade on potential cost-influencing factors such as unplanned postoperative intensive care unit admission and hospital length of stay. Postoperative residual neuromuscular blockade was defined as the presence of a train-of-four ratio measured by acceleromyography of the adductor pollicis muscle of <0.9.[9]

METHODS

Setting and Data

This study is a secondary analysis of a previously published study using data collected between 2008 and 2013 at Massachusetts General Hospital, a tertiary care facility in Boston, MA.[10] The study was approved by the institutional review board and the need for written informed consent was waived by the institutional review board. The study was registered at clinicaltrials.gov (NCT01718860, principal investigator: Matthias Eikermann; date of registration October 29, 2012) and adheres to the applicable STrengthening the Reporting of OBservational studies in Epidemiology guidelines. Train-of-four measurements in the PACU, age, sex, body mass index, postoperative intensive care unit admission, hospital length of stay, as well as principal surgical procedures were recorded. We performed chart review of all postoperative intensive care unit admissions to retrieve information on the principal medical indication for intensive care unit admission and to ensure that only unplanned, rather than scheduled intensive care unit admissions, independent of patient's preoperative clinical status, were recorded. Hospital costs and hospital admission type (inpatient or ambulatory) were retrieved from the Enterprise Performance Systems Inc (Chesterfield, MO) database, a performance improvement and financial planning system, which are outcomes that have been previously validated by our research group.[11,12]

Enterprise Performance Systems Inc separately tracks direct and indirect expenses. Direct costs include expenses that are directly related to patient care, whereas indirect costs are not linked to patient care (eg, financial service department costs). Direct costs can further be subdivided into direct fixed and direct variable costs. Direct variable costs vary with the patient's specific care (performed procedures, required monitoring, medications, etc), whereas direct fixed costs are linked to patient care but are nonvariable (equipment, buildings, etc). The total costs represent the sum of direct and indirect expenses incurred by the institution.

Data on patient characteristics such as the Charlson comorbidity index were obtained from the Research Patient Data Registry (Partners Healthcare, Boston, MA), a centralized registry that retrieves clinical information for research purposes. We retrieved information about perioperative surgical and anesthesia-related parameters, as well as medication administration and physiologic data from patient monitors from the Anesthesia Information Management System. We performed a chart review of body mass index, American Society of Anesthesiologists (ASA) physical status score, and duration of surgery in 300 patients to confirm data validity. Diagnoses were coded based on the International Statistical Classification of Diseases and Related Health Problems, ninth revision.[13]

Population

The study cohort consisted of a consecutive cohort of patients undergoing surgery under general anesthesia and given nondepolarizing neuromuscular blocking agents (ie, atracurium, cisatracurium, vecuronium, or rocuronium) between 2008 and 2013 at Massachusetts General Hospital. Patients were excluded if not extubated directly after the procedure, if <18 years of age, or if they were transferred directly to the intensive care unit after surgery. Further, patients were excluded if they had procedures or conditions that did not allow for T4/T1 to be measured by ulnar nerve stimulation (ie, dual upper extremity bandages or external fixations). Adductor pollicis muscle acceloromyography was recorded on 96% of all screened patients in the original study during the study period, minimizing selection bias.

Exposure

The primary independent variable was postoperative residual neuromuscular blockade. We defined postoperative residual neuromuscular blockade as the presence of a train-of-four ratio of <0.9,[9] measured by acceleromyography of the adductor pollicis muscle using a quantitative train-of-four monitor (TOF-watch SX; Schering-Plough, Kenilworth, NJ). Postoperative residual neuromuscular blockade was a dichotomous variable, the presence of which defined exposure and the absence of which defined nonexposure. Train-of-four monitoring was performed on each patient within 10 minutes of PACU admission. The mean values of 2 consecutive train-of-four ratios were used to generate this variable and postoperative residual neuromuscular blockade was predefined as a train-of-four ratio <0.9. Additional methodological details on postoperative data collection and train-of-four measurements can be found in Supplemental Digital Content, Document, http://links.lww.com/AA/C698.

Outcomes

The primary outcome was hospital costs. This continuous variable was defined as the sum of total direct patient-service costs and total indirect costs allocated to departments in a step-down structure. In addition, we have performed a sensitivity analyses using the previously described breakdowns of total costs as the dependent variable. Direct variables costs vary with individual patient care (eg, procedures, monitoring, medications). Additional parameters of health care utilization such as postoperative intensive care unit admission within 7 days after surgery and hospital length of stay were defined as secondary outcomes. Due to the sensitivity of internal financial figures, and to provide more generalizable cost estimates in the analysis, we did not report specific dollar amounts, but rather the incident rate ratio, as a relative estimate.

Covariates

To control for the numerous patient, surgical, and anesthesia-related variances, a robust confounder control model was created for the adjusted analysis of the primary outcome, hospital costs. The covariates included in this model were age, gender, ASA physical status, emergency status, Charlson comorbidity index, work relative value units, admission type, night surgery, duration of surgery, intraoperative fluids, intraoperative long-acting opioid (morphine) dose equivalents, hypotensive minutes with mean arterial pressure <55 mm Hg, protective ventilation, intraoperative vasopressor dose, age-adjusted minimum alveolar concentration, median inspired oxygen fraction, preoperative beta-blocker use within 28 days, preexisting respiratory failure (within 7 preoperative days), use of neuraxial anesthesia, use of regional anesthesia, admission from a nursing home or skilled nursing facility, and home oxygen dependence. Pre- and postoperative opioid prescription were included as covariates in sensitivity analyses in the secondary analysis evaluating the association of postoperative residual neuromuscular blockade and intensive care unit admission. Furthermore, we included the time of surgery completion into this regression model in an additional sensitivity analysis.

Power Analysis

An a priori power analysis was not conducted due to the retrospective nature of this study. Based on our included observed data, we estimated that we had 80% power to detect an effect size of 0.1, from a 2 independent samples *t* test. This effect size equates to a difference in hospital costs of approximately 19.3% of mean costs, assuming the observed between group mean difference of $3270, a SD of $32,700 for our primary outcome and a mean cost of $16,920 in the group that did not have postoperative residual neuromuscular blockade in PACU.

Statistical Analysis

The analysis for the primary outcome, hospital costs, was performed using adjusted truncated negative binomial regression, to present costs as a ratio and keep institute-specific costs sensitive. The cost data in our dataset was recorded as only positive integers (no zeros, no decimal places), which might also be viewed as the accumulated counts of each 1 dollar. Descriptives of the outcome indicated overdispersion. For this reason, we elected to use truncated negative binomial regression. Further information regarding model selection including a calibration curve is presented in Supplemental Digital Content, Document, Section 6, http://links.lww.com/AA/C698. To enhance the robustness of our model, we performed sensitivity analyses using components of total costs as the dependent variable. In addition, we performed further sensitivity analysis in the subgroup, day of surgery admissions and ambulatory surgery to exclude indirect costs of prior hospital admission up to that point.

We used logistic regression analyses to test the association between postoperative residual neuromuscular blockade in PACU and intensive care unit admission adjusting for the previously listed covariates. Results are presented as odds ratios or incidence rate ratios with 95% CIs.

Missing Data

The primary analysis was performed using the complete case method. In a sensitivity analysis, values for missing covariates were imputed using multiple imputation by chained equations. More specifically, variables with missing data were imputed using all covariates and the outcome of the primary model utilizing 10 burn-in rounds followed by a total of 10 final imputations using the Stata command “mi impute.” The model estimates were combined using variance estimates that combine imprecision both within and across imputations.

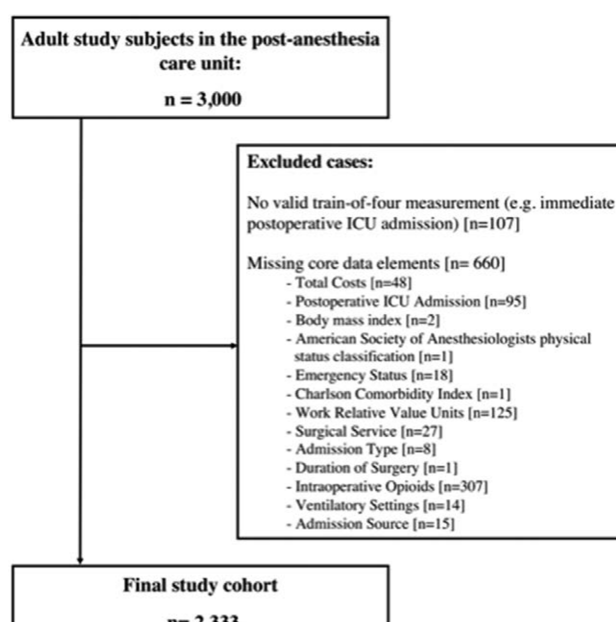


Figure. Study flow: cases excluded from original cohort and cases included for final analysis. ASA indicates American Society of Anesthesiologists; BMI, body mass index; ICU, intensive care unit; TOF, train-of-four.

Data analysis was performed using STATA 13 (StataCorp LP, College Station, TX). A 2-tailed *P* value <.05 was considered statistically significant.

RESULTS

Among the 3000 patients in the database who underwent general anesthesia and who had train-of-four ratio assessment in the PACU, 2233 met inclusion criteria for our primary analysis (Figure). There were 457 (20.5%) patients diagnosed with postoperative residual neuromuscular blockade in the PACU. Proportion of males and mean Charlson comorbidity index were higher in patients experiencing postoperative residual neuromuscular blockade (Table 1). The majority of the study patients were admitted on the day of surgery (n = 1930).

Hospital Costs (Primary Analysis)

On initial unadjusted truncated negative binomial regression analysis, postoperative residual neuromuscular blockade was associated with an increase in total hospital costs

Table 1. Clinical Characteristics of Study Population by Postoperative Residual Paralysis

Characteristics	No Postoperative Residual Neuromuscular Blockade (n = 1776)	Postoperative Residual Neuromuscular Blockade (n = 457)
Age (y), mean ± SD	55.31 ± 15.82	54.92 ± 15.96
Gender (female)[a]	961 (54.2%)	290 (63.5%)
Body mass index (kg/m^2), median (interquartile range)	27.60 (24.26–32.10)	27.80 (24.20–32.90)
ASA physical status		
I	170 (9.6%)	53 (11.6%)
II	1160 (65.3%)	278 (60.8%)
III	443 (24.9%)	123 (26.9%)
IV	3 (0.2%)	2 (0.4%)
V	0 (0.0%)	1 (0.2%)
Charlson comorbidity index, median (interquartile range)[a]	1 (0–2)	2 (0–3)
Duration of surgery (min), mean ± SD	140 ± 82	140 ± 81
Work relative value units, median (interquartile range)	17.31 (11.48–23.25)	17.63 (12.15–23.50)
Admission type		
Ambulatory	409 (23.0%)	97 (21.2%)
Inpatient	1367 (77.0%)	360 (78.8%)
Night surgery	3 (0.2%)	1 (0.2%)
Emergency procedure	32 (1.8%)	5 (1.1%)
Intraoperative fluids (mL), median (interquartile range)	1500 (900–2000)	1350 (1000–2100)
Long-acting opioids (mg IV morphine eq), median (interquartile range)	4.53 (2.27–8.50)	4.53 (2.00–8.33)
Duration of intraoperative hypotension (min), median (interquartile range)	0 (0–1)	0 (0–1)
Protective ventilation	1018 (57.4%)	248 (54.4%)
Vasopressor dose (mg norepinephrine eq), median (interquartile range)	0.00 (0.00–0.02)	0.00 (0.00–0.02)
Age-adjusted minimum alveolar concentration, median (interquartile range)	0.92 (0.78–1.05)	0.92 (0.79–1.06)
Inspired oxygen fraction (%), median (interquartile range)[a]	50 (38–58)	52 (41–58)
Preoperative beta-blocker use	461 (26.0%)	103 (22.5%)
Respiratory failure within 7 preoperative days	7 (0.4%)	1 (0.2%)
Neuraxial anesthesia use	121 (6.8%)	40 (4.8%)
Peripheral block placed	105 (5.9%)	28 (6.1%)
Adverse admission disposition	70 (3.9%)	13 (2.8%)
Oxygen dependence at home	5 (0.3%)	1 (0.2%)
Surgical service[a]		
Radiology	24 (1.4%)	10 (2.2%)
General surgery	283 (16.0%)	94 (20.6%)
Emergency surgery	55 (3.1%)	24 (5.3%)
Gynecology	188 (10.6%)	51 (11.2%)
Laryngeal surgery	12 (0.7%)	6 (1.3%)
Neurosurgery	107 (6.0%)	19 (4.2%)
Oral/maxillofacial surgery	48 (2.7%)	6 (1.3%)
Orthopedic surgery	439 (24.7%)	97 (21.2%)
Plastic surgery	107 (6.0%)	34 (7.4%)
Surgical oncology	78 (4.4%)	21 (4.6%)
Thoracic surgery	82 (4.6%)	26 (5.7%)
Transplant	42 (2.4%)	6 (1.3%)
Urology	241 (13.6%)	52 (11.4%)
Vascular surgery	49 (2.8%)	5 (1.1%)
Burn	21 (1.2%)	6 (1.3%)

Postoperative residual neuromuscular blockade is defined as train-of-four ratio <0.9 at admission to the postanesthesia care unit. Values are percentages unless otherwise stated.

Abbreviation: ASA, American Society of Anesthesiologists.

[a]Statistical significance ($P < .05$) between groups.

Table 2. Association of Postoperative Residual Neuromuscular Blockade and Primary and Secondary Outcomes

	Unadjusted Analysis	Adjusted Analysis
Primary outcome		
Total costs, incidence rate ratio (95% CI)	1.14 (1.06–1.22)[a]	1.04 (0.98–1.11)
Direct variable costs, incidence rate ratio (95% CI)	1.15 (1.07–1.25)[a]	1.03 (0.96–1.11)
Direct fixed costs, incidence rate ratio (95% CI)	1.09 (1.02–1.16)[a]	1.06 (0.99–1.12)
Indirect costs, incidence rate ratio (95% CI)	1.15 (1.07–1.24)[a]	1.04 (0.98–1.12)
Secondary outcomes		
Postoperative intensive care unit admission, odds ratio (95% CI)	2.20 (1.16–4.16)[a]	3.03 (1.33–6.87)[a]
Postoperative hospital length of stay, incidence rate ratio (95% CI)	1.13 (1.02–1.26)[a]	1.09 (1.00–1.19)
Sensitivity analyses		
Imputed database		
Total costs, incidence rate ratio (95% CI)		1.05 (0.99–1.12)
Subgroup same-day admission and ambulatory surgery		
Total costs, incidence rate ratio (95% CI)		1.04 (0.99–1.09)
Adjustment for preoperative opioid prescription		
Postoperative intensive care unit admission, odds ratio (95% CI)		3.40 (1.46–7.91)[a]
Adjustment for postoperative opioid prescription		
Postoperative intensive care unit admission, odds ratio (95% CI)		2.93 (1.28–6.70)[a]
Adjustment for surgery completion time		
Postoperative intensive care unit admission, odds ratio (95% CI)		2.92 (1.27–6.70)[a]

Adjusted regression analyses were performed using covariate adjustment for patient characteristics, intraoperative management, and procedural severity as described in the methods section unless otherwise stated.
[a]Statistical significance ($P < .05$).

(incidence rate ratio, 1.14, 95% CI, 1.06–1.22; P < .001). Following adjustment for our a priori defined confounders, there was no longer a significant difference in hospital costs between patients experiencing postoperative residual neuromuscular blockade and those without residual paralysis (adjusted incidence rate ratio, 1.04, CI, 0.98–1.11; P = .22). The findings from the primary regression analysis remained robust using the imputed database (adjusted incidence rate ratio, 1.05, CI, 0.99–1.12; Table 2). Further assessment of effect modification as suggested by the editor and reviewers is provided in Supplemental Digital Content, Document, Section 4, http://links.lww.com/AA/C698.

Intensive Care Unit Admission and Hospital Length of Stay (Secondary Analysis)

A total of 42 patients of n = 2233 were postoperatively admitted to the intensive care unit, giving an incidence rate of 1.8%. The incidence rates in the postoperative residual neuromuscular blockade and no postoperative residual neuromuscular blockade group were 3.3% (n = 15) and 1.5% (n = 27), respectively. There were no fatalities in this cohort. The adjusted odds of intensive care unit admission in the postoperative residual neuromuscular blockade group compared to the unexposeed group was 3.03, (CI, 1.33–6.87; P = .008). The adjusted incidence rate ratio of hospital length of stay was 1.09 (CI, 1.00–1.19; P = .058) in the postoperative residual neuromuscular blockade group (Table 2).

Exploratory Analyses

Although postoperative residual neuromuscular blockade was defined as a train-of-four ratio <0.9 in this study and in other similar studies,[3,9] we further explored the connection between postoperative residual neuromuscular blockade and our primary outcome, total hospital costs, in patients with postoperative train-of-four ratio <0.8 and train-of-four ratio <0.7, which indicate a deeper level of residual neuromuscular blockade.[9] The adjusted analyses showed no significant differences between the exposure and control groups: train-of-four <0.8 (adjusted incidence rate ratio, 1.05, CI, 0.94–1.17; P = .35) and train-of-four <0.7 (adjusted incidence rate ratio, 1.08, CI, 0.86–1.36; P = .49). Thus, in our cohort, a correlation between postoperative residual neuromuscular blockade and costs of the index hospitalization was not observed even at increased levels of postoperative residual neuromuscular blockade.

Sensitivity Analyses

We repeated our costs analysis using the components of total costs as the dependent variables. As highlighted in Table 2, the unadjusted incidence rate ratio for variable direct costs was 1.15 (CI, 1.07–1.12) and the adjusted incident rate ratio was 1.03 (CI, 0.96–1.11). We performed sensitivity analysis using the subgroup day of surgery admissions and ambulatory surgery to exclude indirect costs of prior hospital admission up to the event "postoperative residual neuromuscular blockade in PACU." In the day of surgery admission subgroup, the adjusted incident rate ratio for increased costs was 1.04 (CI, 0.99–1.09).

When additionally adjusting the secondary regression model for preoperative opioid use, we found a significant association between postoperative residual neuromuscular blockade and higher odds of postoperative intensive care unit admission. Including the opioid prescription on the day of discharge as a covariate in this regression analysis again confirmed robustness of the association between postoperative residual neuromuscular blockade and postoperative intensive care unit admission.

A variable indicating if the surgical case was completed in the morning (7 AM–11:59 AM), in the afternoon (noon – 4:59 PM), or at night (5 PM–6:59 AM) was included as covariate in an additional sensitivity analysis, which confirmed the independent association of postoperative residual neuromuscular blockade and postoperative admission to the intensive care unit (Table 2).

DISCUSSION

In this retrospective study of 2233 patients who underwent general anesthesia, 457 (20.5%) demonstrated postoperative residual neuromuscular blockade on admission to the PACU. Our analyses revealed that postoperative residual neuromuscular blockade was not associated with a significant increase in estimated total or direct variable health care costs. However, we found that postoperative residual neuromuscular blockade in the PACU was associated with a 3-fold increase in the odds of being admitted to the intensive care unit.

Consistent with a previously published incidence rate of 22% of postoperative residual neuromuscular blockade at our institution,[4] we observed an incidence rate of 20.5% of postoperative residual neuromuscular blockade in this cohort. Based on the original protocol, patients within the original study were consecutively screened for recruitment if they received general anesthesia with nondepolarizing neuromuscular blocking agent. The short, predefined time frame of the train-of-four assessment (10 minutes after PACU admission) and the high rate of consecutively enrolled patients (96%) minimized selection bias.

Rates of postoperative residual neuromuscular blockade in other studies vary from 4% to 64%.[3–8] However, these studies did not report reintubations or admissions to the intensive care unit. We previously reported an associated increase in the mean PACU length of stay of 80 minutes with postoperative residual neuromuscular blockade (P = .03).[4] In 2012, Thilen et al[5] studied postoperative residual neuromuscular blockade in 150 patients and reported postoperative residual neuromuscular blockade incidence rate of 52% in their group via adductor pollicis muscle monitoring. Although some patients (n = 13) in that cohort were electively ventilated in the PACU to facilitate regional anesthesia, there were no reported respiratory complications or intensive care unit admissions. The Residual Curarization and its Incidence at Tracheal Extubation study reported one of the highest incidences of postoperative residual neuromuscular blockade across all studies (63.5%), when the phenomenon was screened for in 302 postabdominal surgery patients across 8 Canadian hospitals, with only 1 patient requiring reintubation. This study did not report intensive care unit admission data or costs.[3] Despite these high incidence rates, routine monitoring to evaluate the reversal of postoperative residual neuromuscular blockade is not considered part of minimum monitoring standards in most clinical settings. A large international survey in 2010 revealed that 19.3% of European and 9.4% of US clinicians do not use neuromuscular monitors in postoperative evaluations and that pharmacological reversal was routinely administered by only 18% of European and 34.2% of US clinicians surveyed.[7]

Our secondary analysis demonstrated a 3-fold increase in the odds of intensive care unit admission from the PACU in those determined to have postoperative residual neuromuscular blockade. This finding has not been previously reported. Previous studies have shown an association between postoperative residual neuromuscular blockade and both increased respiratory complications and delayed discharge from the PACU,[1,4] but few have reported unanticipated intensive care unit admission rates. For instance, in 2015, McLean et al[1] demonstrated a dose-dependent association between intermediate-acting neuromuscular blocking agents and postoperative respiratory complications. Over 48,000 cases were included for analysis of the association between dosing of nondepolarizing neuromuscular blocking agent and a composite outcome of respiratory complications within 3 postoperative days. In this study, the reintubation rate was 0.3% and they did not report intensive care unit admission or hospital costs.

Much debate exists within the literature as to whether intensive care unit admission universally translates into better outcomes, despite presumed increased hospital costs.[14,15] Our group has postulated that an acuity threshold may exist below which the risks of intensive care unit admission outweigh the benefits.[16] In this study, we found a trend toward increased hospital length of stay in patients with postoperative residual neuromuscular blockade, which in part may be explained by admission of patients with lower acuity except for residual neuromuscular blockade. In contrast to a previous study,[17] we found differential effects of residual neuromuscular blockade on intensive care unit admission rate. This may be in part explained by low intensive care unit bed occupancy in our study center. Lower occupancy facilitates early intensive care unit admission, as opposed to keeping patients who need extended postoperative care longer in the PACU. The PACU is a very cost-intensive location in the hospital with a nurse-to-patient ratio equivalent to the intensive care unit. Effects of residual neuromuscular blockade on costs of care may be different in a clinical scenario where procedures would need to be canceled as a result of lack of availability of intensive care unit beds. Therefore, based on the results of our analyses, it would be advisable for clinicians to screen for residual neuromuscular blockade in the perioperative setting before transfer to the PACU, and to take appropriate measures ensuring complete recovery of normal neuromuscular physiology to offset the risk of unnecessary intensive care unit admission or increased PACU length of stay. As our study was conducted in a well-resourced academic center with critical care bed elasticity, further studies to validate our findings using large heterogeneous datasets may provide more insight into the problem of postoperative residual neuromuscular blockade in the PACU and its burden on a variety of intensive care unit structures. Our group recently studied the effect of incentivized protocols for checking adequate reversal of nondepolarizing neuromuscular blocking agent in the perioperative setting and found lower odds of postoperative pulmonary complications, lower costs, and shorter duration of hospital stay after implementation of the quality improvement initiative.[18]

Strengths

A major strength of this study is that we measured train-of-four ratio at PACU admission prospectively in a large sample size using industry standard TOFwatch technology (TOF-Watch, Organon, Finland). Our hypothesis was further tested with exploratory analyses using lower train-of-four thresholds for our exposure variable of postoperative residual neuromuscular blockade and still failed to show significantly increased hospital costs. Several sensitivity analyses confirmed the robustness of our findings. We believe our study has face validity, as characterized by (1) the good coverage of surgical patients from Massachusetts General Hospital without preselection of patients causing selection bias; (2) a confounder model that addresses the wide range of comorbidities and procedures; and (3) the absence of cost differences and the minimal beta error observed in our analysis.[19,20] The model results are a good representation of the actual cost. For example, the model predicted increase cost of 27% for patients with a high ASA physical status classification (≥III) compared to patients with a lower ASA physical status (I or II). Similarly, the model predicted a cost increase of 87% moving from lowest to highest costly surgical service. Finally, the incidence rate of postoperative residual neuromuscular blockade in the entire cohort was 20.5%, which we believe to be accurate based on the fact that 96% of consecutively recruited patients in the original study had valid train-of-four values at PACU admission.

Limitations

Our single center, large tertiary referral hospital may not allow generalizability to smaller, less well-resourced health care settings. In addition, despite a robust confounder model, we present observational data where unknown factors may confound the results. Our institution is not able to separate costs before and after PACU admission, so our analysis is limited by data points collected before the exposure, postoperative residual neuromuscular blockade in PACU, which may affect the direct association of postoperative residual neuromuscular blockade on hospital costs.

Perioperative cost data are often dominated by a few outlier patients, which make it hard to identify associations between preventable complications, such as postoperative residual neuromuscular blockade, and costs. One such outlier in our cohort was dependent on home oxygen therapy. Given the highly skewed distribution of costs in our cohort, we conducted a sensitivity analysis excluding this 1 true outlier patient. The main findings did not change when excluding this patient from the analysis; we again found no association of postoperative residual neuromuscular blockade and costs in the adjusted analysis (adjusted incidence rate ratio, 1.03, CI, 0.97–1.10), whereas postoperative residual neuromuscular blockade was significantly associated with postoperative intensive care unit admission. Finally, information about some outcomes (hospital length of stay and costs) was retrieved from administrative data where misclassification is possible.

CONCLUSIONS

We found that postoperative residual neuromuscular blockade in the PACU was not associated with increased health care costs, but with a significant increase in the odds of intensive care unit admission. Residual neuromuscular blockade is prevalent and underdiagnosed, and adequate prevention may decrease rates of unplanned intensive care unit admission associated with residual neuromuscular blockade.

DISCLOSURES

Name: Stephanie D. Grabitz, MD.
Contribution: This author helped with literature review, data extraction, coding, study design, data analysis, writing and revision of the manuscript.
Name: Nishan Rajaratnam, MD.
Contribution: This author helped with literature review, data extraction, coding, data analysis, study design, statistical analysis plan, and writing the manuscript.
Name: Khushi Chhagani, BS.
Contribution: This author helped with data extraction, coding, data analysis, study design, statistical analysis plan, and writing the manuscript.
Name: Tharusan Thevathasan, Cand Med.
Contribution: This author helped with literature review, data extraction, coding, study design, and data analysis.
Name: Bijan J. Teja, MD, MBA.
Contribution: This author helped with study design, statistical analysis plan, data analysis, and writing the manuscript.
Name: Hao Deng, MD, MPH.
Contribution: This author helped with study design and statistical analysis planning.
Name: Matthias Eikermann, MD, PhD.
Contribution: This author conceived the study hypothesis, helped with study design, and approved the final manuscript.
Name: Barry J. Kelly, MD, MSc.
Contribution: This author helped with literature review, study design, statistical analysis plan, data analysis, writing, submission and revision of the manuscript.
This manuscript was handled by: Ken B. Johnson, MD.

REFERENCES

1. McLean DJ, Diaz-Gil D, Farhan HN, Ladha KS, Kurth T, Eikermann M. Dose-dependent association between intermediate-acting neuromuscular-blocking agents and postoperative respiratory complications. *Anesthesiology*. 2015;122:1201–1213.
2. Thevathasan T, Shih SL, Safavi KC, et al. Association between intraoperative non-depolarising neuromuscular blocking agent dose and 30-day readmission after abdominal surgery. *Br J Anaesth*. 2017;119:595–605.
3. Fortier LP, McKeen D, Turner K, et al. The RECITE study: a Canadian Prospective, Multicenter Study of the incidence and severity of residual neuromuscular blockade. *Anesth Analg*. 2015;121:366–372.
4. Butterly A, Bittner EA, George E, Sandberg WS, Eikermann M, Schmidt U. Postoperative residual curarization from intermediate-acting neuromuscular blocking agents delays recovery room discharge. *Br J Anaesth*. 2010;105:304–309.
5. Thilen SR, Hansen BE, Ramaiah R, Kent CD, Treggiari MM, Bhananker SM. Intraoperative neuromuscular monitoring site and residual paralysis. *Survey Anesthesiol*. 2013;57:156–157.
6. Donati F. Residual paralysis: a real problem or did we invent a new disease? *Can J Anaesth*. 2013;60:714–729.
7. Naguib M, Kopman AF, Lien CA, Hunter JM, Lopez A, Brull SJ. A survey of current management of neuromuscular block in the United States and Europe. *Anesth Analg*. 2010;111:110–119.
8. Kumar GV, Nair AP, Murthy HS, Jalaja KR, Ramachandra K, Parameshwara G. Residual neuromuscular blockade affects postoperative pulmonary function. *Anesthesiology*. 2012;117:1234–1244.
9. Murphy GS, Brull SJ. Residual neuromuscular block: lessons unlearned. Part I: definitions, incidence, and adverse physiologic effects of residual neuromuscular block. *Anesth Analg*. 2010;111:120–128.
10. Sasaki N, Meyer MJ, Malviya SA, et al. Effects of neostigmine reversal of nondepolarizing neuromuscular blocking agents on postoperative respiratory outcomes: a prospective study. *Anesthesiology*. 2014;121:959–968.
11. Ladha K, Vidal Melo MF, McLean DJ, et al. Intraoperative protective mechanical ventilation and risk of postoperative respiratory complications: hospital based registry study. *BMJ*. 2015;351:h3646.

12. Brueckmann B, Villa-Uribe JL, Bateman BT, et al. Development and validation of a score for prediction of postoperative respiratory complications. *Anesthesiology*. 2013;118:1276–1285.
13. Quan H, Sundararajan V, Halfon P, et al. Coding algorithms for defining comorbidities in ICD-9-CM and ICD-10 administrative data. *Med Care*. 2005;43:1130–1139.
14. Wunsch H, Gershengorn HB, Cooke CR, et al. Use of intensive care services for Medicare beneficiaries undergoing major surgical procedures. *Anesthesiology*. 2016;124:899–907.
15. Kahan BC, Koulenti D, Arvaniti K, et al; The International Surgical Outcomes Study (ISOS) Group Critical care admission following elective surgery was not associated with survival benefit: prospective analysis of data from 27 countries. *Intensive Care Med*. 2017;43:971–979.
16. Thevathasan T, Copeland CC, Long DR, et al. The impact of postoperative intensive care unit admission on postoperative hospital length of stay and costs: a prespecified propensity-matched cohort study. *Anesth Analg*. 2018 [Epub ahead of print].
17. Dexter F, Blake JT, Penning DH, Sloan B, Chung P, Lubarsky DA. Use of linear programming to estimate impact of changes in a hospital's operating room time allocation on perioperative variable costs. *Anesthesiology*. 2002;96:718–724.
18. Rudolph MI, Chitilian HV, Ng PY, et al. Implementation of a new strategy to improve the peri-operative management of neuromuscular blockade and its effects on postoperative pulmonary complications. *Anaesthesia*. 2018;73:1067–1078.
19. O Neill L, Dexter F. Tactical increases in operating room block time based on financial data and market growth estimates from data envelopment analysis. *Anesth Analg*. 2007;104:355–368.
20. Dexter F, Epstein RH. Typical savings from each minute reduction in tardy first case of the day starts. *Anesth Analg*. 2009;108:1262–1267.