Chapter 39 – Neuromuscular Monitoring

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Traditionally, the degree of **neuromuscular** block during and after anesthesia is evaluated with clinical criteria alone. However, many studies have documented that routine clinical evaluation of recovery of **neuromuscular** function does not exclude clinically significant residual curarization.[1][2][3][4] Therefore, there is a growing understanding that more attention should be paid to objective monitoring of the degree of **neuromuscular** block during and after anesthesia and to the problems of residual curarization.[5][6]

In awake patients, muscle power can be evaluated through tests of voluntary muscle strength, but during anesthesia and recovery from anesthesia this is not possible. Instead, the clinician uses clinical tests to assess muscle power directly and to estimate **neuromuscular** function indirectly (muscle tone, the feel of the anesthesia bag as an indirect measure of pulmonary compliance, tidal volume, and inspiratory force). All of these tests, however, are influenced by factors other than the degree of **neuromuscular** blockade. Therefore, whenever more precise information regarding the status of **neuromuscular** functioning is desired, the response of muscle to nerve stimulation should be assessed. This procedure also takes into account the considerable variation in individual response to muscle relaxants.

This chapter reviews the basic principles of peripheral nerve stimulation and the requirements for effective use of nerve stimulators. It also describes the response to nerve stimulation during depolarizing (phase I and phase II) and nondepolarizing **neuromuscular** blocks. Finally, this chapter discusses methods of evaluating evoked **neuromuscular** responses both with and without the availability of recording equipment.

TYPES OF PERIPHERAL NERVE STIMULATION

Neuromuscular function is monitored by evaluating the muscular response to supramaximal stimulation of a peripheral motor nerve. Two types of stimulation can be used: electrical and magnetic. Electrical nerve stimulation is by far the most commonly used method in clinical practice and is described in detail in this chapter. In theory, magnetic nerve stimulation has several advantages over electrical nerve stimulation.[7][8] It is less painful and does not require physical contact with the body. However, the required equipment is bulky and heavy, it cannot be used for train-of-four stimulation and it is difficult to achieve supramaximal stimulation with this method. Therefore, it is very seldom used in clinical anesthesia.

PRINCIPLES OF PERIPHERAL NERVE STIMULATION

The reaction of a single muscle fiber to a stimulus follows an all-or-none pattern. In contrast, the response of the whole muscle depends on the number of muscle fibers activated. If a nerve is stimulated with sufficient intensity, all fibers supplied by the nerve will react, and the maximum response will be triggered. After administration of a **neuromuscular** blocking drug, the response of the muscle decreases in parallel with the number of fibers blocked. The reduction in response during constant stimulation, reflects the degree of **neuromuscular** blockade.

For the preceding principles to be in effect, the stimulus must be truly maximal throughout the period of monitoring; therefore, the electrical stimulus applied is usually at least 20% to 25% above that necessary for a maximal response. For this reason the stimulus is said to be supramaximal; however, supramaximal electrical stimulation hurts, which is not a concern during anesthesia, but during recovery the patient may be awake enough to experience the discomfort of nerve stimulation. Therefore, some researchers advocate stimulation with submaximal current during recovery. Although several investigations indicate that testing of **neuromuscular** function can be reliably performed postoperatively using submaximal stimulation,[9][10][11] the accuracy of the monitoring is unacceptable at low current.[12]

PATTERNS OF NERVE STIMULATION

For evaluation of **neuromuscular** function the most commonly used patterns of electrical nerve stimulation are single-twitch, train-of-four (TOF), tetanic, post-tetanic count (PTC), and double- burst stimulation (DBS).

Single-Twitch Stimulation

In the single-twitch mode of stimulation, single supramaximal electrical stimuli are applied to a peripheral motor nerve at frequencies ranging from 1.0 Hz (once every second) to 0.1 Hz (once every 10 seconds) (Fig. 39-1). The response to single-twitch stimulation depends on the frequency with which the individual stimuli are applied. If the rate of delivery is increased to more than 0.15 Hz, the evoked response will gradually decrease and settle at a lower level. As a result, a frequency of 0.1 Hz is generally used. Because 1-Hz stimulation shortens the time necessary to determine supramaximal stimulation, this frequency is sometimes employed during induction of anesthesia; however, the apparent time of onset and length of **neuromuscular** blockade depend on the pattern and duration of stimulation. Therefore, results obtained using 1-Hz single-twitch stimulation cannot be compared with results obtained by using, for instance, 0.1-Hz single-twitch stimulation or TOF stimulation.[13]

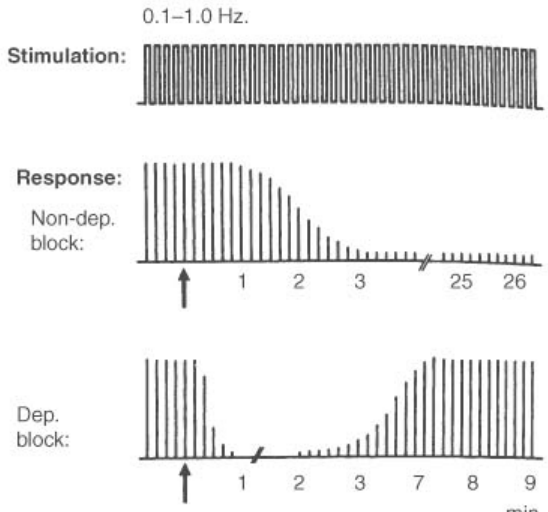

Figure 39-1 Pattern of electrical stimulation and evoked muscle responses to single-twitch nerve stimulation (at frequencies of 0.1 to 1.0 Hz) after injection of nondepolarizing (Non-dep) and depolarizing (Dep) **neuromuscular** blocking drugs (*arrows*). Note that except for the difference in time factors, no differences in the strength of the evoked responses exist between the two types of block.

Train-of-Four Stimulation

In TOF nerve stimulation, introduced by Ali and associates[14][15] during the early 1970s, four supramaximal stimuli are given every 0.5 seconds (2 Hz) (Fig. 39-2). When used continuously, each set (train) of stimuli normally is repeated every 10th to 20th second. Each stimulus in the train causes the muscle to contract, and "fade" in the response provides the basis for evaluation. That is, dividing the amplitude of the fourth response by the amplitude of the first response provides the TOF ratio. In the control response (the response obtained before administration of muscle relaxant), all four responses are ideally the same: The TOF ratio is 1.0. During a partial nondepolarizing block, the ratio decreases (fades) and is inversely proportional to the degree of blockade. During a partial depolarizing block, no fade occurs in the TOF response; ideally, the TOF ratio is approximately 1.0. Fade in the TOF response after injection of succinylcholine signifies the development of a phase II block (discussed later in the section on Depolarizing **Neuromuscular** Blockade).

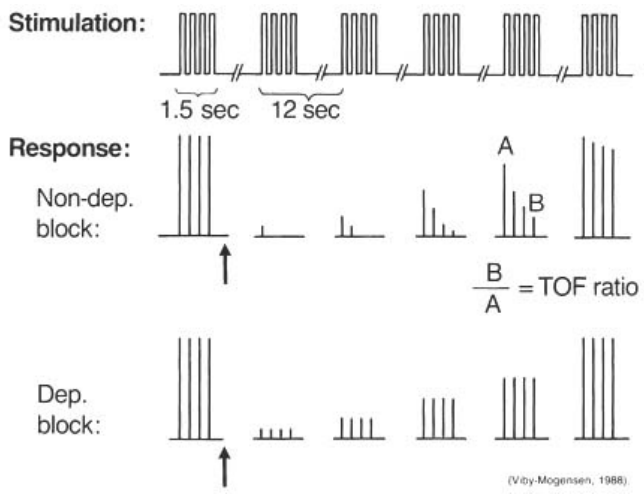

Figure 39-2 Pattern of electrical stimulation and evoked muscle responses to TOF nerve stimulation before and after injection of nondepolarizing (Non-dep) and depolarizing (Dep) **neuromuscular** blocking drugs (*arrows*).

The advantages of TOF stimulation are greatest during nondepolarizing blockade, because the degree of block can be read directly from the TOF response even though a preoperative value is lacking. In addition, TOF stimulation has some advantages over tetanic stimulation: it is less painful and, unlike tetanic stimulation, generally does not affect the degree of **neuromuscular** blockade.

Tetanic Stimulation

Tetanic stimulation consists of very rapid (e.g., 30-, 50-, or 100-Hz) delivery of electrical stimuli. The most commonly used pattern in clinical practice is 50-Hz stimulation given for 5 seconds, although some investigators have advocated the use of 50-, 100-, and even 200-Hz stimulation for 1 second. During normal **neuromuscular** transmission and a pure depolarizing block, the muscle response to 50-Hz tetanic stimulation for 5 seconds is sustained. During a nondepolarizing block and a phase II block after injection of succinylcholine, the response will not be sustained (i.e., fade occurs) (Fig. 39-3).

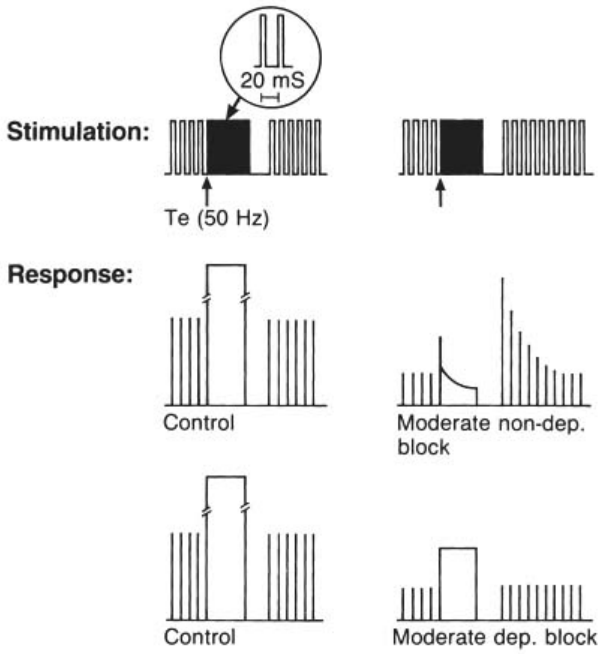

Figure 39-3 Pattern of stimulation and evoked muscle responses to tetanic (50-Hz) nerve stimulation for 5 seconds (Te) and post-tetanic stimulation (1.0-Hz) twitch. Stimulation was applied before injection of **neuromuscular** blocking drugs and during moderate nondepolarizing and depolarizing blocks. Note fade in the response to tetanic stimulation, plus post-tetanic facilitation of transmission during nondepolarizing blockade. During depolarizing blockade, the tetanic response is well sustained and no post-tetanic facilitation of transmission occurs.

Fade in response to tetanic stimulation is normally considered a presynaptic event; the traditional explanation is that at the start of tetanic stimulation, large amounts of acetylcholine are released from immediately available stores in the nerve terminal. As these stores become depleted, the rate of acetylcholine release decreases until equilibrium between mobilization and synthesis of acetylcholine is achieved. Despite this equilibrium, the muscle response caused by tetanic stimulation of the nerve at, for example, 50 Hz, is maintained (given normal **neuromuscular** transmission) simply because the release of acetylcholine is many times greater than the amount necessary to evoke a response. When the "margin of safety"[16] of the postsynaptic membrane (i.e., the number of free cholinergic receptors) is reduced by a nondepolarizing **neuromuscular** blocking agent, the decrease in release of acetylcholine during tetanic stimulation produces fade. In addition to blocking the postsynaptic receptors, nondepolarizing **neuromuscular** blocking drugs may also impair the mobilization of acetylcholine within the nerve terminal. This effect may contribute to the fade in the response to tetanic (and TOF) stimulation. The degree of fade depends primarily on the degree of **neuromuscular** blockade. Fade also depends on the frequency (Hz) and the length (seconds) of stimulation and on how often tetanic stimuli are applied. Unless these variables are kept constant, results from different studies using tetanic stimulation cannot be compared.

During partial nondepolarizing blockade, tetanic nerve stimulation is followed by a post-tetanic increase in twitch tension (i.e., post-tetanic facilitation [PTF] of transmission) (see Fig. 39-3). This event occurs because the increase in mobilization and synthesis of acetylcholine caused by tetanic stimulation continues for some time after discontinuation of stimulation. The degree and duration of PTF depend on the degree of **neuromuscular** blockade, with PTF usually disappearing within 60 seconds of tetanic stimulation. PTF is evident in electromyographic, acceleromyographic, and mechanical recordings during a partial nondepolarizing **neuromuscular** blockade. In contrast, post-tetanic twitch potentiation, which sometimes occurs in mechanical recordings before any **neuromuscular** blocking drug has been given, is a muscular phenomenon that is not accompanied by an increase in the compound muscle action potential.

Tetanic stimulation has several disadvantages. It is very painful and therefore normally not acceptable to the unanesthetized patient. Furthermore, especially in the late phase of **neuromuscular** recovery, tetanic stimulations may produce a lasting antagonism of **neuromuscular** blockade in the stimulated muscle, such that the response of the tested site may no longer be representative of other muscle groups.[17][18]

Traditionally, tetanic stimulation has been used to evaluate residual **neuromuscular** blockade. However, except in connection with the technique of post-tetanic count (see later), tetanic stimulation has very little place in everyday clinical anesthesia. If the response to nerve stimulation is recorded, all the information required can be obtained from the response to TOF nerve stimulation. In contrast, if the response to nerve stimulation is evaluated only by feel[19] or by eye (Viby-Mogensen and colleagues, unpublished observation), even experienced observers are unable to judge the response of tetanic stimulation with sufficient certainty to exclude residual **neuromuscular** blockade.

Post-Tetanic Count Stimulation

Injection of a nondepolarizing **neuromuscular** blocking drug in a dose sufficient to ensure smooth tracheal intubation causes intense **neuromuscular** blockade of the peripheral muscles. Because no response to TOF and single-twitch stimulation occurs under these conditions, these modes of stimulation cannot be used to determine the degree of blockade. It is possible, however, to quantify intense **neuromuscular** blockade of the peripheral muscles by applying tetanic stimulation (50 Hz for 5 seconds) and observing the post-tetanic response to single-twitch stimulation given at 1 Hz starting 3 seconds after the end of tetanic stimulation.[20] During very intense blockade, there is no response to either tetanic or post-tetanic stimulation (Fig. 39-4). However, when the very intense **neuromuscular** blockade dissipates and before the first response to TOF stimulation reappears, the first response to post-tetanic twitch stimulation occurs. As the intense block dissipates, more and more responses to post-tetanic twitch stimulation appear. For a given **neuromuscular** blocking drug, the time until return of the first response to TOF stimulation is related to the number of post-tetanic twitch responses present at a given time (the post-tetanic count)[20][21][22][23][24][25] (Fig. 39-5).

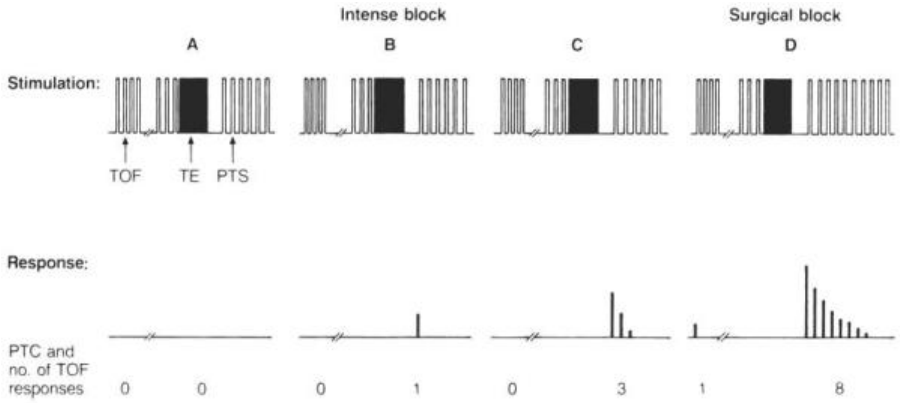

Figure 39-4 Pattern of electrical stimulation and evoked muscle responses to TOF nerve stimulation, 50-Hz tetanic nerve stimulation for 5 seconds (TE), and 1.0-Hz post-tetanic twitch stimulation (PTS) during four different levels of nondepolarizing **neuromuscular** blockade. During very intense blockade of the peripheral muscles (A), no response to any of the forms of stimulation occurs. During less pronounced blockade (B and C), there is still no response to stimulation, but post-tetanic facilitation of transmission is present. During surgical block (D), the first response to TOF appears and post-tetanic facilitation increases further. The post-tetanic count (see text) is 1 during intense block (B), 3 during less intense block (C), and 8 during surgical block (D).

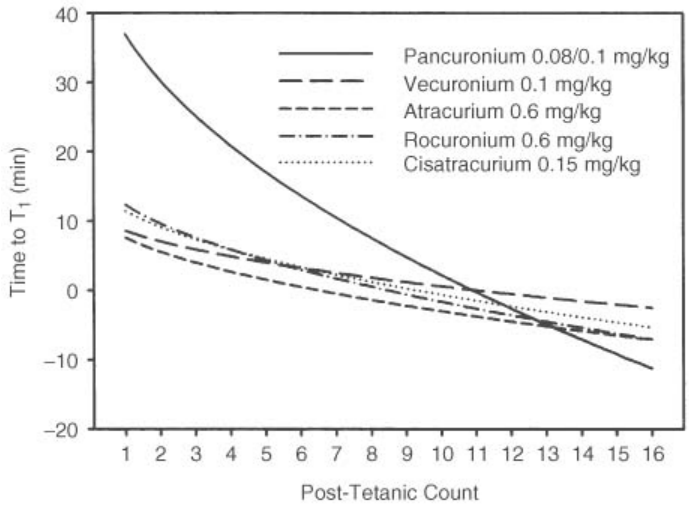

Figure 39-5 Relationship between the post-tetanic count (PTC) and time when onset of train-of-four (T_1) is likely to be elicited for various **neuromuscular** blocking agents. *(From El-Orbany MI, Joseph JN, Salem MR: The relationship of posttetanic count and train-of-four responses during recovery from intense cisatracurium-induced **neuromuscular** blockade. Anesth Analg 97:80, 2003.)*

The main application of the PTC method is in evaluating the degree of **neuromuscular** blockade when there is no reaction to single twitch or TOF nerve stimulation, as may be the

case after injection of a large dose of a nondepolarizing **neuromuscular** blocking drug. However, PTC can also be used whenever sudden movements must be eliminated (e.g., during ophthalmic surgery). The necessary level of block of the adductor pollicis muscle to ensure paralysis of the diaphragm depends on the type of anesthesia and, in the intensive care unit, on the level of sedation.[23][26] To ensure elimination of any bucking or coughing in response to tracheobronchial stimulation, **neuromuscular** blockade of the peripheral muscles must be so intense that no response to post-tetanic twitch stimulation can be elicited (PTC-0)[20][21][22][24][25](Fig. 39-6).

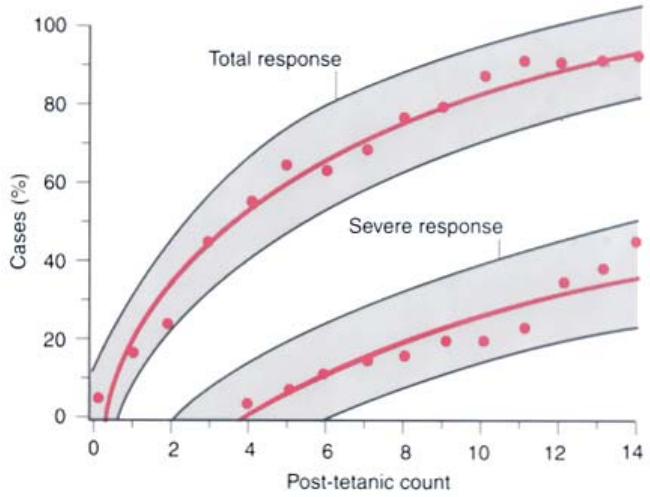

Figure 39-6 Relationship between the rate of muscle response to stimulation of the tracheal carina and the degree of **neuromuscular** blockade of peripheral muscles, as evaluated by using post-tetanic count. The subjects were 25 patients anesthetized with thiopental, nitrous oxide, and fentanyl who were given vecuronium (0.1 mg/kg) for tracheal intubation. For comparison, the first response to TOF stimulation usually occurs when PTC is approximately 10 (range, 6 to 16). The carina was stimulated with a soft sterile rubber suction catheter introduced via the endotracheal tube. The total response consisted of mild responses plus severe response. A mild response was said to occur if stimulation of the carina induced only slight bucking that did not interfere with surgery. A severe response was said to occur if stimulation elicited bucking that interfered with surgery and required intervention. Elimination of severe responses requires an intense **neuromuscular** blockade; PTC must be less than 2 to 3, and elimination of all reactions requires that PTC be 0. *(From Fernando PUE, Viby-Mogensen J, Bonsu AK, et al: Relationship between post-tetanic count and response to carinal stimulation during vecuronium-induced **neuromuscular** blockade. Acta Anaesthesiol Scand 31:593, 1987. Copyright 1987, Munksgaard International Publishers, Ltd. Copenhagen, Denmark.)*

The response to PTC stimulation depends primarily on the degree of **neuromuscular** blockade. It also depends on the frequency and duration of tetanic stimulation, the length of time between the end of tetanic stimulation and the first post-tetanic stimulus, the frequency of the single-twitch stimulation, and also (probably) the length of single-twitch stimulation before tetanic stimulation. When the PTC method is used, these variables should therefore be kept constant. Also, because of possible antagonism of **neuromuscular** blockade in the hand, tetanic stimulation should not be given more often than every 6 minutes.[20] If the hand muscles undergo antagonism of **neuromuscular** blockade while the rest of the body is still paralyzed, the hand muscles are no longer useful for monitoring.

Double-Burst Stimulation

DBS consists of two short bursts of 50-Hz tetanic stimulation separated by 750 msec. The duration of each square wave impulse in the burst is 0.2 msec (Fig. 39-7). Although the number of impulses in each burst can vary, most commonly used is DBS with three impulses in each of the two tetanic bursts ($DBS_{3,3}$).[27][28][29][30]

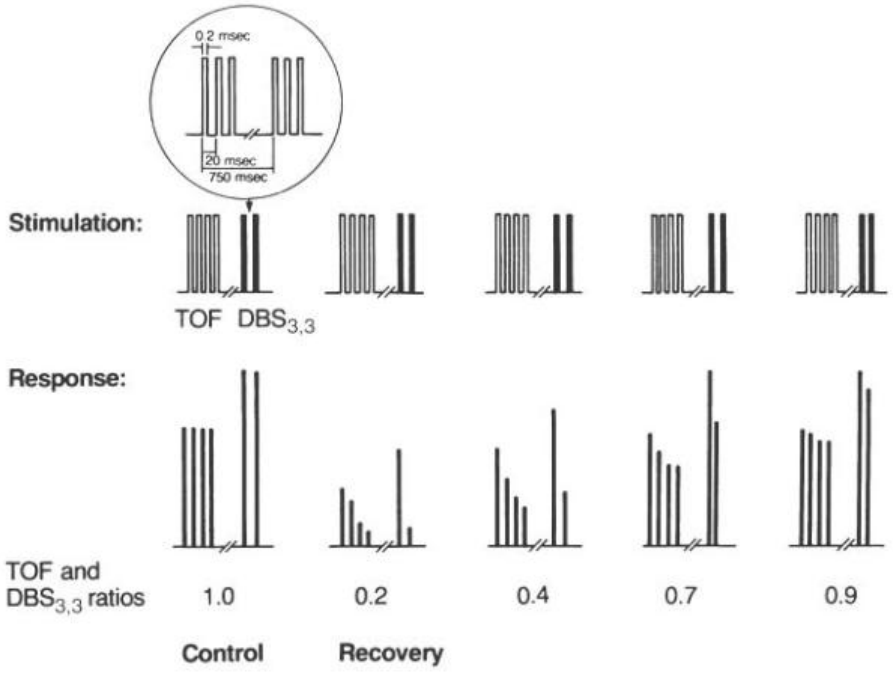

Figure 39-7 Pattern of electrical stimulation and evoked muscle responses to TOF nerve stimulation and double-burst nerve stimulation (i.e., three impulses in each of two tetanic bursts, $DBS_{3,3}$) before injection of muscle relaxants (control) and during recovery from nondepolarizing **neuromuscular** blockade. TOF ratio is the amplitude of the fourth response to TOF divided by the amplitude of the first response. $DBS_{3,3}$ ratio is the amplitude of the second response to $DBS_{3,3}$ divided by the amplitude of the first response. (See text for further explanation.)

In nonparalyzed muscle, the response to $DBS_{3,3}$ is two short muscle contractions of equal strength. In the partly paralyzed muscle, the second response is weaker than the first (i.e., the response fades) (see Fig 39-7). Measured mechanically, the TOF ratio correlates closely with the $DBS_{3,3}$ ratio. DBS was developed with the specific aim of allowing manual (tactile) detection of small amounts of residual blockade under clinical conditions,[27] and during recovery and immediately after surgery, tactile evaluation of the response to $DBS_{3,3}$ is superior to tactile evaluation of the response to TOF stimulation.[29][31][32] However, as shown in Figure 39-8 , absence of fade in the manually evaluated response to $DBS_{3,3}$ (and TOF) does not exclude residual **neuromuscular** blockade.[33]

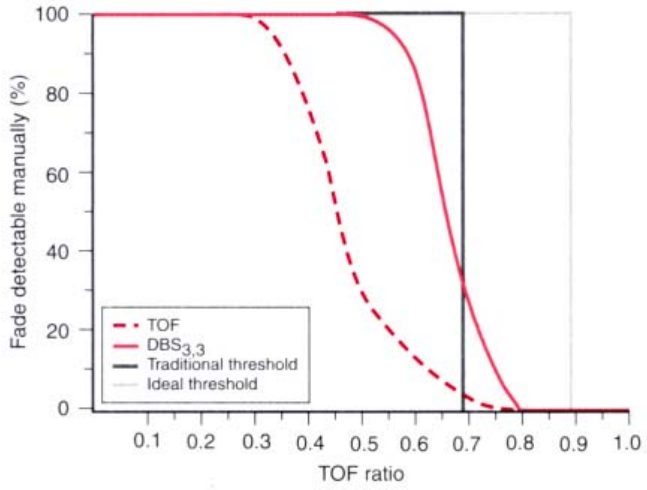

Figure 39-8 Fade detectable by feel in the response to TOF and double burst stimulation ($DBS_{3,3}$) in relation to the true TOF ratio, as measured mechanically. The axis indicates the percentage of instances in which fade can be felt at a given TOF ratio.[28][29] It appears that it is not possible to exclude residual **neuromuscular** block by any of the methods, whether a TOF ratio of 0.7 or 0.9 is taken to reflect adequate recovery of **neuromuscular** function. (See text for further explanation.)

THE NERVE STIMULATOR

Although many nerve stimulators are commercially available, not all meet the basic requirements for clinical use. The stimulus should produce a monophasic and rectangular waveform, and the length of the pulse should not exceed 0.2 to 0.3 msec. A pulse exceeding 0.5 msec may stimulate the muscle directly or cause repetitive firing. Stimulation at a constant current is preferable to stimulation at a constant voltage because current is the determinant of nerve stimulation. Also, for safety reasons, the nerve stimulator should be battery-operated, include a battery check, and be able to generate 60 to 70 mA, but not more than 80 mA. Many commercially available stimulators can deliver only 25 to 50 mA and provide a constant current only when skin resistance ranges from 0 Ω to 2.5 kΩ. This deficiency is a disadvantage; during cooling, skin resistance may increase to approximately 5 kΩ, which may cause the current delivered to the nerve to fall below the supramaximal level, leading to a decrease in the response to stimulation. As a result, the anesthesiologist may misjudge the degree of **neuromuscular** blockade. Ideally, the nerve stimulator should have a built-in warning system or a current level display that alerts the user when the current selected is not delivered to the nerve.

The ideal nerve stimulator should have other features as well. The polarity of the electrodes should be indicated. Also, the apparatus should be capable of delivering the following modes of stimulation: TOF (as both a single train and in a repetitive mode, with TOF stimulation being given every 10 to 20 seconds); single-twitch stimulations at 0.1 and 1.0 Hz; and tetanic stimulation at 50 Hz. In addition, the stimulator should have a built-in time constant system to facilitate post-tetanic count. Tetanic stimulus should last 5 seconds and be followed 3 seconds later by the first post-tetanic stimulus. If the nerve stimulator does not allow objective measurement of the response to TOF stimulation, at least one DBS mode should be available, preferably $DBS_{3,3}$. Single-twitch stimulation at 1 Hz is useful during initiation of monitoring because it shortens the time necessary to determine

supramaximal stimulation. Most investigators agree that there is no need for tetanus at 100 or 200 Hz because 50-Hz tetanic stimulation stresses **neuromuscular** function to the same extent as does a maximal voluntary effort. Furthermore, in contrast to 100- and 200-Hz stimulation, 50-Hz tetanic stimulation does not cause fatigue (fade) in nonparalyzed muscle.

THE STIMULATING ELECTRODES

Electrical impulses are transmitted from stimulator to nerve by means of surface or needle electrodes, the former being the more commonly used in clinical anesthesia. Normally, disposal pregelled silver or silver chloride surface electrodes are used. The actual conducting area should be small, approximately 7 to 8 mm in diameter. Otherwise, the current produced in the underlying nerve may not be adequate. The skin should always be cleansed properly and preferably rubbed with an abrasive before application of the electrodes. When a supramaximal response cannot be obtained by using surface electrodes, needle electrodes should be used. Although specially coated needle electrodes are commercially available, ordinary steel injection needles can be used. The needles should be placed subcutaneously but never in a nerve.

SITES OF NERVE STIMULATION AND DIFFERENT MUSCLE RESPONSES

In principle, any superficially located peripheral motor nerve may be stimulated. In clinical anesthesia, the ulnar nerve is the most popular site; the median, the posterior tibial, common peroneal, and facial nerves are also sometimes used. For stimulation of the ulnar nerve, the electrodes are best applied at the volar side of the wrist (Fig. 39-9). The distal electrode should be placed about 1 cm proximal to the point at which the proximal flexion crease of the wrist crosses the radial side of the tendon to the flexor carpi ulnaris muscle. The proximal electrode preferably should be placed 2 to 5 cm proximal to the distal electrode. With this placement of the electrodes, electrical stimulation normally elicits only finger flexion and thumb adduction. If the one electrode is placed over the ulnar groove at the elbow, thumb adduction is often pronounced because of stimulation of the flexor carpi ulnaris muscle. When this latter placement of electrodes (sometimes preferred in small children) is used, the active negative electrode should be at the wrist to ensure a maximal response. Polarity of the electrodes is less crucial when both electrodes are close to each other at the volar side of the wrist; however, placement of the negative electrode distally normally elicits the greatest **neuromuscular** response.[34] When the temporal branch of the facial nerve is stimulated, the negative electrode should be placed over the nerve, and the positive electrode should be placed somewhere else over the forehead.

Figure 39-9 Evaluation of **neuromuscular** blockade by feeling the response of the thumb to stimulation of the ulnar nerve. *(Courtesy of Organon Ltd., Dublin, Ireland.)*

Because different muscle groups have different sensitivities to **neuromuscular** blocking agents, results obtained for one muscle cannot be extrapolated automatically to other muscles. The diaphragm is among the most resistant of all muscles to both depolarizing[35] and nondepolarizing **neuromuscular** blocking drugs.[36] In general, the diaphragm requires 1.4 to 2.0 times as much muscle relaxant as the adductor pollicis muscle for an identicald egree of blockade (Fig. 39-10).[36] Also of clinical significance are the facts that onset time is normally shorter for the diaphragm than for the adductor pollicis muscle and that the diaphragm recovers from paralysis more quickly than do the peripheral muscles (Fig. 39-11).[37] The other respiratory muscles are less resistant than the diaphragm, as are the larynx and the corrugater supercilii muscles.[38][39][40][41][42][43] Most sensitive are the abdominal muscles, the orbicularis oculi muscle, the peripheral muscles of the limbs, and the geniohyoid, masseter, and upper airway muscles.[44][45][46][47][48] From a practical clinical point of view, it is worth noting that (1) the corrugator supercilii response to facial nerve stimulation reflects the extent of **neuromuscular** blockade of the laryngeal adductor muscles (and the diaphragm?) better than does the response of the adductor pollicis to ulnar nerve stimulation[38][39] and (2) the upper airway muscles seem to be more sensitive than peripheral muscles.[45][46] Although three investigations using acceleromyography have indicated small differences in the response to TOF nerve stimulation in the arm (adductor pollicis muscle) and the leg (flexor hallucis brevis muscle), these differences are probably of little clinical significance.[49][50][51][52]

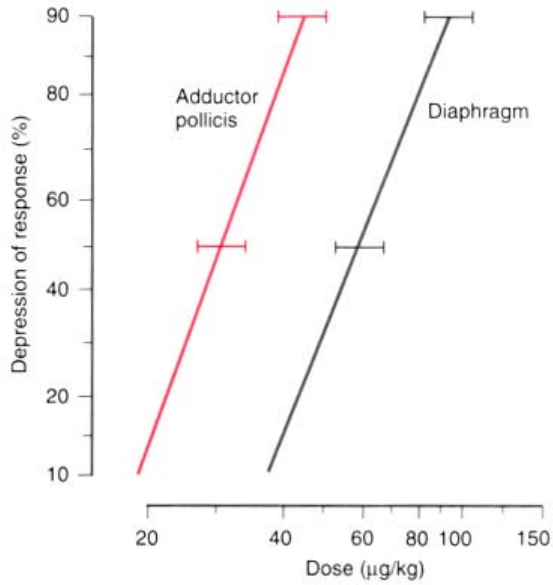

Figure 39-10 Mean cumulative dose-response curve for pancuronium in two muscles shows that the diaphragm requires approximately twice as much pancuronium as does the adductor pollicis muscle for the same amount of **neuromuscular** blockade. The depression in muscle response to the first stimulus in TOF nerve stimulation (probit scale) was plotted against dose (log scale). Force of contraction of the adductor pollicis was measured on a force-displacement transducer; response of the diaphragm was measured electromyographically. *(From Donati F, Antzaka C, Bevan DR: Potency of pancuronium at the diaphragm and the adductor pollicis muscle in humans. Anesthesiology 65:1, 1986.)*

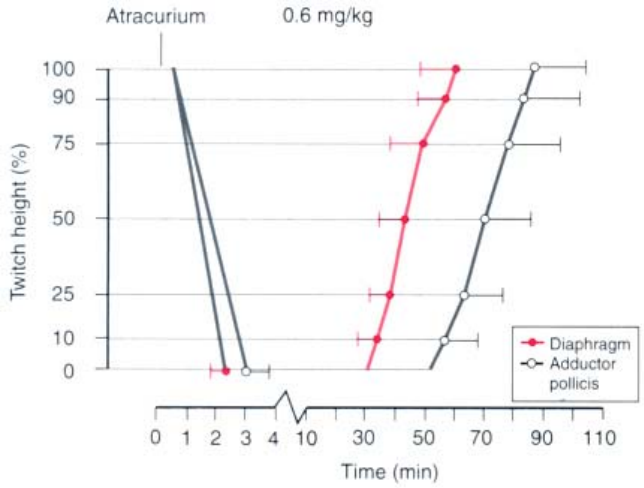

Figure 39-11 Evolution of twitch height (mean ± SD) of the diaphragm (*closed circles*) and of the adductor pollicis muscle (*open circles*) in 10 anesthetized patients after administration of atracurium 0.6 mg/kg. *(From Pansard J-L, Chauvin M, Lebrault C, et al: Effect of an intubating dose of succinylcholine and atracurium on the diaphragm and the adductor pollicis muscle in humans. Anesthesiology 67:326, 1987.)*

The precise source of these differences is unknown. Possible causes may be differences in acetylcholine receptor density, acetylcholine release, acetylcholinesterase activity, fiber composition, innervation ratio (number of **neuromuscular** junctions), blood flow, and muscle temperature.

In assessing **neuromuscular** function, the use of a relatively sensitive muscle such as the adductor pollicis of the hand has both disadvantages and advantages. Obviously, during surgery it is a disadvantage that even total elimination of the response to single-twitch and TOF stimulation does not exclude the possibility of movement of the diaphragm, such as hiccupping and coughing. PTC stimulation, however, allows for evaluation of the very intense blockade necessary to ensure total paralysis of the diaphragm. On the positive side, the risk of overdosing the patient decreases if the response of a relatively sensitive muscle is used as a guide to the administration of muscle relaxants during surgery. Also, during recovery, when the adductor pollicis has recovered sufficiently, it can be assumed that no residual **neuromuscular** blockade exists in the diaphragm or in other resistant muscles.

RECORDING OF EVOKED RESPONSES

The choice of recording method is a practical decision. Five methods are available: measurement of evoked mechanical response of the muscle (mechanomyography [MMG]), measurement of evoked electrical response of the muscle (electromyography [EMG]), measurement of acceleration of the muscle response (acceleromyography [AMG]),

measurement of evoked electrical response in a piezoelectric film sensor attached to the muscle (piezoelectric **neuromuscular** monitors [P_zEMG], and phonomyography [PMG]).

Mechanomyography

A requirement for correct and reproducible measurements of evoked tension is that the muscle contraction be isometric. In clinical anesthesia, this condition is most easily achieved by measuring thumb movement after application of a resting tension of 200 to 300 g (a preload) to the thumb. When the ulnar nerve is stimulated, the thumb (the adductor pollicis muscle) acts on a force-displacement transducer. The force of contraction is then converted into an electrical signal, which is amplified, displayed, and recorded. The arm and hand should be fixed rigidly, and care should be taken to prevent over-loading of the transducer. Also, the transducer should be placed in correct relationship to the thumb (i.e., the thumb should always apply tension precisely along the length of the transducer). It is important to remember that the response to nerve stimulation depends on the frequency with which the individual stimuli are applied and that the time used to achieve a stable control response may influence the subsequent determination of onset time and duration of block.[53] Generally, the reaction to supramaximal stimulation increases during the first 8 to 12 minutes after commencement of the stimulation. Therefore, in clinical studies, control measurements (before injection of muscle relaxant) should not be made before the response has stabilized for 8 to 12 minutes or a 2-second or 5-second 50-Hz tetanic stimulation has been given.[54] Even then, twitch response often recovers to 110% to 150% of the control response after paralysis with succinylcholine. This increase in response, thought to be caused by a change in the contractile response of the muscle, normally disappears within 15 to 25 minutes.

Although numerous methods for mechanical recording of evoked mechanical responses exist, not all meet the criteria outlined.

Electromyography

Evoked EMG records the compound action potentials produced by stimulation of a peripheral nerve. The compound action potential is a high-speed event that for many years could only be picked up by means of a preamplifier and a storage oscilloscope. Modern **neuromuscular** transmission analyzers are able to make on-line electronic analyses and graphic presentations of the EMG response.

The evoked EMG response is most often obtained from muscles innervated by the ulnar or the median nerves. Stimulating electrodes are applied as in force measurements. Although both surface and needle electrodes may be used for recording, no advantage is obtained by using the latter. Most often, the evoked EMG is obtained from the thenar or hypothenar eminence of the hand or from the first dorsal interosseous muscle of the hand, preferably with the active electrode over the motor point of the muscle (Fig. 39-12). The signal picked up by the analyzer is processed by an amplifier, a rectifier, and an electronic integrator. The results are displayed either as a percentage of control or as a TOF ratio.

Figure 39-12 Electrode placement for stimulation of the ulnar nerve and for recording of the compound action potential from three sites of the hand. **A,** Abductor digiti minimi muscle (in the hypothenar eminence). **B,** Adductor pollicis muscle (in the thenar eminence). **C,** First dorsal interosseus muscle. *(Courtesy of Datex-Ohmeda, Helsinki, Finland.)*

Two new sites for recording the electromyography response have been introduced: the larynx and the diaphragm.[39][55][56][57][58] Using a non-invasive disposable laryngeal electrode attached to the tracheal tube and placed between the vocal cords, it is possible to monitor onset of **neuromuscular** block in the laryngeal muscles.[55][56] So far, however, the method is mainly of interest in clinical research when investigating onset times of the laryngeal muscles.[59] In paravertebral surface diaphragmal electromyography the recording electrodes are placed on the right of the vertebrae T12/L1 or L1/L2 for EMG monitoring of the response of the right diaphragmatic crux to transcutaneous stimulation of the right phrenic nerve at the neck.[55][57][58] As is the case with surface laryngeal EMG, surface diaphragmal EMG is mainly of interest in clinical research, because of the difficulties connected with the stimulation of the phrenic nerve transcutaneously at the neck.[59]

Evoked electrical and mechanical responses represent different physiologic events. Evoked EMG records changes in electrical activity of one or more muscles, whereas evoked MMG records changes associated with excitation-contraction coupling and the contraction of the muscle as well. For these reasons, the results obtained with these methods may differ.[60][61] Although evoked EMG responses generally correlate well with evoked mechanical responses,[62] marked differences may occur, especially in the response to succinylcholine and in the TOF ratio during recovery from a nondepolarizing block.[60][61][62]

In theory, recording of evoked EMG responses has several advantages over recording of evoked mechanical responses. Equipment for measuring evoked EMG responses is easier to set up, the response reflects only those factors influencing **neuromuscular** transmission, and the response can be obtained from muscles not accessible to mechanical recording. However, evoked EMG does entail some difficulties. Although good recordings are possible in most patients, results are not always reliable. For one thing, improper placement of electrodes may result in inadequate pickup of the compound EMG signal. If the **neuromuscular** transmission analyzer does not allow observation of the actual waveform of the compound EMG, determining the optimal placement of the electrodes is difficult. Another source of unreliable results may be that fixation of the hand with a preload on the thumb may be more important than generally appreciated,[62][63] as changes in the position of the electrodes in relationship to the muscle may affect the EMG response. In addition, direct muscle stimulation sometimes occurs. If muscles close to the stimulating electrodes are stimulated directly, the recording electrodes may pick up an electrical signal even though **neuromuscular** transmission is completely blocked. Another difficulty is that the EMG response often does not return to control value. Whether this situation is the result of technical problems, inadequate fixation of the hand, or changes in

temperature is unknown (Fig. 39-13). Finally, the evoked EMG response is very sensitive to electrical interference, such as that caused by diathermy.

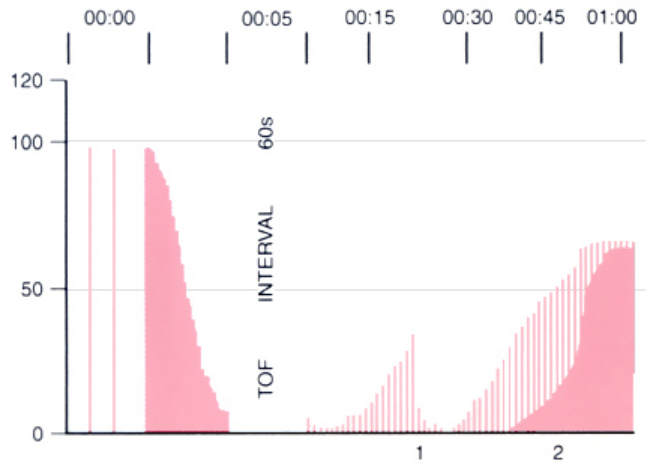

Figure 39-13 Evoked electromyographic printout from a Relaxograph. Initially, single-twitch stimulation was given at 0.1 Hz, and vecuronium (70 µg/kg) was given intravenously for tracheal intubation. After approximately 5 minutes, the mode of stimulation was changed to TOF stimulation every 60 seconds. At a twitch height (first twitch in TOF response) of approximately 30% of control (marker 1), 1 mg of vecuronium was given intravenously. At marker 2, 1 mg of neostigmine was given intravenously, preceded by 2 mg of glycopyrrolate. The printout also illustrates the common problem of failure of the electromyographic response to return to control level. *(Courtesy of Datex-Ohmeda, Helsinki, Finland.)*

Acceleromyography

The technique of AMG is based on Newton's second law: force equals mass times acceleration.[64][65] If mass is constant, acceleration is directly proportional to force. Accordingly, after nerve stimulation, one can measure not only the evoked force but also the acceleration of the thumb.

AMG uses a piezoelectric ceramic wafer with electrodes on both sides. Exposure of the electrode to a force generates an electrical voltage proportional to the acceleration of the thumb in response to nerve stimulation. When the accelerometer is fixed to the thumb and the ulnar nerve is stimulated, an electrical signal is produced whenever the thumb moves. This signal is then analyzed in a specially designed analyzer[65] or perhaps displayed on a recording system. At least one detached monitor based on measurement of acceleration is commercially available: the TOF-Watch (Organon Teknika, Boxtel, Holland) (Fig. 39-14).

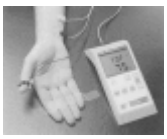

Figure 39-14 TOF-Watch (Organon Ltd., Dublin, Ireland). This **neuromuscular** transmission monitor is based on measurement of acceleration using a piezoelectric transducer.[64][65] Note the transducer fastened to the thumb and the stimulating electrodes. On the display of the TOF-Watch, the TOF ratio is given in percentage.

AMG is a simple method of analyzing **neuromuscular** function, both in the operating room and in the intensive care unit.[66][67] However, although a good correlation exists between the TOF ratio measured by this method and TOF ratio measured with a force-displacement transducer or using EMG,[64][65][68] measurements made with an AMG are not directly comparable with results obtained using the other two methods.[69][70][71][72][73][74][75] When an AMG is used, as originally suggested, with a free-moving thumb,[64] wide limits of agreements in twitch height (T1) and TOF ratio and differences in the onset and recovery course of blockade between AMG and MMG have been found. Also, the AMG control TOF ratio is consistently higher than when measured using a force-displacement transducer. In accordance with this, one study has indicated that when using AMG, the threshold TOF ratio for sufficient postoperative **neuromuscular** recovery is 1.0, rather than 0.9 as when measured with MMG or EMG.[76]

One reason for the wide limits of agreement between AMG and MMG is probably and paradoxically connected with one of the originally claimed advantages of the method, that fixation of the hand could be reduced to a minimum as long as the thumb could move freely.[64] However, in daily clinical practice it is often not possible to ensure that the thumb can move freely, and that the position of the hand does not change during a surgical procedure. The evoked response may therefore vary considerably. Several solutions have been proposed, and ongoing clinical research indicates that the use of an elastic preload to the thumb may improve the agreement between results obtained using AMG and MMG (Fig. 39-15). In spite of the above reservations, it is my opinion that AMG at the thumb is a valuable clinical tool that used with intelligence may eliminate the problem of postoperative residual **neuromuscular** block.[77][78]

Figure 39-15 Hand adaptor (elastic preload) for the TOF-Watch transducer. (Accelleromyography, Organon Ltd., Dublin, Ireland.)

When the thumb is not available for monitoring during surgery, some clinicians prefer to monitor the AMG response of the orbicularis oculi or the corrugator supercilii in response to facial nerve stimulation. However, it is important to realize that **neuromuscular** monitoring with AMG from both these sites are subject to a large uncertainty as a measure of paralysis, and it cannot therefore be recommended for routine monitoring. It only provides a rough estimate of the degree of block of the peripheral muscles.[39][79][80]

Piezoelectric Neuromuscular Monitors

The technique of the piezoelectric monitor is based on the principle that stretching or bending a flexible piezoelectric film, for example, attached to the thumb, in response

to nerve stimulation generates a voltage that is proportional to the amount of stretching or bending.[81][82] At least two devices based on the this principle are available commercially: The ParaGraph **Neuromuscular** Blockade Monitor (Vital Signs, Totowa, NJ) and the M-NMT MechanoSensor, which is a part of the Datex AS/3 monitoring system (Datex-Ohmeda, Helsinki, Finland) (Fig. 39-16).

Figure 39-16 Datex-Engstrøm M-NMT MechanoSensor (a piezoelectric **neuromuscular** monitor).

Few studies have evaluated the function of these monitors.[81][82][83] The scarce data indicate a good relationship between results obtained using P_ZEMG, AMG and MMG, but also wide limits of agreement between the methods. Therefore, although P_ZEMG may be a valuable clinical tool, the values obtained in the individual patient using this method may vary from those obtained using MMG or AMG.

Phonomyography

PMG (acoustic myography) is a relatively new method of monitoring **neuromuscular** function.[84][85][86][87][88][89] The contraction of skeletal muscles generates intrinsic low-frequency sounds, which can be recorded using special microphones. This method has been evaluated for clinical and research purposes. Several reports indicate a good correlation between the evoked acoustic responses and responses obtained using more traditional methods of recording, such as MMG, EMG, and AMG. However, it is uncertain whether PMG will ever be used for monitoring **neuromuscular** block during routine anesthesia. What does make PMG interesting, however, is that in theory the method can be applied not only to the adductor pollicis muscle but also to other muscles of interest such as the diaphragm, the larynx, and the eye muscles. Also, the ease of application is attractive.

For further information on recording evoked responses, the reader is referred to guidelines for Good Clinical Research Practice in pharmacodynamic studies of **neuromuscular** blocking agents, published in Acta Anaesthesiologica Scandinavica.[53]

EVALUATION OF RECORDED EVOKED RESPONSES

Nerve stimulation in clinical anesthesia is usually synonymous with TOF nerve stimulation. Therefore, the recorded response to this form of stimulation is used to explain how to evaluate the degree of **neuromuscular** blockade during clinical anesthesia.

Nondepolarizing Neuromuscular Blockade

After injection of a nondepolarizing **neuromuscular** blocking drug in a dose

sufficient for smooth tracheal intubation, TOF recording demonstrates three phases or levels of **neuromuscular** blockade: intense blockade, moderate or surgical blockade, and recovery (Fig. 39-17).

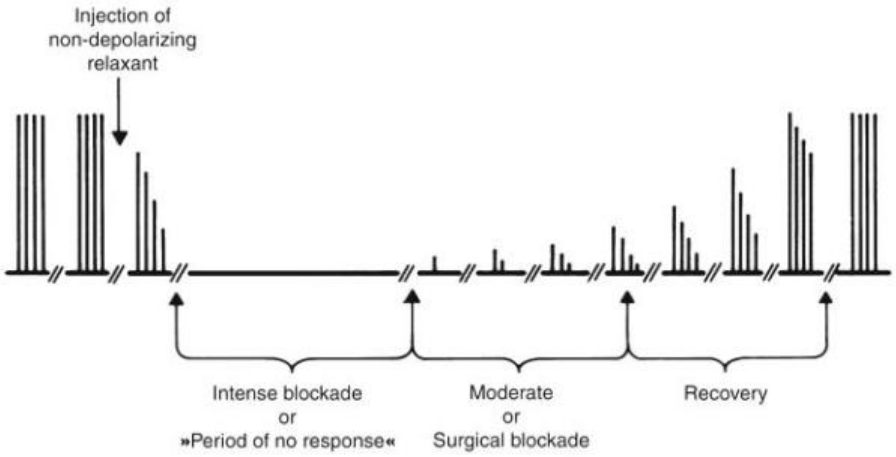

Figure 39-17 Diagram of the changes in response to TOF nerve stimulation during nondepolarizing **neuromuscular** blockade.

Intense **Neuromuscular** Blockade

Intense **neuromuscular** blockade occurs within 3 to 6 minutes of injection of an intubating dose of a nondepolarizing muscle relaxant, depending on the drug and the dose given. This phase is also called the "period of no response" because no response to TOF or single-twitch stimulation occurs. The length of this period varies, again depending primarily on the duration of action of the muscle relaxant and the dose given. The sensitivity of the patient to the drug also affects the period of no response. Although during this phase it is not possible to determine exactly how long intense **neuromuscular** blockade will last, correlation does exist between PTC stimulation and the time to reappearance of the first response to TOF stimulation (see Fig. 39-5).

Moderate or Surgical Blockade

Moderate or surgical blockade begins when the first response to TOF stimulation appears. This phase is characterized by a gradual return of the four responses to TOF stimulation. Furthermore, good correlation exists between the degree of **neuromuscular** blockade and the number of responses to TOF stimulation. When only one response is detectable, the degree of **neuromuscular** blockade (the depression in twitch tension) is 90% to 95%. When the fourth response reappears, **neuromuscular** blockade is usually 60% to 85%.[90][91] The presence of one or two responses in the TOF pattern normally indicates sufficient relaxation for most surgical procedures. During light anesthesia, however, patients may move, buck, or cough. Therefore, when elimination of sudden movements is crucial, a more intense block (or

a deeper level of anesthesia) may be necessary. The more intense block can then be evaluated by using the post-tetanic count (see Fig. 39-6).

Antagonism of **neuromuscular** blockade should normally not be attempted when blockade is intense because reversal will often be inadequate, regardless of the dose of antagonist administered.[92] Also, after the administration of large doses of muscle relaxants, reversal of the block to clinically normal activity is not always possible if only one response in the TOF is present. In general, antagonism should not be initiated before at least two, preferably three or four, responses are observed.

Recovery

The return of the fourth response in the TOF heralds the recovery phase. During **neuromuscular** recovery, a reasonably good correlation exists between the actual TOF ratio measured using MMG and clinical observations, but the relationship between TOF ratio and signs and symptoms of residual blockade varies greatly among patients.[92] When the TOF ratio is 0.4 or less, the patient is generally unable to lift the head or arm. Tidal volume may be normal, but vital capacity and inspiratory force will be reduced. When the ratio is 0.6, most patients are able to lift the head for 3 seconds, open the eyes widely, and stick out the tongue, but vital capacity and inspiratory force are often still reduced. At a TOF ratio of 0.7 to 0.75, the patient can normally cough sufficiently, and lift the head for at least 5 seconds, but the grip strength may still be as low as about 60% of control.[93] When the ratio is 0.8 and higher, vital capacity and inspiratory force are normal.[15][94][95][96] The patient may, however, still have diplopia and facial weakness (Table 39-1).[92]

Table 39-1 -- Clinical signs and symptoms of residual paralysis in awake volunteers after mivacurium-induced neuromuscular block

TOF ratio	Signs and Symptoms
0.70–0.75	Diplopia and visual disturbances
	Decreased hand-grip strength
	Inability to maintain incisor teeth apposition
	"Tongue depressor test" negative
	Inability to sit up without assistance
	Severe facial weakness
	Speaking a major effort
	Overall weakness and tiredness
0.85–0.90	Diplopia and visual disturbances
	Generalized fatigue

From 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 86:765, 1997.

In clinical anesthesia, a TOF ratio of 0.70 to 0.75, or even 0.50, has been thought to reflect adequate recovery of **neuromuscular** function.[96] However, studies have shown that the TOF ratio, whether recorded mechanically or by EMG, must exceed 0.80 or even 0.90 to exclude clinically important residual **neuromuscular** blockade.[5][6][48][62][76][97][98][99][100][101][102] Eriksson and colleagues have shown that moderate degrees of **neuromuscular** block decrease the chemoreceptor sensitivity to hypoxia, leading to insufficient response to a decrease in oxygen tension in blood.[97][98][100][102] They also showed that residual block (TOF < 0.90) is associated with functional impairment of the muscles of the pharynx and upper esophagus, most probably predisposing to regurgitation and aspiration.[48] In accordance with this, it has been documented that residual block (TOF < 0.70) caused by the long-acting muscle relaxant, pancuronium, is a significant risk factor for the development of postoperative pulmonary complications (Table 39-2 and Fig. 39-18).[99] Kopman et associates[93] have documented that even in volunteers without sedation or impaired consciousness a TOF ratio ≤ 0.9 may impair the ability to maintain the airway. Available evidence thus indicates that adequate recovery of **neuromuscular** function requires return of a MMG or EMG TOF ratio to ≥? 0.90, which cannot be guaranteed without objective **neuromuscular** monitoring.[77][78][103][104]

Table 39-2 -- Relationship between train-of-four ratio at first postoperative recording and postoperative pulmonary complications (POPC) *

	Pancuronium (n = 226)			**Atracurium or Vecuronium (n = 450)**		
		Patients with POPC			**Patients with POPC**	
	No. of patients	***n***	***%***	***No. of patients***	***n***	***%***
TOF ≥ 0.70	167	8	4.8	426	23	5.4
TOF < 0.70	59	10	16.9 †	24	1	4.2

* Results from a prospective, randomized, and blinded study of postoperative POPC in a total of 691 adult patients undergoing abdominal, gynecologic, or orthopedic surgery, receiving either pancuronium, atracurium, or vecuronium.[99] In 4 of the 46 patients with POPC (1 in the pancuronium group and 3 in the atracurium and vecuronium groups) the TOF ratio was not available. Because there were no significant differences in the two groups of patients given the intermediate-acting muscle relaxants, the data from these groups are pooled.

† P < 0.02 compared with patients in the same group with TOF ratio ≥0.70.

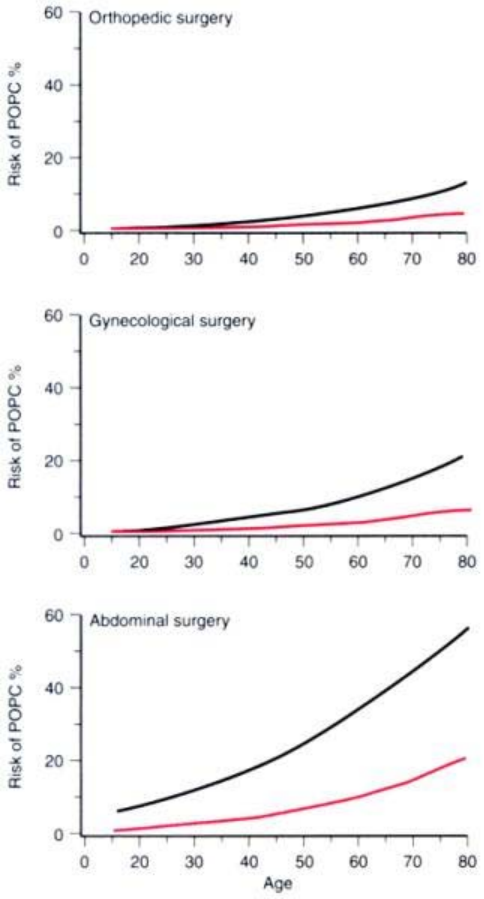

Figure 39-18 Predicted probabilities of postoperative pulmonary complications in different age groups in orthopedic, gynecologic, and major abdominal surgery with a duration of anesthesia of less than 200 minutes. The solid lines represent patients having residual **neuromuscular** block (TOF < 0.70) following the use of pancuronium; the broken lines represent patients with TOF ≥ 0.70 following the use of pancuronium as well as all patients following the use of atracurium and vecuronium, independent of the TOF ratio at the end of anesthesia.[99]

Depolarizing Neuromuscular Blockade (Phase I and II Blocks)

Patients with normal plasma cholinesterase activity who are given a moderate dose of succinylcholine (0.5 to 1.5 mg/kg) undergo a typical depolarizing **neuromuscular** block (phase I block) (i.e., the response to TOF or tetanic stimulation does not fade, and no post-tetanic facilitation of transmission occurs). In contrast, some patients with genetically determined abnormal plasma cholinesterase activity who are given the same dose of succinylcholine undergo a non-depolarizing-like block characterized by fade in the response to TOF and tetanic stimulation and occurrence of post-tetanic facilitation of transmission (Fig. 39-19). This type of block is called a phase II block (dual, mixed, or desensitizing block). Also, phase II blocks sometimes occur in genetically normal patients after prolonged infusion of succinylcholine.

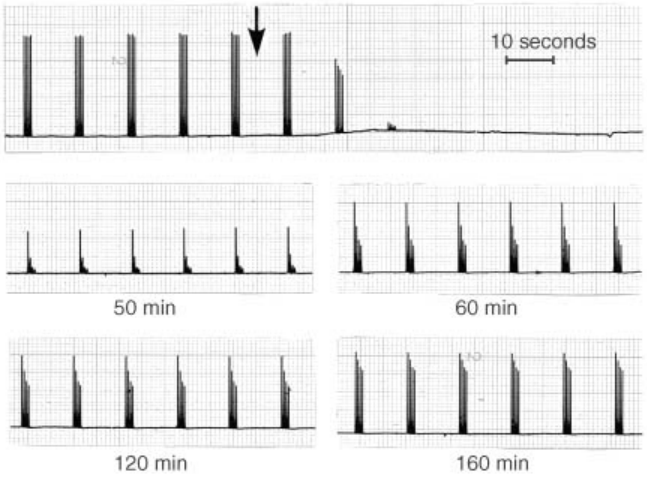

Figure 39-19 Typical recording of the mechanical response (Myograph 2000) to TOF nerve stimulation of the ulnar nerve after injection of 1 mg/kg of succinylcholine (*arrow*) in a patient with genetically determined abnormal plasma cholinesterase activity. The prolonged duration of action and the pronounced fade in the response indicate a phase II block.

From a therapeutic point of view, a phase II block in normal patients must be differentiated from a phase II block in patients with abnormal cholinesterase activity. In normal patients, a phase II block can be antagonized by administering a cholinesterase inhibitor a few minutes after discontinuation of succinylcholine. In patients with abnormal genotypes, the effect of intravenous injection of an acetylcholinesterase inhibitor (e.g., neostigmine) is unpredictable. For example, neostigmine can potentiate the block dramatically, temporarily improve **neuromuscular** transmission, and then potentiate the block or partially reverse the block, all depending on the time elapsed since administration of succinylcholine and the dose of neostigmine given. Therefore, unless the cholinesterase genotype is known to be normal, antagonism of a phase II block with a cholinesterase inhibitor should be undertaken with extreme caution. Even if the **neuromuscular** function improves promptly, patient surveillance should continue for at least 1 hour.

USE OF NERVE STIMULATORS WITHOUT RECORDING EQUIPMENT

Although it is my opinion that **neuromuscular** function should be monitored objectively whenever a **neuromuscular** blocking drug is administered to a patient, tactile or visual evaluation of the evoked response is still the most common form of clinical **neuromuscular** monitoring. The following is a description of how this is best done.

First, for supramaximal stimulation, careful cleansing of the skin and proper placement and fixation of electrodes are essential. Second, every effort should be taken to prevent central cooling as well as cooling of the extremity being evaluated. Both central and local surface cooling of the adductor pollicis muscle may reduce the twitch tension and the TOF ratio.[105][106] Peripheral cooling may affect nerve conduction, decrease the rate of release of acetylcholine and muscle

contractility, increase skin impedance, and reduce blood flow to the muscles, thus decreasing the rate of removal of muscle relaxant from the **neuromuscular** junction. These factors may account for the occasional very pronounced difference in muscle response between a cold extremity and the contralateral warm extremity.[107] Third, when possible, the response to nerve stimulation should be evaluated by feel and not by eye, and the response of the thumb (rather than that of the fifth finger) should be evaluated. Direct stimulation of the muscle often causes subtle movements of the fifth finger when no response is present at the thumb. Finally, the different sensitivities of various muscle groups to **neuromuscular** blocking agents should always be kept in mind.

Figure 39-20 shows which modes of nerve stimulation can be used at various periperative times.

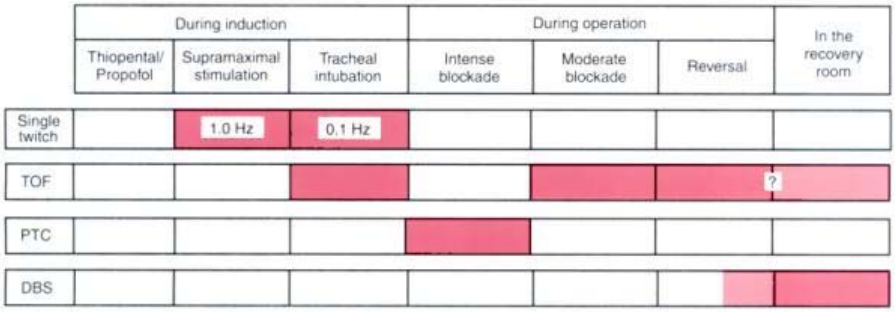

Figure 39-20 This diagram shows when the different modes of electrical nerve stimulation can be used during clinical anesthesia. Dark areas indicate appropriate use; light areas, less effective use. Modes of nerve stimulation: TOF, train-of-four stimulation; PTC, post-tetanic count; DBS, double-burst stimulation; and ?, indicating that TOF is less useful in the recovery room unless measured using mechano-, electro-, or acceleromyography. (See text for further explanation.)

Use of a Peripheral Nerve Stimulator During Induction of Anesthesia

The nerve stimulator should be attached to the patient before induction of anesthesia but should not be turned on until after the patient is unconscious. Single-twitch stimulation at 1 Hz may be used initially when seeking supramaximal stimulation. However, after supramaximal stimulation has been ensured and before muscle relaxant is injected, the mode of stimulation should be changed to TOF (or 0.1-Hz twitch stimulation). Then, after the response to this stimulation has been observed (the control response), the **neuromuscular** blocking agent is injected. Although the trachea is often intubated when the response to TOF stimulation disappears, postponement of this procedure for 30 to 90 seconds, depending upon the muscle relaxant used, usually produces better conditions.

Use of a Peripheral Nerve Stimulator During Surgery

If tracheal intubation is facilitated by the administration of succinylcholine, no more muscle relaxant should be given until the response to nerve stimulation reappears or until the patient shows other signs of returning **neuromuscular** function. If the plasma cholinesterase activity is normal, the muscle response to TOF nerve stimulation reappears within 4 to 8 minutes.

When a nondepolarizing **neuromuscular** drug is used for tracheal intubation, a longer-lasting period of intense blockade usually follows. During this period of no response to TOF and single-twitch stimulation, the time until return of response to TOF stimulation may be evaluated by using post-tetanic count (see Fig. 39-5).

For most surgical procedures requiring muscle relaxation, a twitch depression of approximately 90% will be sufficient, provided the patient is properly anesthetized. If a nondepolarizing relaxant is used, one or two of the responses to TOF stimulation can be felt. However, because the respiratory muscles (including the diaphragm) are less sensitive to **neuromuscular** blocking agents than are the peripheral muscles, the patient may breathe, hiccup, or even cough at this depth of block. To ensure paralysis of the diaphragm, **neuromuscular** blockade of the peripheral muscles must be so intense that PTC stimulation is zero in the thumb.

An added advantage of keeping the **neuromuscular** blockade at a level of one or two responses to TOF stimulation is that antagonism of the block is facilitated at the end of surgery.

Use of a Peripheral Nerve Stimulator During Reversal of Neuromuscular Blockade

Antagonism of a nondepolarizing **neuromuscular** block should not be initiated before at least two responses to TOF stimulation can be felt or before obvious clinical signs of returning **neuromuscular** function are present. To achieve rapid reversal (within 10 minutes) to a TOF ratio of 0.7 in more than 90% of patients, three and preferably four responses should be present at the time of neostigmine injection.[108] It is not possible to achieve a TOF ratio of 0.9 in all patients using this method, but critical episodes of postoperative residual block should be an infrequent occurrence.[109]

During recovery of **neuromuscular** function, when all four responses to TOF stimulation can be felt, an estimation of the TOF ratio may be attempted. However, manual (tactile) evaluation of the response to TOF stimulation (see Fig. 39-8) is not sensitive enough to exclude the possibility of residual **neuromuscular** blockade.[29][104][110] Greater sensitivity is achieved with $DBS_{3,3}$, but even absence of manual fade in the $DBS_{3,3}$ response does not exclude clinically significant residual blockade.[33] Therefore, manual evaluation of responses to nerve stimulation should always be considered in relation to reliable clinical signs and symptoms of residual **neuromuscular** blockade (Table 39-3).

Table 39-3 -- Clinical tests of postoperative neuromuscular recovery

Unreliable
Sustained eye opening
Protrusion of the tongue
Arm lift to opposite shoulder
Normal tidal volume
Normal or near normal vital capacity
Maximum inspiratory pressure <40–50 cm H_2O
Reliable
Sustained head-lift for 5 seconds
Sustained leg lift for 5 seconds
Sustained hand grip for 5 seconds
Sustained "tongue depressor test"
Maximum inspiratory pressure ≥40–50 cm H_2O
(Normal swallowing?)

WHEN TO USE A PERIPHERAL NERVE STIMULATOR

At some institutions, nerve stimulators are used routinely whenever a **neuromuscular** blocking drug is given. In most cases, the response is evaluated by touch, and only in selected cases are the responses recorded. Many anesthesiologists do not agree with an extensive use of nerve stimulators and argue that they manage quite well without these devices. However, the question is not how little an experienced anesthetist can manage with, but rather, how to ensure that all patients receive optimal treatment.

In daily clinical practice significant residual block can be excluded with certainty only if objective methods of **neuromuscular** monitoring are used.[77][78] In my opinion[5] and those of others,[6] good evidence-based practice dictates that clinicians should always quantitate the extent of **neuromuscular** recovery using objective monitoring. At a minimum, the TOF ratio should be measured during recovery whenever a non-depolarizing **neuromuscular** block is not antagonized.[5]

However, in many departments clinicians do not have access to equipment for measuring the degree of block. How then to evaluate and, as far as possible, exclude clinically significant postoperative block? First, long-acting **neuromuscular** blocking agents should not be used. Second, the tactile response to TOF nerve stimulation should be evaluated during surgery. Third, avoid if

possible total twitch suppression. Keep the block so that there is always one or two tactile TOF responses. Fourth, the block should be antagonized at the end of the procedure, but reversal should not be initiated before at least two and preferably three or four responses to TOF stimulation are present. Fifth, during recovery, tactile evaluation of the response to DBS is preferable to tactile evaluation of the response to TOF stimulation, because it is easier to feel fade in the DBS than in the TOF response. Sixth, recognize that absence of tactile fade in both the TOF and the DBS responses does not exclude significant residual block.[33][103][104][110] Finally, reliable clinical signs and symptoms of residual block (see Table 39-3) should be considered in relation to the response to nerve stimulation.

Considering the uncertainty connected with both the use of clinical tests of postoperative **neuromuscular** recovery and tactile evaluation of the response to nerve stimulation, at a minimum every anesthesia department and every recovery room should have at least one apparatus for recording evoked responses. Whether the functioning of such a **neuromuscular** transmission analyzer is based on EMG, MMG, AMG, P_ZEMG or PMG is not crucial, as long as the physician knows how to use the apparatus in question.

KEY POINTS

1. Residual postoperative **neuromuscular** block causes decreased chemoreceptor sensitivity to hypoxia, functional impairment of the muscles of the pharynx and upper esophagus, impaired ability to maintain the airway, and an increased risk for the development of postoperative pulmonary complications.
2. It is difficult, and often impossible, by clinical evaluation of recovery of **neuromuscular** function, to exclude with certainty clinically significant residual curarization.
3. Absence of tactile fade in the response to TOF stimulation, tetanic stimulation and DBS does not exclude significant residual block.
4. Adequate recovery of postoperative **neuromuscular** function cannot be guaranteed without objective **neuromuscular** monitoring.
5. Good evidence-based practice dictates that clinicians should always quantitate the extent of **neuromuscular** blockade using objective monitoring.
6. To exclude clinically significant residual **neuromuscular** blockade the TOF ratio when measured mechanically or by electromyography must exceed 0.9.
7. Avoid total twitch depression during surgery. Keep, whenever possible one or two TOF responses.
8. Antagonism of the **neuromuscular** block should not be initiated before at

least two, preferably three or four, responses to TOF stimulation are observed.

9. If sufficient recovery (TOF ≥ 0.9) has not been documented objectively at the end of the surgical procedure, the **neuromuscular** block should be antagonized.

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