Clinical Evidence
Bibliography

Publications showing how quantitative TOF monitoring can help enhance outcomes and patient safety

SENZIME

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Key to Study Types

Icons used throughout this document help identify the type of study cited.

Featured Review Articles:
Synthesizes and summarizes existing research; does not present new data

TetraGraph® Literature:
Clinical studies and articles featuring the TetraGraph® system

Engineered for **Patient Safety and Accuracy**

Senzime's dedication to advancing neuromuscular management is reflected in the extensive research and development of our monitoring solution. Our bibliography highlights the diverse applications and benefits of quantitative TOF monitoring across various patient populations and clinical settings. From the operating room to the intensive care unit, TetraGraph is shown to enhance patient safety, streamline workflows, and support clinical decision-making. We are committed to delivering reliable, innovative technologies that empower healthcare professionals to achieve the highest standards of care.

Resources

Access more resources, read a recent blog or watch a video about quantitative TOF monitoring at senzime.com/support

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Visit the product portfolio or request a complimentary demo at senzime.com/contact

Guidelines recommending quantitative TOF monitoring

Year	Author	Title	Summary	Citation	Link
2024	Leonardsen AL, Haugen AS, Raeder J, Finjarn TJ, Isern E, Aakre EK, Bruun AMG, Hennum K, Ramstad JP, Sand T, Monsen SA.	The 2024 revision of the Norwegian standard for the safe practice of anaesthesia	The Norwegian standard for the safe practice of anaesthesia was first published in 1991, and revised in 1994, 1998, 2005, 2010 and 2016 respectively. It must be noted that this is a national standard, reflecting the specific opportunities and challenges in a Norwegian setting, which may be different from other countries in some respects.	*Acta Anaesthesiol Scand.* 2024 Apr;68(4):567-574.	https://pubmed.ncbi.nlm.nih.gov/38317613/
2024	Dobson G	Guidelines to the Practice of Anesthesia-Revised Edition 2024	The Guidelines to the Practice of Anesthesia-Revised Edition 2024 (the Guidelines) were prepared by the Canadian Anesthesiologists' Society (CAS)	*Can J Anesth* 2024; 71:8-54	https://pubmed.ncbi.nlm.nih.gov/38253968/
2023	Stephan R. Thilen, Wade A. Weigel, Michael M. Todd, Richard P. Dutton, Cynthia A. Lien, Stuart A. Grant, Joseph W. Szokol, Lars I. Eriksson, Myron Yaster, Mark D. Grant, Madhulika Agarkar, Anne M. Marbella, Jaime F. Blanck, Karen B. Domino	2023 American Society of Anesthesiologists Practice Guidelines for Monitoring and Antagonism of Neuromuscular Blockade: A Report by the American Society of Anesthesiologists Task Force on Neuromuscular Blockade	Evidence-based practice guidelines recommending the use of quantiative neuromuscular monitoring and the use and dosing of antagonistic drugs to prevent residual neuromuscular block.	*Anesthesiology.* 2023; 138:13–41	https://pubs.asahq.org/anesthesiology/article/138/1/13/137379/2023-American-Society-of-Anesthesiologists
2023	Fuchs-Buder T, Romero CS, Lewald H, Lamperti M, Afshari A, Hristovska AM, Schmartz D, Hinkelbein J, Longrois D, Popp M, de Boer HD, Sorbello M, Jankovic R, Kranke P	Peri-operative management of neuromuscular blockade: A guideline from the European Society of Anaesthesiology and Intensive Care	Updated guidelines from the ESAIC including the recommendation to use ulnar nerve stimulation and quantitative neuromuscular monitoring to exclude residual paralysis	*Eur J Anaesthesiol.* 2023 Feb 1;40(2):82-94	https://pubmed.ncbi.nlm.nih.gov/36377554/

Guidelines recommending quantitative TOF monitoring

Year	Author	Title	Summary	Citation	Link
2021	A A Klein, T Meek, E Allcock, T M Cook, N Mincher, C Morris, A F Nimmo, J J Pandit, A Pawa, G Rodney, T Sheraton, P Young	Recommendations for standards of monitoring during anaesthesia and recovery 2021: Guideline from the Association of Anaesthetists	Quantitative neuromuscular monitoring should be used whenever neuromuscular blocking (NMB) drugs are administered, throughout all phases of anaesthesia from before initiation of neuromuscular blockade until recovery of the train-of-four ratio to > 0.9 has been confirmed.	*Anaesthesia* 2021 Sep;76(9):1212-1223.	https://pubmed.ncbi.nlm.nih.gov/34013531/
2020	Nemes, R., Renew, J.R	Clinical Practice Guideline for the Management of Neuromuscular Blockade: What Are the Recommendations in the USA and Other Countries?	A panel of experts have called for abandoning practices using a peripheral nerve stimulator (subjective) and clinical assessment in favor of adopting quanitative monitoring (objective).	*Curr Anesthesiol Rep* 10, 90–98 (2020)	https://link.springer.com/article/10.1007/s40140-020-00389-3#citeas
2020	Plaud B, Baillard C, Bourgain JL, Bouroche G, Desplanque L, Devys JM, Fletcher D, Fuchs-Buder T, Lebuffe G, Meistelman C, Motamed C, Raft J, Servin F, Sirieix D, Slim K, Velly L, Verdonk F, Debaene B	Guidelines on muscle relaxants and reversal in anaesthesia	"... the French Society of Anaesthesia and Intensive Care (SFAR) recommends the use of a device to monitor neuromuscular blockade throughout anaesthesia."	*Anaesth Crit Care Pain Med*. 2020 Feb;39(1):125-142	https://pubmed.ncbi.nlm.nih.gov/31926308/
2018	Naguib M, Brull SJ, Kopman AF, Hunter JM, Fülesdi B, Arkes HR, Elstein A, Todd MM, Johnson KB	Consensus Statement on Perioperative Use of Neuromuscular Monitoring	Recommends that subjective methods (such as those obtained with a peripheral nerve stimulator, PNS, or clinical signs), should be abondoned in favor of objective/ quantitative monitoring"	*Anesth Analg*. 2018 Jul;127(1):71-80	https://pubmed.ncbi.nlm.nih.gov/29200077/

The basics of neuromuscular block management

Year	Author	Title	Summary	Citation	Link
2024	Rodney G	Neuromuscular block management: evidence-based principles and practice	An up-to-date review of the latest recommendations for the safe administration, maintenance and antagonism of neuromuscular block in routine clinical setting.	*BJA Educ* 2024 Jan;24(1):13-22.	https://pubmed.ncbi.nlm.nih.gov/38495745/
2023	Epstein R, Perez O, Hofer I, Renew J, Nemes R, Brull S	Validation of convolutional neural network that reliably identifies electromyographic compound motor action potentials following train-of-four stimulation: an algorithm development experimental study	Modified a convolutional neural network (CNN) to classify EMG waveforms at the adductor pollicis as a valid cMAP. The CNN distinguished valid cMAP's with >99.5% accuracy.	*BJA Open*, 8 (C): 100236 (2023)	https://www.bjaopen.org/article/S2772-6096%2823%2900115-6/fulltext
2018	Murphy GS	Neuromuscular Monitoring in the Perioperative Period	The use of quantitative monitors is essential in excluding clinically important muscle weakness at the time of tracheal extubation.	*Anesth Analg*. 2018 Feb;126(2):464-468	https://pubmed.ncbi.nlm.nih.gov/28795964/
2017	Naguib M, Brull SJ, Johnson KB	Conceptual and technical insights into the basis of neuromuscular monitoring	Clarifies the key elements of neuromuscular monitoring. A "must" read.	*Anaesthesia*. 2017 Jan;72 Suppl 1:16-37	https://pubmed.ncbi.nlm.nih.gov/28044330/
2017	Brull SJ, Kopman AF	Current Status of Neuromuscular Reversal and Monitoring: Challenges and Opportunities	Covers all aspects of neuromuscular blockade. Side effects (residual block), the magnitude of the problem of residual block, complications, neuromuscular monitoring, reversal recommendations, etc.	*Anesthesiology*. 2017 Jan;126(1): 173-190	https://pubmed.ncbi.nlm.nih.gov/27820709/

Incidence of RNMB and postoperative complications

Year	Author	Title	Summary	Citation	Link
2021	Brull SJ, Murphy GS	The "True" Risk of Postoperative Pulmonary Complications and the Socratic Paradox: "I Know that I Know Nothing"	"Despite the inconclusive evidence provided by current literature, we strongly believe that decreasing the risk of residual block by routine quantitative monitoring and judicious administration of sugammadex are paramount to optimizing patient safety."	*Anesthesiology.* 2021 Jun 1;134(6):828-831	https://pubmed.ncbi.nlm.nih.gov/33909882/
2021	Uzawa K, Seki H, Yorozu T	Residual paralysis caused by 50 mg rocuronium after reversal with 4 mg/kg sugammadex: a case report	In this case study the recommended dose of sugammadex failed to antagonize a Rocuronium induced block.	*BMC Anesthesiol.* 2021 May 20;21(1):154.	https://pubmed.ncbi.nlm.nih.gov/34016059/
2020	Kheterpal S, Vaughn MT, Dubovoy TZ, Shah NJ, Bash LD, Colquhoun DA, Shanks AM, Mathis MR, Soto RG, Bardia A, Bartels K, McCormick PJ, Schonberger RB, Saager L	Sugammadex versus Neostigmine for Reversal of Neuromuscular Blockade and Postoperative Pulmonary Complications (STRONGER): A Multicenter Matched Cohort Analysis	In a study comparing patients receiving sugammadex vs neostigmine, those who received sugammadex had a 30% reduced risk of pulmonary complications, 47% reduced risk of pneumonia, and 55% reduced risk of respiratory failure.	*Anesthesiology.* 2020 Jun;132(6):1371-1381	https://pubmed.ncbi.nlm.nih.gov/32282427/
2020	Raval AD, Uyei J, Karabis A, Bash LD, Brull SJ	Incidence of residual neuromuscular blockade and use of neuromuscular blocking agents with or without antagonists: A systematic review and meta-analysis of randomized controlled trials	"Sugammadex has the potential to lower the occurrence of rNMB and very early on (within 5 min for moderate block and 15 min for deep block), however rNMB is still not 0% among these patients."	*J Clin Anesth.* 2020 Apr 15;64:109818	https://pubmed.ncbi.nlm.nih.gov/32304958/
2020	Carvalho H, Verdonck M, Cools W, Geerts L, Forget P, Poelaert J	Forty years of neuromuscular monitoring and postoperative residual curarisation: a meta-analysis and evaluation of confidence in network meta-analysis	Quantitative neuromuscular monitoring out performs both subjective and no neuromuscular monitoring and was associated with a significantly lower incidence of residual neuromuscular block	*Br J Anaesth.* 2020 Oct;125(4):466-482	https://pubmed.ncbi.nlm.nih.gov/32680607/

Incidence of RNMB and postoperative complications

Year	Author	Title	Summary	Citation	Link
2019	Saager L, Maiese EM, Bash LD, Meyer TA, Minkowitz H, Groudine S, Philip BK, Tanaka P, Gan TJ, Rodriguez-Blanco Y, Soto R, Heisel O	Incidence, risk factors, and consequences of residual neuromuscular block in the United States: The prospective, observational, multicenter RECITE-US study	64.7% of patients in the study had rNMB at extubation despite neostigmine administration and use of peripheral nerve stimulator	*J Clin Anesth.* 2019 Aug;55:33-41	https://pubmed.ncbi.nlm.nih.gov/30594097/
2019	Domenech G, Kampel MA, García Guzzo ME, Novas DS, Terrasa SA, Fornari GG	Usefulness of intra-operative neuromuscular blockade monitoring and reversal agents for postoperative residual neuromuscular blockade: a retrospective observational study	Study shows that the incidence of rNMB is decreased with intraoperative quantitative NMB monitoring and use of Sugammadex	*BMC Anesthesiol.* 2019 Aug 7;19(1):143	https://pubmed.ncbi.nlm.nih.gov/31390986/
2019	Grabitz SD, Rajaratnam N, Chhagani K, Thevathasan T, Teja BJ, Deng H, Eikermann M, Kelly BJ	The Effects of Postoperative Residual Neuromuscular Blockade on Hospital Costs and Intensive Care Unit Admission: A Population-Based Cohort Study	Postoperative residual neuromuscular blockade continues to be a frequent occurence, with a reported incidence up to 64%. There were significantly higher odds of intensive care unit admission in patients with post-operative residual neuromuscular blockade compared to those without.	*Anesth Analg.* 2019 Jun;128(6):1129-1136	https://pubmed.ncbi.nlm.nih.gov/31094777/
2019	Naguib M, Brull SJ, Hunter JM, Kopman AF, Fülesdi B, Johnson KB, Arkes HR	Anesthesiologists' Overconfidence in Their Perceived Knowledge of Neuromuscular Monitoring and Its Relevance to All Aspects of Medical Practice: An International Survey	The anesthesiologists surveyed are over confident in their knowledge of how to monitor neuromuscular blockade. It is hoped that the results of this survey will serve as an eye opener regarding the "facts and fiction" of the role of neuromuscular monito ring in safe clinical anesthesia practice.	*Anesth Analg.* 2019 Jun;128(6):1118-1126	https://pubmed.ncbi.nlm.nih.gov/31094776/
2018	Hunter JM, Naguib M	Sugammadex-induced bradycardia and asystole: how great is the risk?	The author's consesus is that "in patients with underlying cardiovascular conditions who may be receiving medication recognised to slow the heartrate. We recommend that sugammadex should only be administered in the necessary dose and at a slow rate with full ECG monitoring in an attempt to reduce the incidence of these adverse effects"	*Anaesth.* 2018 Jul;121(1):8-12	https://pubmed.ncbi.nlm.nih.gov/29935599/

Incidence of RNMB and postoperative complications

Year	Author	Title	Summary	Citation	Link
2018	Rudolph MI, Ng PY, Deng H, Scheffenbichler FT, Grabitz SD, Wanderer JP, Houle TT, Eikermann M	Comparison of a novel clinical score to estimate the risk of Residual neuromuscular block Prediction Score and the last train-of-four count documented in the electronic anaesthesia record: A retrospective cohort study of electronic data on file	Risk factors for RNMBA: hepatic failure, neurological disease, high-neostigmine dose, metastatic tumour, female sex, short time between neuromuscular blocking agent administration and extubation, aminosteroidal neuromuscular blocking agent, BMI more than 35, absence of nurse anaesthetist and having an experienced surgeon	*Eur J Anaesthesiol*. 2018 Nov;35(11):883-892	https://pubmed.ncbi.nlm.nih.gov/30020144/
2017	Belcher AW, Leung S, Cohen B, Yang D, Mascha EJ, Turan A, Saager L, Ruetzler K	Incidence of complications in the post-anesthesia care unit and associated healthcare utilization in patients undergoing non-cardiac surgery requiring neuromuscular blockade 2005-2013: A single center study	Retrospective analysis of adults having non-cardiac surgery between 2005-2013. Patients with Neostigmine had major complication in 1.7% cases, re-intubation of 0.8%, and unplanned ICU admission of 0.8%	*J Clin Anesth*. 2017 Dec;43:33-38	https://pubmed.ncbi.nlm.nih.gov/28972924/
2016	Aytac I, Postaci A, Aytac B, Sacan O, Alay GH, Celik B, Kahveci K, Dikmen B	Survey of postoperative residual curarization, acute respiratory events and approach of anesthesiologists	Out of 415 patients receiving general anesthesia with intermediate-acting NMBAs, Aytac et al reported that 27% (n=38) of those with TOFRs ≤0.9 had a CRE.	*Braz J Anesthesiol*. 2016 Jan-Feb;66(1):55-62	https://pubmed.ncbi.nlm.nih.gov/26768931/
2016	Yu B, Ouyang B, Ge S, Luo Y, Li J, Ni D, Hu S, Xu H, Liu J, Min S, Li L, Ma Z, Xie K, Miao C, Wu X	RECITE–China Investigators. Incidence of postoperative residual neuromuscular blockade after general anesthesia: a prospective, multicenter, anesthetist-blind, observational study	1571 patients, the incidence of rNMB at extubation was 57.8%	*Curr Med Res Opin*. 2016;32(1):1-9	https://pubmed.ncbi.nlm.nih.gov/26452561/

Incidence of RNMB and postoperative complications

Year	Author	Title	Summary	Citation	Link
2015	Xará D, Santos A, Abelha F	Adverse respiratory events in a post-anesthesia care unit	Observational study of 340 patients, saw post-operative acute respiratory events occur in 19.7% of patients. And residual Neuromuscular blockade was an independent risk factor for ARE	*Arch Bronconeumol.* 2015 Feb;51(2):69-75. English, Spanish	https://pubmed.ncbi.nlm.nih.gov/24974136/
2015	Murphy GS, Szokol JW, Avram MJ, Greenberg SB, Shear TD, Vender JS, Parikh KN, Patel SS, Patel A	Residual Neuromuscular Block in the Elderly: Incidence and Clinical Implications	In this study of 150 elderly and 150 younger patients, the incidence of postoperative RNMB was high in both groups. It was higher in the elderly 58% to 30%, and associated with hypoxemia, pulmonary complications, and increased length of stay.	*Anesthesiology.* 2015 Dec;123(6):1322-36	https://pubmed.ncbi.nlm.nih.gov/26448469/
2015	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	The use of higher doses of intermediate-acting NMBAs is associated with an increased risk of postoperative pulmonary complications of 28%	*Anesthesiology.* 2015 Jun 1;122(6):1201–13	https://pubs.asahq.org/anesthesiology/article/122/6/1201/12461/Dose-dependent-Association-between-Intermediate
2015	Fortier LP, McKeen D, Turner K, de Médicis É, Warriner B, Jones PM, Chaput A, Pouliot JF, Galarneau A	The RECITE Study: A Canadian Prospective, Multicenter Study of the Incidence and Severity of Residual Neuromuscular Blockade	In a prospective study with 302 patients, the incidence of rNMB at extubation was 63.5%	*Anesth Analg.* 2015 Aug;121(2):366-72	https://pubmed.ncbi.nlm.nih.gov/25902322/
2013	Norton M, Xará D, Parente D, Barbosa M, Abelha FJ	Residual neuromuscular block as a risk factor for critical respiratory events in the post anesthesia care unit	Critical Respiratory Events were 3 times more likely in patients receiving NMBA's with TOFR < 0.9	*Rev Esp Anestesiol Reanim.* 2013 Apr;60(4):190-6	https://pubmed.ncbi.nlm.nih.gov/23453244/#:~:text=Patients%20with%20residual%20neuromuscular%20block,P%3D0.031)%2C%20inability%20to
2012	Thilen SR, Hansen BE, Ramaiah R, Kent CD, Treggiari MM, Bhananker SM	Intraoperative neuromuscular monitoring site and residual paralysis	"Patients having qualitative TOF monitoring of eye muscles had a greater than 5-fold higher risk of postoperative residual paralysis than those monitored at the adductor pollicis."	*Anesthesiology. 2012 Nov;117(5):964-72*	https://pubmed.ncbi.nlm.nih.gov/23001053/

Incidence of RNMB and postoperative complications

Year	Author	Title	Summary	Citation	Link
2010	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	68% of US respondents reported that clinical signs (such as the ability to sustain a 5-s head lift) were reliable indicators of the adequacy of neuromuscular recovery	*Anesth Analg.* 2010 Jul;111(1):110-9	https://pubmed.ncbi.nlm.nih.gov/19910616/
2010	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	"Postoperative residual curarization (PORC) is an independent predictor of postoperative PACU length of stay, potentially affecting OR utilization. PORC is also associated with delayed hospital discharge. The authors recommend increased use of neuromuscular monitoring."	*Br J Anaesth.* 2010 Sep;105(3):304-9	https://pubmed.ncbi.nlm.nih.gov/20576632/
2008	Murphy GS, Szokol JW, Marymont JH, Greenberg SB, Avram MJ, Vender JS	Residual neuromuscular blockade and critical respiratory events in the postanesthesia care unit	"7459 patients were observed. Of patients experiencing a CRE in the PACU, acceptable neuromuscular recovery (TOF >0.9) was present in only 9.5% of cases versus 90.5% of controls"	*Anesth Analg.* 2008 Jul;107(1):130-7	https://pubmed.ncbi.nlm.nih.gov/18635478/
2005	Murphy GS, Szokol JW, Marymont JH, Franklin M, Avram MJ, Vender JS	Residual paralysis at the time of tracheal extubation	Only 12% of patients had achieved the recommended criterion of TOFR >0.9 prior to being extubated.	*Anesth Analg.* 2005 Jun;100(6): 1840-1845	https://pubmed.ncbi.nlm.nih.gov/15920224/
2003	Debaene B, Plaud B, Dilly MP, Donati	Residual paralysis in the PACU after a single intubating dose of nondepolarizing muscle relaxant with an intermediate duration of action	"After a single dose of intermediate-duration muscle relaxant and no reversal, residual paralysis is common, even more than 2 h after the administration of muscle relaxant. Quantitative measurement of neuromuscular transmission is the only recommended method to diagnose residual block."	*Anesthesiology.* 2003 May;98(5): 1042-8	https://pubmed.ncbi.nlm.nih.gov/12717123/

Ease of use in implementing quantitative TOF monitoring

Year	Author	Title	Summary	Citation	Link
2021	Renew JR, Hex K, Johnson P, Lovett P, Pence R	Ease of Application of Various Neuromuscular Devices for Routine Monitoring	It takes 19 seconds longer to apply NMT device than a PNS	*Anesth Analg*. 2021 May 1;132(5):1421-1428.	https://pubmed.ncbi.nlm.nih.gov/33002932/
2015	Todd MM, Hindman BJ	The Implementation of Quantitative Electromyographic Neuromuscular Monitoring in an Academic Anesthesia Department: Follow-Up Observations	Reported that "in the two years since the start of our quantitative monitoring efforts, we had seen no PACU reintubations because of residual paralysis compared with 2 to 4 such events per year in the years preceding our project"	*Anesth Analg*. 2015 Sep;121(3):836-838	https://pubmed.ncbi.nlm.nih.gov/26287308/
2014	Todd MM, Hindman BJ, King BJ	The implementation of quantitative electromyographic neuromuscular monitoring in an academic anesthesia department	Implementation of a universal EMG based NMT monitor resulted in a significant reduction of incompletely reversed patients in the PACU	*Anesth Analg*. 2014 Aug;119(2):323-331	https://pubmed.ncbi.nlm.nih.gov/24878683/

Electromyography (EMG) and other technologies

Year	Author	Title	Summary	Citation	Link
2024	Ebert T, Vogt J, Kaur R, Iqbal Z, Peters D, Cummings C, Stekiel T	Train-of four ratio, counts and post tetanic counts with the TetraGraph electromyograph in comparison to mechanomyography	Clincal validation of the TetraGrpah compared to MMG technology at all depths of block (onset, depth, reversal) when tested at the ulnar nerve and AP.	*J Clin Monit Comput* 39, 149–156 (2025)	https://link.springer.com/article/10.1007/s10877-024-01225-3#Sec8
2024	Epstein R, Nemes R, Renew J, Brull S	Area under the curve and amplitude of the compound motor action potential are clinically interchangable quantitative measures of neuromuscular block: a method comparison study	The study demonstrates that both compound motor action potential (cMAP) amplitude and area under the curve (AUC) provide accurate and interchangeable measurements for monitoring neuromuscular blockade depth.	*BJA Open*, 11 (C): 100293 (2024)	https://www.bjaopen.org/article/S2772-6096%2824%2900037-6/fulltext
2024	Radkowski P, Baranska A, Mieszkowski M, Dawidowska-Fidrych J, Podhorodecks K	Methods for Clinical Monitoring of Neuromuscular Transmission in Anesthesiology - A Review	Review of objective TOF monitoring technologies used during anesthesia, highlighting their importance for accurately assessing muscle relaxation and improving patient safety compared to subjective techniques.	*Int J Gen Med.* 2024;17:9-20	https://www.dovepress.com/methods-for-clinical-monitoring-of-neuromuscular-transmission-in-anest-peer-reviewed-fulltext-article-IJGM
2024	Verdonck M, Carvalho H, Fuchs-Buder T, Brull S, Poelaert J	Machine learning based analysis and detection of trend outliers for electromyographic neuromuscular monitoring	The study concludes that machine learning models, particularly those utilizing engineered features, can effectively detect anomalies in EMG-based neuromuscular monitoring data. Implementing such models could improve the reliability of neuromuscular monitoring.	*J Clin Monit Comput* 38, 1163–1173 (2024)	https://rdcu.be/emouO
2024	Wedemeyer Z, Jelacic S, Michaelsen K, Silliman W, Togashi K, Bowdle A.	Comparative performance of stimpod electromyography with mechanomyography for quantitative neuromuscular blockade monitoring	The electromyograph produced results that were comparable to the mechanomyograph.	*J Clin Monit Comput* 2024;38:205-212	https://pubmed.ncbi.nlm.nih.gov/37831378/

Electromyography (EMG) and other technologies

Year	Author	Title	Summary	Citation	Link
2023	Motamed C	Intraoperative Monitoring of Neuromuscular Blockade	Quantitative neuromuscular monitoring significantly improves patient safety by reducing residual paralysis and ensuring optimal neuromuscular blocker management throughout all phases of anesthesia compared to subjective assessment methods even with Sugammadex.	*Life*, 13(5), 1184	https://www.mdpi.com/2294282
2023	Iwasaki H, Takahoko K, Matsui T, Takada Y, Takahashi Y, Sugawara A, Kurosawa A	The impact of electrosurgical devices on electromyography-based neuromuscular monitoring during abdominal laparotomy: a case series	The use of EMG-based neuromuscular monitoring in lower abdominal laparotomy cases, was found to not be affected by electrical interference. Out of 3091 measurements, at 20-sec intervals, only 94 readings failed (3.5%).	*J Clin Monit Comput* 37, 1111–1114 (2023)	https://rdcu.be/emoh8
2023	Renew J, Hernandez-Torres V, Chaves-Cardona H, Logvinov I, Brull S	Comparison of visual and electromyographic assessments with train-of-four stimulation of the ulnar nerve: a prospective cohort study	"Clinicians subjectively overestimated the response of the adductor pollicis muscle following neurostimulation of the ulnar nerve 47% of the time when compared with objective EMG measurements."	*Can J Anesth/J Can Anesth* 70, 878-885 (2023)	https://rdcu.be/emoqC
2023	Chaves-Cardona H, Fouda E, Hernandez-Torres V, Torp K, Logvinov I, Heckman M, Renew J	Comparison of onset of neuromuscular blockade with electromyographic and acceleromyographic monitoring: a prospective clinical trial	TetraGraph detected a longer onset time for neuromuscular blockade compared to ToFscan, but both devices reliably indicated adequate conditions for intubation when TOFC reached zero.	*Brazilian Journal of Anesthesiology* (2023)	https://www.sciencedirect.com/science/article/pii/S0104001423000301
2023	Carvalho H, Verdonck M, Eleveld DJ, Ramirez D, D'Haese J, Flamée P, Geerts L, Wylleman J, Cools W, Barbe K, Struys MMRF, Poelaert J	Neuromuscular end-point predictive capability of published rocuronium pharmacokinetic/pharmacodynamic models: An observational trial	"Published rocuronium PK/PD models overestimated clinically registered TOF ratios"	*J Clin Anesth.* 2023 Nov;90:111225	https://pubmed.ncbi.nlm.nih.gov/37542918/

Electromyography (EMG) and other technologies

Year	Author	Title	Summary	Citation	Link
2022	Iwasaki H, Yamamoto M, Sato H, Doshu-Kajiura A, Kitajima O, Takagi S, Luthe SK, Suzuki T	A Comparison Between the Adductor Pollicis Muscle Using TOF-Watch SX and the Abductor Digiti Minimi Muscle Using TetraGraph in Rocuronium-Induced Neuromuscular Block: A Prospective Observational Study	"TOF-Watch SX overestimated recovery from rocuronium-induced neuromuscular block compared with TetraGraph"	*Anesth Analg.* 2022 Aug 1;135(2):370-375	https://pubmed.ncbi.nlm.nih.gov/35061641/
2021	Nemes R, Lengyel S, Nagy G, Hampton DR, Gray M, Renew JR, Tassonyi E, Fülesdi B, Brull SJ	Ipsilateral and Simultaneous Comparison of Responses from Acceleromyography- and Electromyography-based Neuromuscular Monitors	EMG vs AMG	*Anesthesiology* 2021; 135:597–611	https://pubmed.ncbi.nlm.nih.gov/34329371/
2021	Nemes R, Lengyel S, Nagy G, Hampton DR, Gray M, Renew JR, Tassonyi E, Fülesdi B, Brull SJ	Ipsilateral and Simultaneous Comparison of Responses from Acceleromyography- and Electromyography-based Neuromuscular Monitors	EMG vs AMG	*Anesthesiology* 2021; 135:597–611	https://pubmed.ncbi.nlm.nih.gov/34329371/
2021	Giudici G, Piccioni F, Proto P, Valenza F	A comparison of accelerometric monitoring by TOF-Watch® SX and electromyographic monitoring by TetraGraph® for recovery from neuromuscular blockade	"Bias between the TOF-Watch SX and the TetraGraph TOF-ratios is in line with previous results for AMG and EMG monitors."	*J Clin Anesth.* 2021 Dec;75:110481	https://pubmed.ncbi.nlm.nih.gov/34388509/

Electromyography (EMG) and other technologies

Year	Author	Title	Summary	Citation	Link
2021	Lee W	The latest trend in neuromuscular monitoring: return of the electromyography	The use of recently released EMG-based devices is expected to increase because their accurate measurements do not need normalization, nor are they limited by access to a freely moving hand necessary for intraoperative monitoring.	*Anesth Pain Med* (Seoul). 2021 Apr;16(2):133-137	https://pubmed.ncbi.nlm.nih.gov/33845547/
2020	Creighton, A.; Phillips, S.; Kim, Dukyeon; Liang, Sophie S.; Stewart, P. A.	Comparison of two muscles using a novel electromyographic device to assess recovery from muscle relaxants in patients undergoing general anaesthesia	Compares muscle recovery of FDI & ADM	*Anaesthesia and Intensive Care*. 48(1, Supplement):1-48	https://wslhd.intersearch.com.au/wslhdjspui/handle/1/2345
2019	Bowdle A, Bussey L, Michaelsen K, Jelacic S, Nair B, Togashi K, Hulvershorn J	A comparison of a prototype electromyograph vs. a mechanomyograph and an acceleromyograph for assessment of neuromuscular blockade. Anaesthesia	Electromyography most closely resembled mechanomyographic assessment of neuromuscular blockade, whereas acceleromyography frequently produced train-of-four ratio values > 1.0, complicating the interpretation of acceleromyography results in the clinical setting.	2020 Feb;75(2):187-195	https://pubmed.ncbi.nlm.nih.gov/31617199/
2018	Iwasaki H, Nemes R, Brull S, Renew J	Quantitative neuromuscular monitoring: current devices, new technological advances, and use in clinical practice	This article reviews advances in quantitative neuromuscular monitoring technologies and underscores their critical role in enhancing patient safety and outcomes during anesthesia through precise assessment of neuromuscular function.	*Curr Anesthesiol* Rep 8, 134–144 (2018)	https://rdcu.be/emebr
2016	Salminen J, van Gils M, Paloheimo M, Yli-Hankala A	Comparison of train-of-four ratios measured with Datex-Ohmeda's M-NMT MechanoSensor™ and M-NMT ElectroSensor™	KMG (kinemyography) overestimates the recovery from neuromuscular blockade compared with EMG. TOF ratio > 90% can not be considered as adequate level of recovery with all monitoring devices.	*J Clin Monit Comput*. 2016 Jun;30(3):295-300	https://pubmed.ncbi.nlm.nih.gov/26152603/

Electromyography (EMG) and other technologies

Year	Author	Title	Summary	Citation	Link
2013	Liang SS, Stewart PA, Phillips S	An ipsilateral comparison of acceleromyography and electromyography during recovery from nondepolarizing neuromuscular block under general anesthesia in humans	AMG (acceleromyography) is less precise than EMG and overestimates EMG TOF ratio by at least 0.15. Residual neuromuscular block can not be excluded on reaching an AMG TOF ratio of 1.00 unless the final TOFR value is normalized to the baseline value.	*Anesth Analg*. 2013 Aug;117(2):373-9	https://pubmed.ncbi.nlm.nih.gov/23821356/
2011	Murphy GS, Szokol JW, Avram MJ, Greenberg SB, Marymont JH, Vender JS, Gray J, Landry E, Gupta DK	Intraoperative acceleromyography monitoring reduces symptoms of muscle weakness and improves quality of recovery in the early postoperative period	AMG monitoring reduces incidence of residual block and improves quality of recovery	*Anesthesiology*. 2011 Nov;115(5):946-54	https://pubmed.ncbi.nlm.nih.gov/21946094/

Reversal agents and quantitative monitoring

Year	Author	Title	Summary	Citation	Link
2025	Renew J, Linn D	Pro: The Use of Sugammadex Does Not Preclude the Need for Objective Neuromuscular Monitoring	Despite Sugammadex's effectivenss in reversing neuromuscular blockade, its use does not eliminate the necessity for objective neuromuscular monitoring to ensure complete recovery and prevent postoperative residual neuromuscular block	*Journal of Cardiothoracic and Vascular Anesthesia* (2025)	https://www.jcvaonline.com/article/S1053-0770%2825%2900278-2/abstract
2025	Liu H, Yang Q, Li Z, Yan S, Ming S	Systemic analysis of sugammadex-related adverse drug reaction signals using FAERS database	The instance of adverse drug events (ADEs) through data compiled from the Food and Drug Administration's Adverse Event Reporting System (FAERS) from 2009 through 2023. There were 3562 ADEs found within the 1505 patient reports to the FDA. 80% of these reports have come in the last 8 years.	*International Journal of Surgery* 111(2):p 1988-1994, February 2025	http://dx.doi.org/10.1097/JS9.0000000000002194
2023	Bowdle TA, Haththotuwegama KJ, Jelacic S, Nguyen ST, Togashi K, Michaelsen KE	A Dose-finding Study of Sugammadex for Reversal of Rocuronium in Cardiac Surgery Patients and Postoperative Monitoring for Recurrent Paralysis	"When sugammadex was titrated to effect, the dose was usually less than the recommended dose, but it was more in some patients. Therefore, quantitative twitch monitoring is essential for ascertaining that adequate reversal has taken place after sugammadex administration. Recurrent paralysis was observed in two patients."	*Anesthesiology*. 2023 Jul 1;139(1):6-15	https://pubmed.ncbi.nlm.nih.gov/37027807/
2023	Thilen SR, Liang T, Kruse TN, Cain KC, Treggiari MM, Bhananker SM	Evaluation of a Protocol for the Management of Maintenance and Reversal of Rocuronium Block Using Neostigmine or Sugammadex	The use of a protocol that specifies rocuronium dosing and selective use of sugammadex versus neostigmine based on qualitative assessment of TOF count and fade resulted in an incidence of postoperative residual block of 3% (95% CI, 1-7) at PACU arrival. Quantitative monitoring is needed to further reduce this incidence.	*Anesth Analg* 2023; 136:1143-53	https://pubmed.ncbi.nlm.nih.gov/37205804/

Reversal agents and quantitative monitoring

Year	Author	Title	Summary	Citation	Link
2021	Li G, Freundlich RE, Gupta RK, Hayhurst CJ, Le CH, Martin BJ, Shotwell MS, Wanderer JP	Postoperative Pulmonary Complications' Association with Sugammadex versus Neostigmine: A Retrospective Registry Analysis	"Among 10,491 patients at a single academic tertiary care center, the authors found that switching neuromuscular blockade reversal agents was not associated with the occurrence of postoperative pulmonary complications"	*Anesthesiology.* 2021 Jun 1;134(6):862-873	https://pubmed.ncbi.nlm.nih.gov/33730169/
2020	Krause M, McWilliams SK, Bullard KJ, Mayes LM, Jameson LC, Mikulich-Gilbertson SK, Fernandez-Bustamante A, Bartels K	Neostigmine Versus Sugammadex for Reversal of Neuromuscular Blockade and Effects on Reintubation for Respiratory Failure or Newly Initiated Noninvasive Ventilation: An Interrupted Time Series Design	"A system wide transition from neostigmine to sugammadex was associated with a decrease in the odds of adverse postoperative respiratory outcomes."	*Anesth Analg.* 2020 Jul;131(1):141-151	https://pubmed.ncbi.nlm.nih.gov/31702700/
2020	Iwasaki H, Kurosawa A, Iida T, Sasakawa T, Kanda H	Use of intraoperative neuromuscular monitor reduces the reversal dose of sugammadex: a single-center retrospective study	This study shows that the reversal dose of sugammadex was reduced by using a quantitative neuromuscular monitor intraoperatively	*J Anesth.* 2020 Apr;34(2):276-280	https://pubmed.ncbi.nlm.nih.gov/31993747/
2019	Domenech G, Kampel MA, García Guzzo ME, Novas DS, Terrasa SA, Fornari GG	Usefulness of intra-operative neuromuscular blockade monitoring and reversal agents for postoperative residual neuromuscular blockade: a retrospective observational study	Sugammadex administration in the absence of NMB monitoring is not an effective strategy to avoid RNMB -16% incidence of RNMB	*BMC Anesthesiol.* 2019 Aug 7;19(1):143	https://pubmed.ncbi.nlm.nih.gov/31390986/
2018	de Boer HD, Carlos RV, Brull SJ	Is lower-dose sugammadex a cost-saving strategy for reversal of deep neuromuscular block? Facts and fiction	An appropriately large dose of sugammadex based on objective determination of the depth of neuromuscular block should be administered to avoid residual or recurrent neuromuscular block and attendant postoperative complications	*Anesthesiol.* 2018 Nov 6;18(1):159	https://pubmed.ncbi.nlm.nih.gov/30400850/

Reversal agents and quantitative monitoring

Year	Author	Title	Summary	Citation	Link
2017	Hristovska AM, Duch P, Allingstrup M, Afshari A	Efficacy and safety of sugammadex versus neostigmine in reversing neuromuscular blockade in adults	Results of this study show that sugammadex has a better safety profile than neostigmine and also suggests that sugammadex can more rapidly reverse rocuronium-induced neuromuscular block than neostigmine.	*Cochrane Database Syst Rev.* 2017 Aug 14;8(8):CD012763	https://pubmed.ncbi.nlm.nih.gov/28806470/
2016	Martinez-Ubieto J, Ortega-Lucea S, Pascual-Bellosta A, Arazo-Iglesias I, Gil-Bona J, Jimenez-Bernardó T, Muñoz-Rodriguez L	Prospective study of residual neuromuscular block and postoperative respiratory complications in patients reversed with neostigmine versus sugammadex	"The use of rocuronium-sugammadex significantly reduces the incidence of PORC in the PACU"	*Minerva Anestesiol.* 2016 Jul;82(7):735-42	https://pubmed.ncbi.nlm.nih.gov/26472231/
2016	Boon M, Martini C, Broens S, van Rijnsoever E, van der Zwan T, Aarts L, Dahan A	Improved postoperative oxygenation after antagonism of moderate neuromuscular block with sugammadex versus neostigmine after extubation in 'blinded' conditions	After antagonism, the anesthesiologist was blinded to the TOF and extubation was based on clinical grounds only (head lift, hand grip, open eyes, tongue protrusion, etc.). 70% of the patients treated with neostigmine had a TOF ratio of <0.9 upon extubation (vs. 4% of sugammadex).	*Br J Anaesth.* 2016 Sep;117(3):410-1	https://pubmed.ncbi.nlm.nih.gov/27543551/
2013	Kotake Y, Ochiai R, Suzuki T, Ogawa S, Takagi S, Ozaki M, Nakatsuka I, Takeda J	Reversal with sugammadex in the absence of monitoring did not preclude residual neuromuscular block	Despite the use of sugammadex, the risk of TOFR <0.9 remains as high as 9.4% in a setting where neuromusuclar monitoring (objective or subjective) was not used.	*Anesth Analg.* 2013 Aug;117(2):345-51	https://pubmed.ncbi.nlm.nih.gov/23757472/
2004	Kim KS, Cheong MA, Lee HJ, Lee JM	Tactile assessment for the reversibility of rocuronium-induced neuromuscular blockade during propofol or sevoflurane anesthesia	The median time to achieve a TOFR >0.9 from TOF counts 3 and 4 were 16 (7-44) and 10 (5-26) minutes, respectively.	*Anesth Analg.* 2004 Oct;99(4): 1080-1085	https://pubmed.ncbi.nlm.nih.gov/15385354/

Quantitative monitoring in the **ICU** and Pediatrics

Year	Author	Title	Summary	Citation	Link
2020	Renew JR, Ratzlaff R, Hernandez-Torres V, Brull SJ, Prielipp RC	Neuromuscular blockade management in the critically Ill patient	"Transitioning from subjective evaluation to precisely meauring the level of blockade with quantitative monitoring represents a significant improvement in neuromuscular blockade management in the critical care setting and reduces inter-observer variability."	*J Intensive Care.* 2020 May 24;8:37	https://pubmed.ncbi.nlm.nih.gov/32483489/
2016	Murray MJ, DeBlock H, Erstad B, Gray A, Jacobi J, Jordan C, McGee W, McManus C, Meade M, Nix S, Patterson A, Sands MK, Pino R, Tescher A, Arbour R, Rochwerg B, Murray CF, Mehta S	Clinical Practice Guidelines for Sustained Neuromuscular Blockade in the Adult Critically Ill Patient	Updated clinical practice guidelines provided by SCCM for sustained used of NMBAs in the critically ill adult patient.	*Crit Care Med.* 2016 Nov;44(11):2079-2103	https://pubmed.ncbi.nlm.nih.gov/27755068/
2013	Greenberg SB, Vender J	The use of neuromuscular blocking agents in the ICU: where are we now?	"A collaborative multidisciplinary approach coupled with constant review of the pharmacology, dosing, drug interactions, and monitoring techniques may reduce the adverse events associated with the use of neuromuscular blocking agents."	*Crit Care Med.* 2013 May;41(5):1332-44	https://pubmed.ncbi.nlm.nih.gov/23591211/

Quantitative monitoring in the ICU and **Pediatrics**

Year	Author	Title	Summary	Citation	Link
2024	Faulk D, Karlik J, Strupp K, Tran S, Twite M, Brull S, Yasgter M, Austin T	The Incidence of Residual Neuromuscular Block in Pediatrics: A Prospective, Pragmatic, Multi-institutional Cohort Study	29.7% of patients receiving neostigmine, experienced RNMB, despite qualitative (PNS) TOF assessments that showed full recovery vs 0% of those who received sugammadex, highlighting the unreliability of qualitative assessment and the need for quanitative TOF monitoring.	*Cureus* 16(3): e56408	https://pmc.ncbi.nlm.nih.gov/articles/PMC11024486/
2024	Espinal LM, Kalsotra S, Rice-Weimer J, Yemele Kitio SA, Tobias JD	Tolerance to preoperative placement of electrodes for neuromuscular monitoring using the TetraGraph™	In patients greater than 4 years of age, preoperative placement of the adhesive sensor for EMG-based TOF monitoring may be feasible. For patients younger than 4 years old, additional interventions may be required.	*Saudi J Anaesth* 2024	https://journals.lww.com/sjan
2024	Salaün JP, Décary E, Veyckemans F	Recurarisation after sugammadex in children: review of case reports and recommendations	Reviews instances of muscle reweakening (recurarisation) following the administration of sugammadex in pediatric patients, highlighting the importance of EMG neuromuscular monitoring in detecting and managing these cases, and providing clinical recommendations to mitigate such occurrences.	*Br J Anaesth*. 2024 Feb;132(2):410-414.	https://pubmed.ncbi.nlm.nih.gov/38170632/
2023	Kalsotra S, Rice-Weimer J, Tobias JD.	Intraoperative electromyographic monitoring in children using a novel pediatric sensor	Neuromuscular monitoring can be performed intraoperatively in pediatric patients who are less than 8 years of age using a novel commercially available EMG-based monitor with a recently developed pediatric sensor. The novel sensor allows use of an EMG-based monitor in infants and children in whom acceleromyography or subjective (visual) observation of the TOF response may not be feasible. Automatic detection of neuromuscular stimulating parameters (supramaximal current intensity level, baseline amplitude of the muscle action potential) was feasible in pediatric patients of all sizes including those weighing less than 15 kilograms or when there was limited access to the extremity being monitored.	*Saudi J Anaesth*. 2023 Jul-Sep;17(3): 378-382.	https://pubmed.ncbi.nlm.nih.gov/37601498/

Quantitative monitoring in the ICU and **Pediatrics**

Year	Author	Title	Summary	Citation	Link
2022	Owusu-Bediako K, Munch R, Mathias J, Tobias JD.	Feasibility of intraoperative quantitative neuromuscular blockade monitoring in children using electromyography.	Neuromuscular monitoring can be performed intraoperatively in pediatric patients weighing between 20 and 60 kg using the new commercially available EMG-based monitor.	*Saudi J Anaesth.* 2022 Oct-Dec;16(4):412-418.	https://pubmed.ncbi.nlm.nih.gov/36337401/
2022	Cha, Y.M., Faulk, D.J	Management of Neuromuscular Block in Pediatric Patients — Safety Implications	This pediatric study suggests that objective TOF monitoring should be encouraged for appropriate management and reversal of NMBAs, even when using sugammadex.	*Curr Anesthesiol Rep* 12, 439–450 (2022)	https://link.springer.com/article/10.1007/s40140-022-00537-x#citeas
2019	Klucka J, Kosinova M, Krikava I, Stoudek R, Toukalkova M, Stourac P	Residual neuromuscular block in paediatric anaesthesia	In a pediatric trial measuring incidence of RNB just before extubation in the OR and RNB in PACU, the incidence in the OR was 48.2% and 26.9% in the PACU.	*Br J Anaesth.* 2019 Jan;122(1):e1-e2.	https://pubmed.ncbi.nlm.nih.gov/30579414/
2015	Ledowski T, O'Dea B, Meyerkort L, Hegarty M, von Ungern-Sternberg BS	Postoperative Residual Neuromuscular Paralysis at an Australian Tertiary Children's Hospital	In a study aiming to identify the incidence of RNMB in a pediatric facility, the incidence of RNMB was 28.1% overall (without reversal: 19.4%; after neostigmine: 37.5%)	*Anesthesiol Res Pract.* 2015;2015:410248	https://pubmed.ncbi.nlm.nih.gov/26064105/

Classics in neuromuscular monitoring

Year	Author	Title	Summary	Citation	Link
1971	Waud BE	The relation between tetanic fade and receptor occlusion in the presence of competitive neuromuscular block	Seminal work that describes how a twitch response to neurostimulation can be normal when 75-80% of receptors are blocked - meaning that ONLY 20-25% of receptors are functioning!	Waud BE, Waud DR. The relation between tetanic fade and receptor occlusion in the presence of competitive neuromuscular block. *Anesthesiology*. 1971 Nov;35(5):456-64. PMID: 4329144.	https://pubmed.ncbi.nlm.nih.gov/4329144/
1972	Waud BE	The relation between the response to "train-of-four" stimulation and receptor occlusion during competitive neuromuscular block	Similar to the work from 1971, the authors showed that the response to the 4th stimulus in a train-of-four (T4) returns to normal (TOFR=100%) when about 25-30% of receptors are functional.	Waud BE, Waud DR. The relation between the response to "train-of-four" stimulation and receptor occlusion during competitive neuromuscular block. *Anesthesiology*. 1972 Oct;37(4):413-6. PMID: 5074722.	https://pubmed.ncbi.nlm.nih.gov/5074722/
1973	Epstein RA	The electromyogram and the mechanical response of indirectly stimulated muscle in anesthetized man following curarization.	The authors investigated EMG and tension (MMG) and reported that post-tetanic potentiation without neuromuscular block was present in MMG but not EMG recordings. They concluded that EMG is more sensitive than MMG for monitoring the neuromuscular block.	Epstein RA, Epstein RM. The electromyogram and the mechanical response of indirectly stimulated muscle in anesthetized man following curarization. *Anesthesiology*. 1973 Mar;38(3):212-23. PMID: 4349000.	https://pubmed.ncbi.nlm.nih.gov/180849/
1976	Ali HH, Savarese JJ	Monitoring of neuromuscular function.	A brilliant review of the mechanisms of normal NMJ, neuromuscular block, and effects of disease and pharmacologic agents on neuromuscular transmission.	Ali HH, Savarese JJ. Monitoring of neuromuscular function. *Anesthesiology*. 1976 Aug;45(2):216-49. PMID: 180849.	https://pubmed.ncbi.nlm.nih.gov/180849/

Classics in neuromuscular monitoring

Year	Author	Title	Summary	Citation	Link
1983	Stanec A	The adductor pollicis monitor—apparatus and method for the quantitative measurement of the isometric contraction of the adductor pollicis muscle	A comprehensive review of a complete MMG apparatus that could be used clinically to monitor neuromuscular block.	Stanec A, Stanec G. The adductor pollicis monitor--apparatus and method for the quantitative measurement of the isometric contraction of the adductor pollicis muscle. *Anesth Analg*. 1983 Jun;62(6):602-5. PMID: 6846883.	https://pubmed.ncbi.nlm.nih.gov/6846883/
1984	Kopman AF	Milliamperage requirements for supramaximal stimulation of the ulnar nerve with surface electrodes	One of the first reports to investigate and report the relationship between current intensity and evoked neuromuscular responses. Established the threshold current and defined supramaximal current.	Kopman AF, Lawson D. Milliamperage requirements for supramaximal stimulation of the ulnar nerve with surface electrodes. *Anesthesiology*. 1984 Jul;61(1):83-5. PMID: 6742488.	https://pubmed.ncbi.nlm.nih.gov/6742488/
1985	Viby-Mogensen J	Tactile and visual evaluation of the response to train-of-four nerve stimulation.	Study that established the inability to detect neuromuscular TOF fade with subjective (visual or tactile) means.	Viby-Mogensen J, Jensen NH, Engbaek J, Ording H, Skovgaard LT, Chraemmer-Jørgensen B. Tactile and visual evaluation of the response to train-of-four nerve stimulation. *Anesthesiology*. 1985 Oct;63(4):440-3. PMID: 4037404.	https://pubmed.ncbi.nlm.nih.gov/4037404/
1987	Fernando PU	Relationship between posttetanic count and response to carinal stimulation during vecuronium-induced neuromuscular blockade	Study that established that to ensure total diaphragmatic paralysis, the neuromuscular block of the peripheral muscles should be so intense that no response to posttetanic twitch stimulation (PTC = 0) can be elicited.	Fernando PU, Viby-Mogensen J, Bonsu AK, Tamilarasan A, Muchhal KK, Lambourne A. Relationship between posttetanic count and response to carinal stimulation during vecuronium-induced neuromuscular blockade. *Acta Anaesthesiol Scand*. 1987 Oct;31(7):593-6. PMID: 2891238.	https://pubmed.ncbi.nlm.nih.gov/2891238/

Classics in neuromuscular monitoring

Year	Author	Title	Summary	Citation	Link
1990	Brull SJ	Stimulation with submaximal current for train-of-four monitoring	The first study to establish that TOF monitoring using a submaximal stimulus is more comfortable for the awake patient who is suspected of residual weakness, and that T4/T1 testing can be reliably accomplished intraoperatively as well as postoperatively using submaximal stimuli.	Brull SJ, Ehrenwerth J, Silverman DG. Stimulation with submaximal current for train-of-four monitoring. *Anesthesiology.* 1990 Apr;72(4):629-32. PMID: 2321779.	https://pubmed.ncbi.nlm.nih.gov/2321779/
2001	Harper NJ	Neuromuscular monitoring in intensive care patients: milliamperage requirements for supramaximal stimulation.	Supramaximal current requirement in critically ill patients is increased in the presence of peripheral edema. The authors recommend that nerve stimulators used for neuromuscular monitoring in the ICU be capable of delivering a stimulus current of at least 100 mA.	Harper NJ, Greer R, Conway D. Neuromuscular monitoring in intensive care patients: milliamperage requirements for supramaximal stimulation. *Br J Anaesth.* 2001 Oct;87(4): 625-7. PMID: 11878733.	https://pubmed.ncbi.nlm.nih.gov/11878733/

Cost avoidance with quantitative TOF monitoring

Year	Author	Title	Summary	Citation	Link
2024	Haberkorn S, Twite M,Klockau K, Whitney G, Faulk D	Quantitative Monitoring Maximizes Cost-Saving Strategies When Antagonizing Neuromuscular Block With Sugammadex	Using EMG-based monitoring to guide sugammadex dosing and aliquoted 50mg doses resulted in a net savings of $46 per case with projected annual savings of $370,000. 40% of these savings can be traced back to patients who spontaneously recovered (TOFr >90%) and DID NOT REQUIRE REVERSAL.	*Cureus*. 2024 Sep 3;16(9):e68551	https://pmc.ncbi.nlm.nih.gov/articles/PMC11449403/
2024	Linn D, Renew J	The impact of sugammadex dosing and administration practices on potential cost savings for pharmacy departments	This study evaluates how adjusting sugammadex dosing based on body weight and neuromuscular blockade depth, along with practices like vial splitting, can reduce medication waste and potentially lower costs for pharmacy departments.	*American Journal of Health-System Pharmacy*, Volume 81, Issue 19, 1 October 2024, Pages e575–e583	https://academic.oup.com/ajhp/article-abstract/81/19/e575/7667983
2023	Thilen SR, Sherpa JR, James AM, Cain KC, Treggiari MM, Bhananker SM	Management of Muscle Relaxation With Rocuronium and Reversal With Neostigmine or Sugammadex Guided by Quantitative Neuromuscular Monitoring	"A protocol that includes quantitative monitoring to guide reversal with neostigmine or sugammadex and to confirm TOF ratio ≥0.9 before extubation resulted in the complete prevention of PRNB. With current pricing of drugs, the selective use of sugammadex reduced the total cost of reversal drugs compared to the projected cost associated with routine use of sugammadex for all patients."	*Anesth Analg*. 2023 May 12	https://pubmed.ncbi.nlm.nih.gov/37171989/
2022	Weigel WA, Williams BL, Hanson NA, Blackmore CC, Johnson RL, Nissen GM, James AB, Strodtbeck WM	Quantitative Neuromuscular Monitoring in Clinical Practice: A Professional Practice Change Initiative	After implementing quantitative neuromuscular monitoring, inpatients had shorter postanesthesia care unit lenghts of stay, less pulmonary complications, and shorter hospital stays.	*Anesthesiology*. 2022 Jun 1;136(6):901-915	https://pubmed.ncbi.nlm.nih.gov/35188958/

Cost avoidance with quantitative TOF monitoring

Year	Author	Title	Summary	Citation	Link
2021	Edwards L-A, Ly N, Shinefeld J, Morewood G	Universal Quantitative Neuromuscular Blockade Monitoring at an Academic Medical Center—a multimodal analysis of the potential impact on clinical outcomes and total cost of care.	Universal quantitative monitoring may be justified for soley for the potential institutional cost savings.	*Perioperative Care and Operating Room Management*. 2021 Sept;24:100184	https://www.sciencedirect.com/science/article/abs/pii/S2405603021000303
2020	Merkow RP, Shan Y, Gupta AR, Yang AD, Sama P, Schumacher M, Cooke D, Barnard C, Bilimoria KY	A Comprehensive Estimation of the Costs of 30-Day Postoperative Complications Using Actual Costs from Multiple, Diverse Hospitals	Using cost data from four diverse hospitals, the two complications with the highest adjusted cost per event were prolonged ventilation ($48,168) and unplanned intubation ($26,718).	*Jt Comm J Qual Patient Saf*. 2020 Oct;46(10):558-564	https://pubmed.ncbi.nlm.nih.gov/32888813/
1998	Niederman MS, McCombs JS, Unger AN, Kumar A, Popovian R	The cost of treating community-acquired pneumonia	The cost to treat a post anesthesia pneumonia case was $6,042	*Clin Ther*. 1998 Jul-Aug;20(4):820-37	https://pubmed.ncbi.nlm.nih.gov/9737840/

TetraGraph Literature

Year	Author	Title	Summary	Citation	Link
2024	Ebert T, Vogt J, Kaur R, Iqbal Z, Peters D, Cummings C, Stekiel T	Train-of four ratio, counts and post tetanic counts with the TetraGraph electromyograph in comparison to mechanomyography	Clincal validation of the TetraGrpah compared to MMG technology at all depths of block (onset, depth, reversal) when tested at the ulnar nerve and AP. TetraGraph outperformed in accuracy and precision when measuring TOFR without NMBAs and performed on par with MMG.	*J Clin Monit Comput* 39, 149–156 (2025)	https://link.springer.com/article/10.1007/s10877-024-01225-3#Sec8
2024	Epstein R, Nemes R, Renew J, Brull S	Area under the curve and amplitude of the compound motor action potential are clinically interchangable quantitative measures of neuromuscular block: a method comparison study	The study demonstrates that both compound motor action potential (cMAP) amplitude and area under the curve (AUC) provide accurate and interchangeable measurements for monitoring neuromuscular blockade depth.	*BJA Open*, 11 (C): 100293 (2024)	https://www.bjaopen.org/article/S2772-6096%2824%2900037-6/fulltext
2024	Espinal LM, Kalsotra S, Rice-Weimer J, Yemele Kitio SA, Tobias JD"	Tolerance to preoperative placement of electrodes for neuromuscular monitoring using the TetraGraph™	In patients greater than 4 years of age, preoperative placement of the adhesive sensor for EMG-based TOF monitoring may be feasible. This study confirmed the design of this pediatric electrode and feasibility of recommending placement of electrode before OR.	*Saudi J Anaesth* 2024	https://journals.lww.com/sjan
2024	Haberkorn S, Twite M,Klockau K, Whitney G, Faulk D	Quantitative Monitoring Maximizes Cost-Saving Strategies When Antagonizing Neuromuscular Block With Sugammadex	Using TetraGraph to guide sugammadex dosing and aliquoted 50mg doses resulted in a net savings of $46 per case with projected annual savings of $370,000. 40% of these savings can be traced back to patients who spontaneously recovered (TOFr >90%) and DID NOT REQUIRE REVERSAL.	*Cureus*. 2024 Sep 3;16(9):e68551	https://pmc.ncbi.nlm.nih.gov/articles/PMC11449403/

TetraGraph Literature

Year	Author	Title	Summary	Citation	Link
2024	Radkowski P, Baranska A, Mieszkowski M, Dawidowska-Fidrych J, Podhorodecks K	Methods for Clinical Monitoring of Neuromuscular Transmission in Anesthesiology — A Review	Review of objective TOF monitoring technologies used during anesthesia, highlighting their importance for accurately assessing muscle relaxation and improving patient safety compared to subjective techniques.	*Int J Gen Med.* 2024;17:9-20	https://www.dovepress.com/methods-for-clinical-monitoring-of-neuromuscular-transmission-in-anest-peer-reviewed-fulltext-article-IJGM
2024	Verdonck M, Carvalho H, Fuchs-Buder T, Brull S, Poelaert J	Machine learning based analysis and detection of trend outliers for electromyographic neuromuscular monitoring	The study concludes that machine learning models, particularly those utilizing engineered features, can effectively detect anomalies in EMG-based neuromuscular monitoring data. Implementing such models could improve the reliability of neuromuscular monitoring.	*J Clin Monit Comput* 38, 1163–1173 (2024)	https://rdcu.be/emouO
2023	Chaves-Cardona H, Fouda E, Hernandez-Torres V, Torp K, Logvinov I, Heckman M, Renew J	Comparison of onset of neuromuscular blockade with electromyographic and acceleromyographic monitoring: a prospective clinical trial	TetraGraph detected a longer onset time for neuromuscular blockade compared to TOFscan, but both devices reliably indicated adequate conditions for intubation when TOFC reached zero.	*Brazilian Journal of Anesthesiology* (2023)	https://www.sciencedirect.com/science/article/pii/S0104001423000301
2023	Epstein R, Perez O, Hofer I, Renew J, Nemes R, Brull S	Validation of convolutional neural network that reliably identifies electromyographic compound motor action potentials following train-of-four stimulation: an algorithm development experimental study	Modified a convolutional neural network (CNN) to classify EMG waveforms at the adductor pollicis as a valid cMAP. The CNN distinguished valid cMAP's with >99.5% accuracy.	*BJA Open*, 8 (C): 100236 (2023)	https://www.bjaopen.org/article/S2772-6096%2823%2900115-6/fulltext
2023	Iwasaki H, Takahoko K, Matsui T, Takada Y, Takahashi Y, Sugawara A, Kurosawa A	The impact of electrosurgical devices on electromyography-based neuromuscular monitoring during abdominal laparotomy: a case series	The use of TetraGraph in lower abdominal laparotomy cases, was found to not be affected by electrical interference. Out of 3091 measurements, at 20-sec intervals, only 94 readings failed (3.5%).	*J Clin Monit Comput* 37, 1111–1114 (2023)	https://rdcu.be/emoh8

TetraGraph Literature

Year	Author	Title	Summary	Citation	Link
2023	Kalsotra S, Rice-Weimer J, Tobias JD.	Intraoperative electromyographic monitoring in children using a novel pediatric sensor	TetraGraph monitoring can be performed intraoperatively in pediatric patients who are less than 8 years of age using a novel commercially available EMG-based monitor with a recently developed pediatric sensor. The novel sensor allows use of an EMG-based monitor in infants and children in whom acceleromyography or subjective (visual) observation of the TOF response may not be feasible. Automatic detection of neuromuscular stimulating parameters (supramaximal current intensity level, baseline amplitude of the muscle action potential) was feasible in pediatric patients of all sizes including those weighing less than 15 kilograms or when there was limited access to the extremity being monitored.	*Saudi J Anaesth.* 2023 Jul-Sep;17(3) :378-382.	https://pubmed.ncbi.nlm.nih.gov/37601498/
2023	Motamed C	Intraoperative Monitoring of Neuromuscular Blockade	Quantitative neuromuscular monitoring significantly improves patient safety by reducing residual paralysis and ensuring optimal neuromuscular blocker management throughout all phases of anesthesia compared to subjective assessment methods even with Sugammadex.	*Life*, 13(5), 1184	https://www.mdpi.com/2294282
2023	Renew J, Hernandez-Torres V, Chaves-Cardona H, Logvinov I, Brull S	Comparison of visual and electromyographic assessments with train-of-four stimulation of the ulnar nerve: a prospective cohort study	"Clinicians subjectively overestimated the response of the adductor pollicis muscle following neurostimulation of the ulnar nerve 47% of the time when compared with objective EMG measurements."	*Can J Anesth/J Can Anesth* 70, 878-885 (2023)	https://rdcu.be/emoqC
2022	Cha, Y.M., Faulk, D.J	Management of Neuromuscular Block in Pediatric Patients — Safety Implications	This pediatric study suggests that objective TOF monitoring should be encouraged for appropriate management and reversal of NMBAs, even when using sugammadex.	*Curr Anesthesiol Rep* 12, 439–450 (2022)	https://link.springer.com/article/10.1007/s40140-022-00537-x#citeas

TetraGraph Literature

Year	Author	Title	Summary	Citation	Link
2022	Iwasaki H, Yamamoto M, Sato H, Doshu-Kajiura A, Kitajima O, Takagi S, Luthe SK, Suzuki T	A Comparison Between the Adductor Pollicis Muscle Using TOF-Watch SX and the Abductor Digiti Minimi Muscle Using TetraGraph in Rocuronium-Induced Neuromuscular Block: A Prospective Observational Study	"TOF-Watch SX overestimated recovery from rocuronium-induced neuromuscular block compared with TetraGraph"	*Anesth Analg.* 2022 Aug 1;135(2):370-375	https://pubmed.ncbi.nlm.nih.gov/35061641/
2022	Owusu-Bediako K, Munch R, Mathias J, Tobias JD.	Feasibility of intraoperative quantitative neuromuscular blockade monitoring in children using electromyography.	TetraGraph monitoring can be performed intraoperatively in pediatric patients weighing between 20 and 60 kg using the new commercially available EMG-based monitor.	*Saudi J Anaesth.* 2022 Oct-Dec;16(4):412-418.	https://pubmed.ncbi.nlm.nih.gov/36337401/
2021	Giudici G, Piccioni F, Proto P, Valenza F	A comparison of accelerometric monitoring by TOF-Watch® SX and electromyographic monitoring by TetraGraph® for recovery from neuromuscular blockade	Bias between the TOF-Watch SX (AMG) and TetraGraph (EMG) TOF-ratios was consistent with prior comparisons of AMG and EMG monitors. Additionally, relative intraobserver variability was lower with the TetraGraph, suggesting more consistent measurements.	*J Clin Anesth.* 2021 Dec;75:110481	https://pubmed.ncbi.nlm.nih.gov/34388509/
2021	Lee W	The latest trend in neuromuscular monitoring: return of the electromyography	The use of recently released EMG-based devices is expected to increase because their accurate measurements do not need normalization, nor are they limited by access to a freely moving hand necessary for intraoperative monitoring.	*Anesth Pain Med* (Seoul). 2021 Apr;16(2):133-137	https://pubmed.ncbi.nlm.nih.gov/33845547/
2021	Nemes R, Lengyel S, Nagy G, Hampton DR, Gray M, Renew JR, Tassonyi E, Fülesdi B, Brull SJ	Ipsilateral and Simultaneous Comparison of Responses from Acceleromyography- and Electromyography-based Neuromuscular Monitors	The EMG-based monitor (TetraGraph) had higher precision and greater repeatability than AMG. AMG showed normalized TOF ratio greater than or equal to 80% earlier than EMG.	*Anesthesiology* 2021; 135:597–611	https://pubmed.ncbi.nlm.nih.gov/34329371/

TetraGraph Literature

Year	Author	Title	Summary	Citation	Link
2021	Renew JR, Hex K, Johnson P, Lovett P, Pence R	Ease of Application of Various Neuromuscular Devices for Routine Monitoring	It takes 19 seconds longer to apply NMT device than a PNS. The difference in connection time between the TetraGraph and the IntelliVue NMT device was not statistically significant. However, the authors reported that calibration was easier with the TetraGraph than with the IntelliVue.	*Anesth Analg.* 2021 May 1;132(5):1421-1428.	https://pubmed.ncbi.nlm.nih.gov/33002932/
2020	Renew JR, Ratzlaff R, Hernandez-Torres V, Brull SJ, Prielipp RC	Neuromuscular blockade management in the critically Ill patient	"Transitioning from subjective evaluation to precisely meauring the level of blockade with quantitative monitoring represents a significant improvement in neuromuscular blockade management in the critical care setting and reduces inter-observer variability."	*J Intensive Care.* 2020 May 24;8:37	https://pubmed.ncbi.nlm.nih.gov/32483489/
2018	de Boer HD, Carlos RV, Brull SJ	Is lower-dose sugammadex a cost-saving strategy for reversal of deep neuromuscular block? Facts and fiction	An appropriately large dose of sugammadex based on objective determination of the depth of neuromuscular block should be administered to avoid residual or recurrent neuromuscular block and attendant postoperative complications	*Anesthesiol.* 2018 Nov 6;18(1):159	https://pubmed.ncbi.nlm.nih.gov/30400850/

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