Comparison of Electrical and Mechanical Recording of Spontaneous and Evoked Muscle Activity

The Clinical Value of Continuous Recording as an Aid to the Rational Use of Muscle Relaxants During Anesthesia

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The electrical and mechanical responses of peripheral skeletal muscle to nerve stimulation, and the integrated abdominal electromyogram were studied during anesthesia and operation to determine the feasibility of their routine use as a guide to the administration of neuromuscular blocking agents. The integrated electromyogram provided a good guide to the degree of relaxation produced by anesthetic agents, as well as the neuromuscular blockers. The electrical and mechanical responses of the muscle to nerve stimulation were not significantly modified by the anesthetics but were affected by the neuromuscular blockers. The mechanical response of the muscle to nerve stimulation was found to be the most accurate, convenient and useful guide to the administration of the neuromuscular blockers. Extensive experience with the routine use of a nerve stimulator during anesthesia and operation led to the conclusion that any time a neuromuscular blocking agent is given, the use of a nerve stimulator to monitor the effects should seriously be considered.

Neuromuscular blocking agents are used to provide muscle relaxation or to prevent reflex movements in response to surgical stimulation. Determination of dosage, response, and duration of action of these agents is usually based upon their respiratory effects, the "feel" of the anesthetic reservoir bag, the opinion of the surgeon, or past experience of the anesthesiologist with average doses. Although these guides are often useful for clinical management, a more quantitative method of assessing the effects of the neuromuscular blockers is desirable and would be helpful in providing a more rational method of giving relaxants. During the past three years, the electrical and mechanical responses of the adductor pollicis muscle to ulnar nerve stimulation, and the integrated electromyogram (IEMG) of the oblique-transversus group of abdominal muscles have been studied during anesthesia and operation to determine the feasibility of their routine use as a guide to the administration of neuromuscular blockers.

Methods

Patients ranging in age from 4 weeks to 92 years were studied during anesthesia and operation. Most of the patients received atropine or scopolamine (0.1–0.6 mg.), secobarbital or pentobarbital (10–100 mg.) and/or meperidine (10–100 mg.). Anesthesia was usually induced with an intravenous thiobarbiturate or with open inhalation of cyclopropane or halothane. The agents used for maintenance included nitrous oxide, cyclopropane, halothane, fluoxetine, halopropane, trichloroethylene and methoxyflurane. The trachea was intubated when necessary. Ventilation was spontaneous, assisted, or controlled (manually or with a Frumin-Lee, Stevenson or Takaoka respirator). Brachial arterial blood samples were analyzed for pH and PCO2 with an Ingold pH electrode and modified Severinghaus PCO2 electrode, or by the Astrup technique.

The integrated electromyogram (IEMG) of the oblique-transversus group of abdominal muscles was obtained by inserting 2 needle electrodes (standard 22-gauge, 1.5-inch-long metal needles) between the iliac crest and

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costal margin. The needles were advanced until they penetrated the muscle; the distance between the needles was approximately 10–20 mm. A 25-gauge metal hypodermic needle placed subcutaneously served as the ground electrode. The electrical activity was measured on an Offner EMG integrating amplifier and recorded on an Invengeneering polygraph utilizing Offner components. Each patient served as his own control. The control height of the IEMG was 10–30 mm. Except for the recorder used, the technique is similar to that reported by Fink.1

The muscle response to indirect stimulation was studied in the following manner: the patient's hand was carefully fixed in place on a molded plaster armboard which prevented gross movements. A supramaximal stimulus from a Grass stimulator (Model SC4) was applied to the ulnar nerve at the elbow or wrist by means of surface electrodes or 25-gauge needle electrodes placed subcutaneously. Twitch responses were elicited with square pulse stimuli of 110–150 volts for 0.3 msec. duration delivered at a rate of 0.3 c.p.s. (18 per minute). Tetanus was obtained by stimulating at a frequency of 30 c.p.s. The resulting adduction of the thumb (attributable predominantly to the adductor pollicis muscle) activated a force displacement transducer (Grass FT-03). The output of the transducer was amplified and recorded on the polygraph. The amplitude of this tracing (twitch height) was used as a measure of neuromuscular response in a given patient. Each patient served as his own control. The control twitch height was set at 30–50 mm. The electrical response of the indirectly stimulated adductor pollicis muscle, obtained from surface or needle electrodes, was measured with the Offner EMG integrating amplifier and recorded on the polygraph described above. In some patients, nerve stimulators designed and built for the author by Burroughs Wellcome and Co. (U. S. A.) Inc. were used.

In 10 patients, the electrical response to ulnar nerve stimulation of the adductor pollicis muscle (electrical twitch height), the mechanical response to ulnar nerve stimulation of the adductor pollicis muscle (mechanical twitch height) and IEMG of the oblique-transversus group of abdominal muscles were compared simultaneously. Two of these three responses were measured simultaneously in 30 patients while in over 500 patients one of these responses was measured. In most of the patients, the IEMG and twitch responses were obtained after the induction of anesthesia; in some, prior to induction.

The following neuromuscular blockers were given intravenously: succinylcholine, 2 per cent; d-tubocurarine, 0.3 per cent; dimethyl tubocurarine, 0.1 per cent; decamethonium, 0.1 per cent; hexamethylene carbaminoxycholine (Imbretil), 0.1 per cent; and gallamine, 2 per cent. Because of the variation in response from patient to patient, a test dose of each agent was often used. The approximate test doses were: succinylcholine, 0.3 mg./kg.; d-tubocurarine, 0.1 mg./kg.; dimethyl tubocurarine, 0.03 mg./kg.; decamethonium, 0.03 mg./kg.; Imbretil, 0.03 mg./kg.; gallamine, 0.7 mg./kg. Subsequent doses depended upon the response to the test dose and the clinical situation.

Results

Integrated Electromyogram (IEMG). With constant ventilation and depth of anesthesia (defined as the relationship between surgical stimulation and concentration of anesthetic agents), the IEMG provided a good guide to the degree of relaxation produced by the neuromuscular blockers (fig. 1A). Following the injection of a neuromuscular blocking agent, there was a decrease in IEMG activity which was similar to the decrease in electrical and/or mechanical twitch height. As the action of the neuromuscular blocker gradually waned, there was a parallel increase in the IEMG and twitch height. The decrease in neuromuscular block was usually noted in the IEMG or twitch height recording several minutes to an hour before any changes were clinically detectable by the anesthesiologist or the surgeon.

The IEMG was affected by the depth of anesthesia (fig. 1B, 1C, and 2). When the skin incision was made, the IEMG activity often increased (fig. 1B). This frequently occurred in the absence of changes in finger tone, frequency or depth of respiration, or other clinical signs. The IEMG was not increased when the line of incision was previ-
Fig. 1. Effects of succinylcholine, hyperventilation and changes in depth of anesthesia on the abdominal integrated electromyogram (IEMG). Panel A: At arrow succinylcholine (0.3 mg./kg.) injected. Note decrease in IEMG followed by gradual recovery. Panel B: At arrow skin incised. Note increase in IEMG. Panel C: After local infiltration with 1 per cent lidocaine, skin incision at arrow did not affect IEMG. Panel D: Injection of thiopental (1.1 mg./kg.) at arrow decreased IEMG. Panel E: At arrow 1 hyperventilation started. Note decrease in IEMG. At arrow 2 hyperventilation discontinued.

Fig. 2. Effects of methoxyflurane on the abdominal IEMG. Panels A-H: Variations in IEMG activity associated with changes in depth of anesthesia.
ously infiltrated with 1 per cent lidocaine (fig. 1C). Increasing the concentration of the in-
hulation agent, or injection of thiamylal or thiopental, decreased the IEMG (fig. 1D).

Ventilatory changes, as previously reported,2 could alter the IEMG (fig. 1E). Although
neither hypoventilation, nor hyperventilation induced by 10 per cent CO₂ inhalation, af-
fected the IEMG, manual hyperventilation markedly decreased the IEMG. This effect
was attributable to hyperventilation itself rather than to changes in acid-base balance.2

Although the IEMG is a useful index of muscle relaxation, there are some drawbacks
to its use. Satisfactory IEMG's could not be obtained in every patient. This was due
either to inability to place the needles properly because of obesity or inaccessibility of the
area, or because of electrical interference from roentgen-ray, diathermy, or cautery used in
the operating room area. In some patients the needles were inadvertently dislodged by
the surgeon or when the patient's position was changed. Diminution of the IEMG by manual
hyperventilation was occasionally misleading. In some instances, after a long-acting neu-
romuscular blocker had been given and the lungs hyperventilated, the peritoneum could
not be satisfactorily closed despite a flat IEMG. It was then realized that the neuromuscular
block was waning or absent and that the flat IEMG was attributable to the hyperventilation.

Fig. 3. Effect of d-tubocurarine on mechanical twitch height. At arrow 1 d-tubocurarine
(0.1 mg./kg.). At second arrow 1 mg. of d-tubocurarine (0.14 mg./kg.) produced a per-
ceptible decrease in twitch height.

Fig. 4. Example of continuous monitoring (168 minutes) of mechanical twitch height.
Panels A–E: Effect of gallamine during cholecystectomy in a 75-kg, patient. Record is con-
tinuous except for 34 minutes between panels A and B during which no twitch response was
present. Doses of gallamine (in mg./kg.): arrow 1 (0.8 mg./kg.), arrow 2 (0.8 mg./kg.),
arrows 3 (0.133 mg./kg.), arrow 4 (0.267 mg./kg.). At arrow 5 edrophonium (0.14 mg./kg.)
given to antagonize residual block. One minute between signal marks at top of record.
Mechanical Twitch Height. The mechanical twitch height of the adductor pollicis muscle provided an excellent guide to the degree of relaxation produced by the neuromuscular blockers. The effect of as little as 1 mg. of d-tubocurarine could be detected (fig. 3). The natural recovery or reversal of the action of the neuromuscular blocking agent could be carefully followed (fig. 4). Changes in ventilation had minimal effect on the mechanical twitch height unless marked changes in arterial pH (0.2–0.3 units change from control) were produced either by the inhalation of 10 per cent CO₂ or by hyperventilation of 25 liters/minute. Under these circumstances, ventilation did affect the mechanical twitch height (increased with alkalosis and decreased with acidosis). The depth of anesthesia had no effect on the mechanical twitch height unless the patient was so lightly anesthetized that he could move his thumb. This could easily be detected as a change in baseline of the twitch recording.

Electrical Twitch Height. The electrical twitch height also provided an excellent guide to the degree of muscle relaxation (fig. 5). When the mechanical and electrical twitch responses were simultaneously recorded, they were quite similar and often superimposable. However, they differed in their response to alkalosis or acidosis (a change from control of 0.2–0.3 pH units) produced by inhalation of 10 per cent CO₂ or hyperventilation of 25 liters/minute. The electrical twitch height, unlike the mechanical twitch height, was usually not significantly affected by changes in pH or P CO₂. The electrical twitch height could sometimes not be obtained satisfactorily because of interference from other machines in or near the operating room. This was much less of a problem when the mechanical response to nerve stimulation was recorded on a force displacement transducer. It was also difficult or impossible in some patients to eliminate the stimulus artifact when recording electrical twitch height.

Other Observations. The classical responses to tetanic stimulation were usually observed: (1) well-sustained tetanus and post-tetanic facilitation in the absence of a neuromuscular block; (2) well-sustained tetanus and absence of post-tetanic facilitation with a phase 1 depolarizing block; (3) poorly-sustained tetanus (Wedensky inhibition) and post-tetanic facilitation with a nondepolarizing block. In addition, two other patterns of response were sometimes observed. During a 40–50 per cent d-tubocurarine block, post-tetanic facilitation was seen, as expected, but tetanus was well maintained. This effect may be attributed to recovery of sufficient motor units to sustain tetanus. The other pattern observed developed after relatively large doses of decamethonium (20 mg. in 60–90 minutes) were antagonized by edrophonium (Tensilon). Although edrophonium restored the twitch height to the control level, tetanus was sustained at only 10–25 per cent of the initial tetanic response. During the following 30 to 45 minutes, the level at which tetanus was sustained gradually increased until it was well sustained at the initial tetanic level.

It was observed that many of the surgeons considered muscle relaxation satisfactory when
the mechanical twitch height was 25 per cent of control. All surgeons but one were satisfied with muscle relaxation when the twitch height was 5–10 per cent of control. On several occasions, muscle relaxation was deemed to be inadequate by the surgeon at a time when the twitch response was absent. Satisfactory conditions could usually be obtained by improving the position of the patient on the operating table or by better placement of the retractors.

A flat IEMG or an absent mechanical or electrical twitch did not necessarily mean that the patient was totally paralyzed. Some patients who received a sleep-inducing dose of thiobarbiturate followed by nitrous oxide, oxygen and a neuromuscular blocking agent, showed an IEMG that was flat and an absent twitch response, but some movements were still possible. The patient might wink, wrinkle his forehead, move his arms or legs slightly, hiccup, turn his head, or, rarely, take a breath. Hyperventilation or the intravenous injection of a barbiturate or narcotic usually eliminated these responses.

Of the three methods of monitoring muscle relaxation, the mechanical twitch response was most convenient and most reliable. After some experience, the anesthesiologist could judge the degree of neuromuscular block without looking at the twitch height recording on the polygraph, but by watching the thumb movement. He was usually able to distinguish absence of twitch, less than 25 per cent of control, approximately 50 per cent of control and 75 per cent or greater. It was possible by this monitoring technique to use relatively large amounts of the neuromuscular blocking agent over long periods of time without requiring antagonists.

Discussion

There are many methods used by anesthesiologists to assess relaxation and neuromuscular blockade. The most commonly used methods are based on clinical judgment and are usually satisfactory. However, as Fink\(^1\) has pointed out, "even the best judgment sometimes errs and a practicable method of relating the dose more critically to physiological requirements is desirable." Uma et al.\(^3\) measured grip strength with a dynamometer. Bendixen et al.\(^4\) measured inspiratory force (the negative pressure developed against an occluded airway) to demonstrate residual weakness due to neuromuscular blockade. Hampton et al.\(^5\) applied a tetanizing current to a motor point of the tibialis anticus muscle and determined the degree of response by palpation and observation of the muscle contraction. Poulsen and Hougs,\(^6\) Churchill-Davidson and Richardson,\(^7\) and Thesleff\(^8\) used the muscle response to nerve stimulation as an index of neuromuscular blockade. Poulsen and Hougs,\(^6\) and Churchill-Davidson and Richardson\(^7\) measured the electrical response (EMG) while Thesleff\(^8\) used the mechanical response (twitch tension output). Fink\(^1,9\) used the integrated abdominal EMG as a guide to management of muscle relaxation. Of these methods for monitoring muscle relaxation, the ones reported by Poulsen and Hougs,\(^6\) Churchill-Davidson and Richardson,\(^7\) Thesleff\(^8\) and Fink\(^1,9\) seemed the most likely to lend themselves to practical use in the operating room. Before discussing the usefulness of these techniques, it is of value to consider what they measure.

The electrical and mechanical activities of a muscle may differ. Rosenblueth, Wills and Hoagland,\(^10\) and Loofbourrow,\(^11\) studying the cat sartorius and tibialis anticus respectively, found that the action potential amplitude could not be quantitatively related to the tension developed in the muscle. This lack of correlation is to be expected since it was shown by Adrian and Bronk\(^12\) that the strength of contraction of the cat diaphragm depended not upon the amplitude of action potentials, but upon the number of motor units active and their frequency of discharge. Lippold\(^13\) showed that the integrated action potentials of the human calf muscle were linearly related to the tension produced by voluntary isometric contraction. Inman et al.\(^14\) compared the action potential amplitude (direct EMG), the integrated EMG and the isometric tension developed during voluntary contraction of the human biceps brachii. The tension developed during isometric contraction was unrelated to the amplitude of the direct EMG, but correlated well with the integrated EMG. This correlation did not hold, however, if the muscle was allowed to vary in length during an isometric contraction. However, Bigland and
Lippold found in human calf muscle that there was a linear relationship between IEMG and tension exerted during shortening and lengthening of a muscle as long as the change in length occurred at a constant velocity. Katz et al. showed that the IEMG of the diaphragm correlated well with tidal volume in the cat during spontaneous respiration with an unobstructed airway and a constant position of the diaphragmatic electrode.

The abdominal IEMG and muscle responses to nerve stimulation measure different things. The abdominal IEMG measures spontaneous activity which depends upon the afferent input to the central nervous system, the central nervous system, the efferent nerve to the muscle, neuromuscular transmission and the muscle itself. Therefore, changes in surgical stimulation, central nervous system activity, neuromuscular transmission, or the muscle itself, will affect the abdominal IEMG. On the other hand, the muscle response to supramaximal nerve stimulation is an evoked response which is affected mainly by changes in the structures beyond the point of stimulation.

Theoretically, the abdominal IEMG would appear to offer the best guide to abdominal relaxation since it is affected by the muscle-relaxing action of the general anesthetic agents (fig. 2), as well as the neuromuscular blockers (fig. 1A). In practice, however, it was found that the abdominal IEMG was not suitable for regular clinical use, a conclusion substantially in agreement with Fink. Since the current clinical practice is to produce muscle relaxation with the blocking agent rather than with "deep" anesthesia, the recording of the muscle response to nerve stimulation appears to be an excellent guide to the administration of neuromuscular blockers. As to the method of recording the muscle response (electrical or mechanical) to nerve stimulation, the author is in agreement with Botelho who concluded, after comparing the simultaneously recorded electrical and mechanical responses to nerve stimulation, "If a choice between mechanical and electrical activity must be made, we believe that the recording of mechanical activity would be more useful, more accurate, more convenient and less expensive." A further argument for the mechanical recording is the freedom from electrical artifact in the system. This is important in view of the rapid proliferation of electronic gadjery in the operating room.

Can a valid case be made for the regular and almost routine monitoring of muscle relaxation produced by neuromuscular blockers? Three years' experience with routine recording indicate the ease and the desirability of using this form of monitoring. Measuring the mechanical twitch response was invaluable when hexafturonium and succinylcholine were used and produced a "tight reservoir breathing bag," but good relaxation. The use of the nerve stimulator helped distinguish between the need for additional neuromuscular blocking agent and better placement of retractors or improved positioning of the patient on the operating table. During prolonged surgery and mechanical ventilation, the nerve stimulator was clearly of value. The nerve stimulator could also be used to help determine the etiology of apnea at the end of an operation. Finally, because of the wide variation in response to neuromuscular blockers which we and others have seen, the use of a test dose and the observed response placed the choice of subsequent doses of the neuromuscular blocker on a sounder pharmacological basis than the use of "average" doses for a given weight.

Every time a neuromuscular blocking agent is given, the use of a nerve stimulator to monitor the effect should seriously be considered. Any standard nerve stimulator and either surface or needle electrodes can be used to stimulate the ulnar nerve at the wrist or elbow. With experience, no more than 30 seconds should be required to obtain a suitable twitch response. A recording device is not absolutely necessary, since with a little practice the approximate degree of block can be determined merely by watching the movement of the hand and fingers. The nature of the block, depolarizing or nondepolarizing, can be determined by the response to twitch and tetanus.

The extensive experience with the routine use of a nerve stimulator during anesthesia and operation convinced us of the need for a clinical device for the routine continuous measurement of neuromuscular blockade. With the aid of several colleagues and the kindness
of Burroughs Wellcome and Co. (U. S. A.) Inc., a simple, inexpensive nerve stimulator has been developed and tested at this institution. The use of this or similar devices would improve the clinical care of patients undergoing anesthesia and operation.

Summary
The electrical and mechanical responses of peripheral skeletal muscle to nerve stimulation, and the integrated abdominal electromyogram were studied during anesthesia and operation to determine the feasibility of their routine use as a guide to the administration of neuromuscular blocking agents. The integrated electromyogram provided a good guide to the degree of relaxation produced by the anesthetic agents, as well as the neuromuscular blocking agents. The electrical and mechanical responses of the muscle to nerve stimulation were not significantly modified by the anesthetic agents but were affected by the neuromuscular blocking agents. The mechanical response of the muscle to nerve stimulation was found to be the most accurate, convenient and useful guide to the administration of the neuromuscular blocking agents. Extensive experience with the routine use of a nerve stimulator during anesthesia and operation led to the conclusion that any time a neuromuscular blocking agent is given, the use of a nerve stimulator to monitor the effects should seriously be considered.

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