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The physics of neuromuscular monitors in anaesthesia

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Introduction

Neuromuscular monitoring plays a crucial role in ensuring patient safety during anaesthesia. It allows anaesthesiologists to accurately assess the level of muscular blockade, enabling them to administer medications and adjust dosages accordingly. Underlying neuromuscular monitoring is a complex interplay of physics principles, which govern the functioning and interpretation of these devices. In this paper, we will explore the physics behind neuromuscular monitors, including single-twitch, double-burst, and post-tetanic count, and their significance in enhancing patient care.

The physiology of neuromuscular blockade

Before delving into the physics behind neuromuscular monitors, it is essential to understand the physiological basis of neuromuscular blockade. Skeletal muscles are controlled by signals transmitted from motor neurons through the neuromuscular junction (NMJ). Here, acetylcholine released by the nerves facilitates the transmission of electrical impulses, ultimately producing muscle contraction.[1]

Neuromuscular monitors consist of surface electrodes, stimulating electrodes, and sensors that measure the resulting muscle response. The primary objective is to assess the transmission of nerve impulses across the NMJ by stimulating the nerve or muscle and quantifying the response parameters.

Neural stimulation

The neural response depends on current density, not voltage. To achieve a consistent and repeatable maximal response, the current density must be greater than what is needed to get a maximal response.[2]

Using Ohm's law[3] where: V = IR

Potential difference (voltage) = current × resistance

Current = voltage / resistance

To produce a constant current with changes in skin resistance (normal between 500 and 2 000 Ω) requires a change in voltage. Current nerve stimulators are constant current stimulators, which through feedback, detect changes in the current delivered and alter the voltage accordingly, so the desired current is always given.

The controls on the nerve stimulator determine the required current, mode of stimulation and frequency. A microprocessor determines voltage output from the battery, receiving feedback from the current generator and altering voltage requirements. The oscillator provides the pulse in the current generator and the current generator delivers current to the patient.[2]

Determinants of neural stimulation

Table I: Factors determining nerve response to a stimulus[4]

Rheobase of the nerve	The minimum current required to depolarise a nerve is given an infinite duration of stimulation.
Chronaxie of the nerve	The minimum time required for excitation of a structure (such as a neuron) by a constant electric current of twice the threshold voltage.
Polarity of the electrodes	Negative (black electrodes) are more efficient at causing a nerve to depolarise.
Distance of the nerve from the electrode	The further the nerve is from the electrode, the more current is needed to stimulate it. Coulomb's law:[3] current required = minimal current / distance^2
Area of the electrode	Smaller electrodes will produce a greater current density.

Patterns of stimulation

Single-twitch

A single-twitch stimulation involves the application of a single electrical impulse to the nerve or muscle.[5] A single pulse, 0.2 ms in duration, produces a short-duration muscle contraction, providing essential information about baseline neuromuscular function and the degree of muscular blockade.[6] The physics behind single-twitch monitoring involves understanding the electrical properties of the tissue, nerve conduction, and the mechanics of muscle contraction.

i. Electrical properties of tissue

Tissues have varying electrical properties that influence the transmission of electrical signals. These properties include conductivity, resistivity, capacitance, and impedance. Conductivity refers to the ability of a tissue to conduct electrical current. Different tissues, such as muscle, nerve, and skin, exhibit distinct conductivity properties due to variations in their composition and structure. Understanding these electrical properties is crucial for accurate interpretation of the electrical signals measured during single-twitch monitoring.[4]

ii. Nerve conduction

Nerve conduction is an essential component of single-twitch monitoring. It involves the transmission of electrical impulses along the nerve fibres that innervate muscles. When a nerve is stimulated, an action potential travels along its length, leading to the release of acetylcholine at the NMJ. This chemical communication triggers the muscle fibres to contract. Understanding the physics of nerve conduction, including concepts such as action potentials, membrane potential, and ion channels, is fundamental to accurately assessing the neuromuscular response during single-twitch monitoring.[7]

iii. Mechanics of muscle contraction

The mechanics of muscle contraction are vital to interpreting the response observed during single-twitch monitoring. When a nerve impulse triggers muscle contraction, it leads to the sliding of actin and myosin filaments within the muscle fibres, resulting in tension generation. This mechanical process involves concepts such as sarcomere length, force production, and muscle-tendon mechanics. Understanding these principles aids in evaluating the strength and characteristics of the single-twitch response, providing insights into neuromuscular function.[6]

Double-burst stimulation (DBS)

DBS is used to assess the depth of neuromuscular blockade and the recovery of neuromuscular function. It involves delivering two short bursts of electrical pulses with a brief interval between them.[5] The first burst stimulates a submaximal twitch response, and the second burst assesses the fade response or the decrease in muscle contraction strength. A burst of two or three impulses is separated by 0.75 seconds. Two patterns are used, 3:2 or 3:3, representing the number of twitches in each burst. Each burst occurs at a rate of 50 Hz, (three twitches take 0.06 seconds and 2 twitches 0.04 seconds, as seen in Figure 1).[8] The physics behind double-burst stimulation includes considerations of electrical pulse synchronisation, muscle fatigue, and the mechanics of force generation.

i. Electrical pulse synchronisation

Double burst stimulation utilises two short bursts of electrical pulses to evaluate the response of the NMJ and muscle. The timing and synchronisation of these pulses are critical for accurate assessment. The physics behind this aspect involves ensuring precise timing between the two bursts, analysing the impact of pulse duration and interval, and understanding the principles of electrical circuitry. Proper synchronisation ensures consistent and reliable measurement of the muscle response and helps evaluate the level of neuromuscular blockade.

ii. Muscle fatigue

Muscle fatigue can impact the response observed during DBS. With repetitive stimulation, the muscle fibres may experience fatigue, leading to a decrease in force production. This phenomenon can result from various factors, including a limited supply of adenosine triphosphate (ATP), accumulation of metabolic by-products, and impaired muscle contractile properties. Understanding the physics of muscle fatigue allows anaesthesiologists to interpret the fade response during DBS accurately. It helps identify the depth of the neuromuscular blockade and assess the potential recovery of muscle function.

iii. Mechanics of force generation

The mechanics of force generation are integral to the assessment of muscle response during DBS. The force produced by a muscle depends on factors such as the number of active motor units, muscle fibre recruitment, and the length-tension relationship. When evaluating a fade response during the second burst, it is essential to consider the mechanics of force generation. The physics involved include understanding the principles of muscle contraction, muscle-tendon mechanics, and lever systems. This knowledge aids in quantifying the strength of muscle contractions and determining the level of neuromuscular blockade.

By considering electrical pulse synchronisation, muscle fatigue, and the mechanics of force generation, anaesthesiologists can effectively utilise DBS to assess neuromuscular function. This technique provides valuable information about the depth of neuromuscular blockade and the likelihood of recovery. Accurate interpretation of the muscle response during DBS plays a crucial role in adjusting anaesthesia administration, optimising muscle relaxation, and enhancing patient safety during surgery.

Post-tetanic count (PTC)

PTC is a technique used to evaluate the depth of neuromuscular blockade and its recovery by delivering a series of rapid, high-frequency stimuli. This results in a sustained contraction known as a tetanic contraction. The subsequent muscle twitch response following the tetanic contraction is analysed to determine the degree of neuromuscular blockade.[6] It uses the mobilised acetylcholine from a tetanic stimulation to evaluate intense blockade when no twitch is present on a Train-of-Four (TOF), three seconds after a tetanic stimulus a single twitch at one-second intervals is delivered, as seen in Figure 1.[8] The number of twitches present allows an estimation of how long it will take until T1 appears on a TOF.[5] The physics involved in PTC monitoring includes understanding the nerve refractory period, neuronal synchronisation, and the mechanics of muscle contraction.

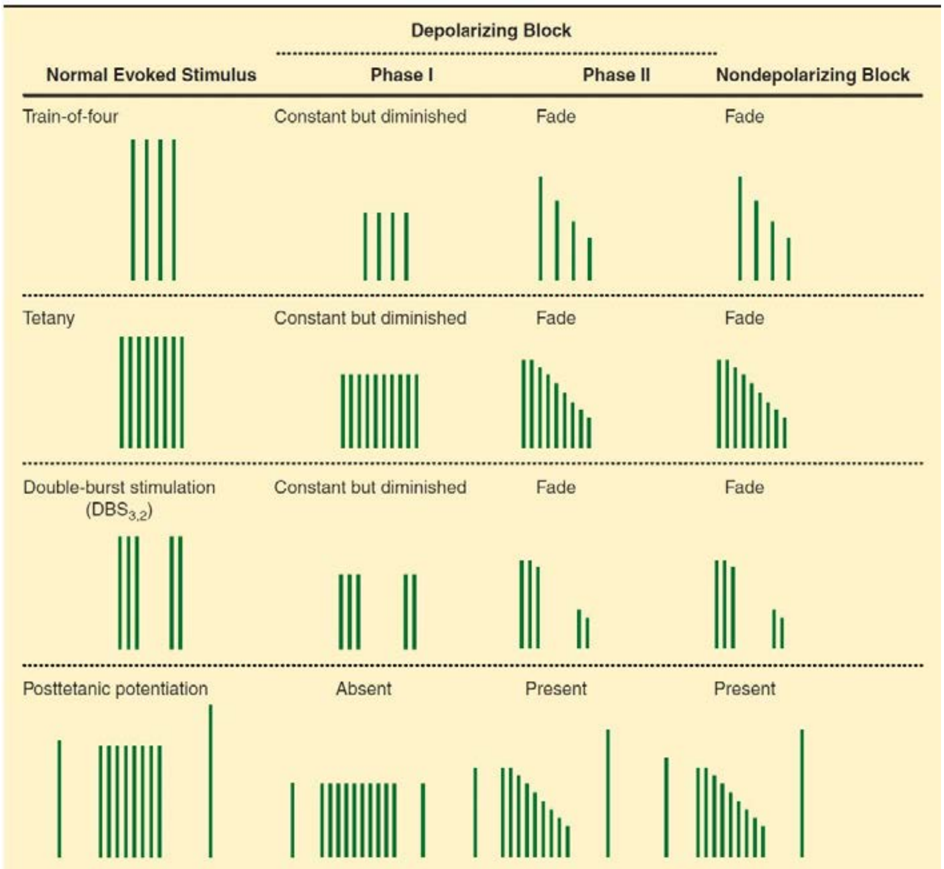

Figure 1: Evoked responses during depolarising (Phase I and Phase II) and nondepolarising block[8]

i. Nerve refractory period

The nerve refractory period is a critical factor in understanding PTC monitoring. After a nerve is stimulated, it enters a refractory period during which it is unresponsive to further stimulation. This period allows the nerve to reset and regain its excitability. Understanding the duration and characteristics of the nerve refractory period is crucial for effective PTC monitoring. The physics involved here includes studying the electrical properties of nerves and their response to stimulation.

ii. Neuronal synchronisation

Neuronal synchronisation plays a significant role in PTC monitoring. During high-frequency stimulation, multiple motor neurons may be activated simultaneously. The synchronisation of these neurons' firing patterns contributes to the generation of the sustained tetanic contraction. Monitoring the subsequent muscle twitch response following the tetanic contraction helps assess the level of neuromuscular blockade and the recovery of neuromuscular function. The physics involved in neuronal synchronisation includes understanding the electrical signals transmitted by neurons and the principles of signal superposition.

iii. Mechanics of muscle contraction

The mechanics of muscle contraction is another important aspect of PTC monitoring. During the sustained tetanic contraction, numerous muscle fibres are actively contracting simultaneously. The mechanics of force generation in muscle fibres involve principles of muscle physiology, muscle-tendon mechanics, and lever systems. Understanding these principles helps interpret the subsequent muscle twitch response following the tetanic contraction and evaluate the level of neuromuscular blockade.[9]

TOF

The TOF is another commonly used technique in neuromuscular monitoring. It involves the application of a series of four consecutive electrical stimuli to assess the level of neuromuscular blockade and the recovery of neuromuscular function, as seen in Figure 1.[8] It is a series of four twitches in two seconds (2 Hz frequency), each 0.2 ms long.[5,6]

i. Electrical stimulation

During TOF monitoring, four electrical stimuli are delivered in quick succession. The timing and characteristics of these stimuli are crucial for accurate assessment. The physics involved in the electrical stimulation include considerations of pulse duration, amplitude, frequency, and synchronisation. These parameters are carefully selected to elicit muscle responses that can be quantitatively evaluated.

ii. Muscle response

The muscle response elicited by electrical stimulation during TOF monitoring is influenced by various factors. Understanding the physics behind muscle response is essential for accurate interpretation of the resulting data. Several principles come into play, including the recruitment of motor units, muscle fibre characteristics, and the length-tension relationship. The magnitude and characteristics of the muscle response, such as twitch height and duration, provide valuable information about neuromuscular function and the degree of blockade.

iii. Fade response

The fade response observed during TOF monitoring is a unique characteristic that helps assess the level of neuromuscular blockade. It refers to the progressive reduction in muscle contraction strength observed in response to the four consecutive stimuli. Fade can manifest as a decrease in twitch height or duration, or both.[5] The physics behind this phenomenon involves understanding the synchronisation of nerve impulses, recruitment of motor units, and muscle fatigue. Fade response is influenced by the depth of blockade and the recovery of neuromuscular function.[10]

The TOF count (TOFC) is defined as the number of detectable evoked responses, and it correlates with the degree of neuromuscular block, as follows:[8,10]

- TOFC 1: > 95% of nicotinic acetylcholine receptors (nAChRs) blocked.
- TOFC 2: 85–90% of nAChRs blocked.
- TOFC 3: 80–85% of nAChRs blocked.
- TOFC 4: 70–75% of nAChRs blocked.

Clinical use of nerve stimulating patterns[7]

- DBS: Demonstrates recovery from blockade where no objective monitor is available.
- PTC: Demonstrates recovery from intense blockade to a single twitch on TOF, i.e. the depth of block.
- TOF: Demonstrates recovery of blockade back to normal and even complete reversal.

Clinical endpoints of neuromuscular blocking agents[7]

- Deep block with no movement possible: PTC 0 or 1.
- Surgical block where movement may occur: TOF T1–T2.
- Reversal with neostigmine possible: TOF > T2.
- Return of airway reflexes: TOF ratio > 90%.

Qualitative versus quantitative monitoring

Qualitative monitoring refers to visual or tactile (i.e. holding the patient's thumb and feeling movement) evaluation of the TOFC or degree of TOF fade in response to neurostimulation provided by a peripheral nerve stimulator. Qualitative monitoring is sometimes referred to as subjective monitoring.

Quantitative, or objective, monitors measure the response of the muscle to the neurostimulation and should be used whenever they are available.[9]

Quantitative monitors

Electromyography (EMG)

EMG, a technique used by neuromuscular monitors, measures electrical activity produced by muscles. The sensors in neuromuscular monitors detect these signals, which can be influenced by electrode-skin impedance and electrode placement. Understanding the electrical properties of tissue, electronic circuitry, and the physics of signal amplification is crucial in accurately interpreting the EMG signals. The physics behind EMG involves concepts such as signals, noise, amplification, filtering, and signal processing.[7,9]

Acceleromyography (AMG)

A piezoelectric crystal is usually attached to the thumb and its acceleration is measured after having the ulnar nerve stimulated. Newton's second law is applied:[3] force = mass × acceleration. The thumb provides a constant mass, therefore the force of contraction equals acceleration. For AMG, the arm position must stay the same throughout the monitoring period, and the thumb must be free to move, unimpeded by surgical drapes or positioning. Consequently, AMG cannot be applied to an arm that is tucked at the patient's side, unless the arm is placed in a special protective device.[7,9]

Properties of an ideal nerve stimulator[4]

The following are some important properties of an ideal nerve stimulator in anaesthesia practice.

Accuracy and precision

An ideal nerve stimulator should deliver precise and accurate stimulation to assess neuromuscular function reliably. It should provide consistent and reproducible results, allowing accurate evaluation of muscle response. This accuracy is crucial for determining the appropriate dosage of neuromuscular blocking agents and ensuring patient safety.

Customisability

Different patients may have unique neuromuscular characteristics, requiring customised stimulation parameters. An ideal nerve stimulator should allow for easy customisation of stimulation parameters, such as pulse duration, frequency, and current intensity. This ensures that the stimulator can adapt to individual patient needs and provide optimal neuromuscular monitoring.

User-friendly interface

The nerve stimulator should have a user-friendly interface that is intuitive and easy to operate. Anaesthesiologists and healthcare professionals need to navigate through stimulation settings efficiently and interpret the results accurately. A clear and user-friendly interface aids in quick and efficient usage, reducing the likelihood of errors or confusion.

Multiple stimulation modes

An ideal nerve stimulator should offer various stimulation modes to cater to different clinical scenarios and preferences. Common modes include single-twitch, TOF, DBS, and tetanic stimulation. Having multiple stimulation modes allows for a comprehensive assessment of neuromuscular function and enhances clinical versatility.

Safety features

Safety is of utmost importance in anaesthesia practice. An ideal nerve stimulator should incorporate safety features to minimise the risk of adverse events. This may include visual and audible alarms to warn against excessive stimulation or prolonged muscle blockade. The stimulator should also have built-in protection against electrical shocks and short circuits, ensuring the safety of both patients and healthcare professionals.

Wireless connectivity and integration

Incorporating wireless connectivity in a nerve stimulator provides convenience and flexibility in clinical practice. It allows for seamless communication with other monitoring devices and anaesthesia equipment. Integration with data management systems enables real-time monitoring, data logging, and analysis, facilitating comprehensive patient assessment and documentation.

Portability

Portability is crucial in anaesthesia practice, particularly in operating rooms and other clinical settings. An ideal nerve stimulator should be compact, lightweight, and battery-powered for easy mobility. This allows for convenient transportation and use in various clinical environments, improving workflow efficiency and patient care.

Durability and longevity

A nerve stimulator should be designed to withstand the demands of daily clinical use. It should be robust, durable, and able to survive frequent handling and accidental drops. Long battery life is desirable to prevent disruptions during critical procedures.

Cost-effectiveness

While maintaining high quality and performance, an ideal nerve stimulator should be cost-effective. It should provide value for money, considering its accuracy, reliability, and durability. Cost-effectiveness ensures wider accessibility and utilisation, benefiting healthcare facilities of all sizes.

Compatibility

An ideal nerve stimulator should be compatible with various monitoring systems and accessories commonly used in anaesthesia practice. This includes integration with anaesthesia workstations, patient monitors, and other devices. Compatibility enables seamless data exchange and aids in comprehensive patient monitoring.

Conclusion

Neuromuscular monitors in anaesthesia rely on the application of various physics principles to accurately assess the level of neuromuscular blockade. From the single twitch response to the DBS and PTC, each technique provides valuable information about neuromuscular function and the depth of blockade. By leveraging physics principles such as EMG, biomechanics, and electrode impedance, anaesthesiologists can effectively monitor neuromuscular blockade, tailor anaesthesia administration, and ensure patient safety.

The comprehensive understanding of the physics underlying neuromuscular monitors enhances patient care by reducing the risk of complications associated with inadequate paralysis or excessive muscle relaxation during surgery. Incorporating physics into the interpretation and use of neuromuscular monitors allows anaesthesiologists to make informed decisions based on quantitative data, improving the efficacy and safety of anaesthesia administration. Advances in neuromuscular monitoring technology will further deepen our understanding of the physics behind these devices and contribute to continuous improvement in patient care in the field of anaesthesia.

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