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Advancing Intraoperative Neurophysiological Monitoring With Human Reflexes

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Human reflexes are simple motor responses that are automatically elicited by various sensory inputs. These reflexes can provide valuable insights into the functioning of the nervous system, particularly the brainstem and spinal cord. Reflexes involving the brainstem, such as the blink reflex, laryngeal adductor reflex, trigeminal hypoglossal reflex, and masseter H reflex, offer immediate information about the cranial-nerve functionality and the overall state of the brainstem. Similarly, spinal reflexes such as the H reflex of the soleus muscle, posterior root muscle reflexes, and sacral reflexes provide crucial information about the functionality of the spinal cord and peripheral nerves. One of the critical benefits of reflex monitoring is that it can provide continuous feedback without disrupting the surgical process due to no movement being induced in the surgical field. These reflexes can be monitored in real time during surgical procedures to assess the integrity of the nervous system and detect potential neurological damage. It is particularly noteworthy that the reflexes provide motor and sensory information on the functional integrity of nerve fibers and nuclei. This article describes the current techniques used for monitoring various human reflexes and their clinical significance in surgery. We also address important methodological considerations and their impact on surgical safety and patient outcomes. Utilizing these methodologies has the potential to advance or even revolutionize the field of intraoperative continuous monitoring, ultimately leading to improved surgical outcomes and enhanced patient care.

Keywords intraoperative neurophysiological monitoring; brainstem reflexes; spinal reflexes.

INTRODUCTION

Intraoperative neurophysiological monitoring plays a vital role in modern surgical procedures, enabling surgeons to assess and preserve the integrity of critical neural structures. Only intraoperative monitoring (IOM) of the conducting system (long tracts) has been available from the beginning of intraoperative neurophysiology. Later, mapping techniques of the different nervous structures (motor cortex, cranial nerves, motor nuclei within the brainstem, and the corticospinal tract within the brain and spinal cord) became available. IOM of the brainstem and spinal cord reflexes is paramount to these structures because they maintain essential physiological functions. Therefore, online monitoring of gray matter of the brainstem and spinal cord (processing system) opens a new dimension of intraoperative neurophysiology. The following sections are written by experts in intraoperative neurophysiology and monitoring reflexes, and they explore the significance of the IOM of brainstem and spinal cord reflexes, its techniques, and its impact on surgical safety and patient outcomes.

Significance of brainstem and spinal cord reflexes

The brainstem and spinal cord reflexes are critical components for the function of the central nervous system, governing essential functions such as respiration, cardiovascular regulation, chewing, swallowing, coughing, and motor control. These reflexes involve complex neural pathways that transmit information within the brainstem and between the brain and the periphery, the brain and the brainstem, the brain and the spinal cord, and the spinal cord and the periphery. Their disruption during surgical interventions can lead to severe complications, including neurological deficits. Thus, monitoring these reflexes intraoperatively is crucial for identifying potential insults and minimizing postoperative morbidity.

Impact on surgical safety and outcomes

Real-time detection of neurological complications

IOM of brainstem and spinal cord reflexes allows surgeons to detect neurological insults in real time. The immediate identification of compromised neural structures facilitates prompt interventions, such as altering the surgical technique, repositioning the patient, or increasing the blood pressure to mitigate potential damage. Minimizing the duration and extent of an insult improves surgical safety and reduces the risk of permanent neurological deficits.

Tailoring anesthetic and surgical strategies

Monitoring reflexes provides crucial information translating into a patient's neurological status postoperatively. Surgeons can use this information to tailor anesthetic and surgical strategies so as to optimize patient outcomes. Adjustments to anesthetic depth, blood pressure management, and patient positioning can be made based on the monitored responses in order to prevent neurological deficits.

Predictive value for prognosis

IOM of brainstem and spinal cord reflexes also holds prognostic value. Serial assessments of reflexes throughout the surgery can help predict postoperative neurological outcomes. By comparing preoperative baseline values with intraoperative responses, intraoperative neurophysiologists can estimate the likelihood of neurological deficits and possibly better plan appropriate postoperative care and rehabilitation strategies.

BRAINSTEM REFLEXES

Blink reflex

Previous research found that the blink reflex (BR) could not be elicited in unconscious patients who had received doses of anesthetics comparable to those used in surgery.[1,2] Møller and Jannetta[3,4] first reported the successful elicitation of the BR response during surgery and its subsequent disappearance after microvascular decompression (MVD) of the facial nerve in patients with hemifacial spasm (HFS) (Fig. 1). However, it was subsequently suggested that the electrical response that they elicited could have been due to the lateral axon-axonal spread of excitation in the facial nerve fibers instead of excitation in the trigeminal afferent nerve.[5]

Methodology

In 2009, Deletis et al.[6] introduced a new method for eliciting the early response (R1) component of the BR in anesthetized patients. A set of subdermal needle electrodes were inserted into the orbicularis oculi muscles for recording, and electrical stimulation was applied using two needle electrodes placed subcutaneously to target the supraorbital nerve. R1 was induced using a train of one to seven rectangular constant current stimuli, with an interstimulus interval of 2 ms, a duration of 0.3–0.5 ms, an intensity of 20–40 mA, and a train repetition rate at 0.4 Hz. This response involves an oligosynaptic reflex arc comprising the trigeminal nerve, brainstem connections at the pons, and the facial nerve.

BR application during surgery

Fernández-Conejero et al.[7] reported intraoperative recordings of the BR during MVD surgery. They noted that the stimuli intensity and/or the number of stimuli in the train had to be increased to elicit the BR immediately after MVD in HFS patients and presumed that this change in the BR was a result of decreased hyperexcitability of the facial motor nucleus following effective decompression of the facial nerve.

Choi et al.[8] recently investigated the prognostic and predictive value of using the BR as an IOM technique during MVD in 41 patients with HFS. They compared the results

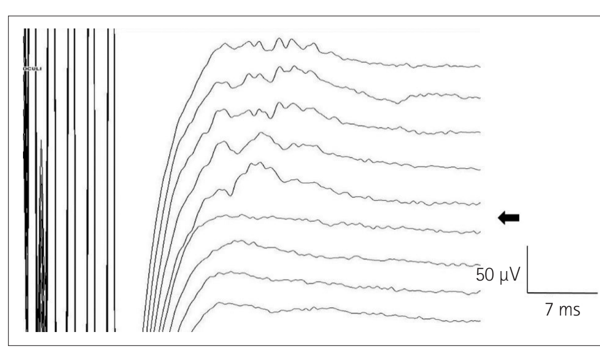

Fig. 1. Intraoperative blink reflex (BR) monitoring during microvascular decompression for hemifacial spasm. During the surgical procedures, the intraoperative BR was resolved immediately after inserting a Teflon pad (arrow).

from monitoring the BR and lateral-spread response (LSR) with the clinical outcomes at different postoperative time points: 1 day, 1 month, and 6 months. The BR was monitored by recording the excitability of the facial motor nucleus and nerve while keeping the stimulus parameters constant during surgery after baseline measurements were made. BR resolution was defined as the disappearance of an electrical response for that fixed intensity of stimulation, which indicated a change in the hyperexcitability of the facial motor nucleus and nerve after MVD. The outcome of facial spasm resolution at all three time points was significantly better in the subjects with BR resolved than in those whose BR persisted during MVD. However, the same outcome compared between patients exhibiting a persistent and resolved LSR was statistically significant only at the 1-day and 1-month time points (i.e., not at 6 months). Choi et al.[8] suggested that the BR could be a more reliable predictor of surgical outcomes than the LSR and a potentially helpful methodology in optimizing the degree of facial nerve decompression during MVD surgery.

Blink synkinesis (BS) can be elicited in HFS patients by electrically stimulating the supraorbital nerve, which induces electrical responses not only in the orbicularis oculi but also in the orbicularis oris and other facial muscles.[9,10] Møller and Jannetta[4] observed that decompression of the facial nerve led to the disappearance of both BS and the LSR, supporting that HFS might be related to hyperexcitability of the facial motor nucleus. In 2019, Hsu et al.[11] reported the utility of BS monitoring during MVD for HFS, concluding that the sensitivity and predictive values were higher for BS than for other conventional IOM methodologies, including the LSR and the facial nerve motor evoked potential (MEP).

BR and BS monitoring clearly have potential as new IOM methodologies for predicting surgical outcomes and serving as indicators of optimal decompression of the facial nerve during MVD for HFS, supplementing the limitations of the LSR. These reflex-based methodologies also enable the simultaneous monitoring of trigeminal afferents and brainstem connections involved in the reflex arc. However, relatively few studies have investigated using the BR and BS, which necessitates further prospective research with larger samples and longer follow-ups to confirm the utility of these reflex monitoring techniques.

The laryngeal adductor reflex

The laryngeal adductor reflex (LAR) is a protective mechanism of the airway, which prevents aspiration by causing contraction of the adductor laryngeal muscles—thyroarytenoid, lateral cricoarytenoid, and interarytenoid muscles—and, therefore, the bilateral closure of the vocal folds (VFs).[12]

The LAR is triggered by afferent sensations from the supraglottic mucosa, which is carried by the internal branch of the superior laryngeal nerve and the vagus nerve to the nucleus of the solitary tract in the brainstem. From there, fibers project to the nucleus ambiguus bilaterally, located in the medulla. The laryngeal motoneurons in the nucleus ambiguus send efferent signals to the laryngeal muscles through the vagus nerve and the recurrent laryngeal nerve (RLN).[13-15]

The reflex consists of two responses recorded from laryngeal adductor muscles: an early R1 component with an approximate latency of 20 ms and the R2 component with an approximate 50−60 ms latency (Fig. 2).[16-19] Both components are bilateral, in contrast to what has been described by classical studies.[12,20] This fact has recently been demonstrated in awake and under anesthesia patients.[16,20] R1 is the electrical event that initiates the vocal cord's mechanical adduction.[21] The LAR is a robust and stable response under total intravenous anesthesia (TIVA). However, the inhalational agents and local anesthetics, such as sevoflurane and lidocaine, suppress the reflex responses.

The LAR constitutes a comprehensive new methodology for evaluating the integrity of the vagus and laryngeal nerves and the medullary structures involved in the arc reflex. Advantages of LAR monitoring over current techniques include simplicity, the ability to monitor neural function continuously without placing additional neural probes, the absence of movement in the surgical field, and the ability to assess the integrity of both sensory and motor pathways.

Methodology

In 2017, a new tube-based methodology was developed for LAR assessments under general anesthesia.[17] Anesthesia is induced with propofol and succinylcholine and maintained using TIVA with propofol and opioids. Patients are intubated using an endotracheal tube designed to monitor the laryngeal muscles, with two pairs of electrodes attached or embedded on the surface that contact the right and left VFs, respectively. A GlideScope Video Laryngoscope guides the intubation to ensure correct positioning of the electrodes. The laryngeal mucosa is electrically stimulated using a pair of electrodes (single pulse or short train of 2−3 pulses, 0.2−1 ms, <20 mA), and the contralateral R1 is recorded using the pair of electrodes located on the contralateral side of the tube (30−1,000 Hz filters). Three derivations are used for the recording: a bipolar derivation (VF+/VF-) and two referential derivations using a subdermal needle placed on the sternum (VF+/Ref, VF-/Ref). Right/left LARs are denominated based on the recording side.

Some limitations of this technique are the tube displacement and the far-field recording. For this, it is crucial to en-

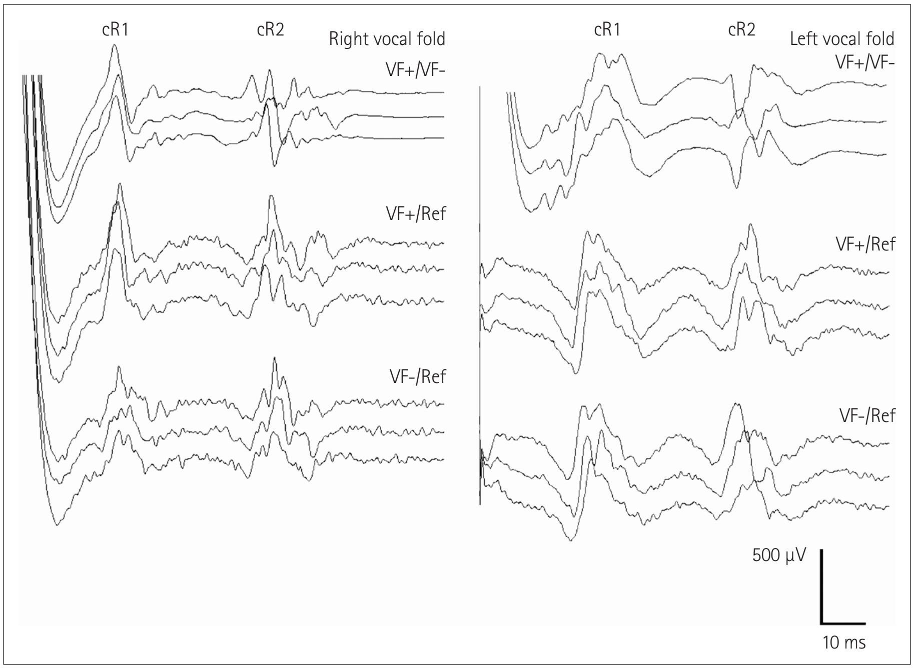

Fig. 2. The laryngeal adductor reflex (LAR). The right LAR is recorded in the right vocal fold (VF) after stimulating the left laryngeal mucosa. Conversely, the left LAR is recorded in the left VF after stimulating the right laryngeal mucosa. The recorded components are the contralateral R1 and R2 (cR1 and cR2), respectively.

sure the correct fixation of the tube, and minimum amplitude of the LAR greater than 150 µV is required, optimally >200 µV, to be considered a reliable response.

The LAR can also be elicited using two hook-wire electrodes inserted in each VF by an ear-nose-throat specialist after intubation.[22]

LAR application during surgery

The LAR monitoring has broad applicability to various surgeries where the laryngeal nerves, vagus nerve, or the brainstem structures involved in the reflex are at risk of injury.

In neck endocrine surgery, including thyroid and parathyroid surgery, the amplitude of the LAR frequently decreases with surgical maneuvers that put traction on the RLN and are reversible upon releasing the stretched tissue.[23] The continuous information about the functional status of the RNL allows us to detect the impending damage before permanent lesions happen and to adapt the surgical maneuvers to prevent neural damage. A significantly decreased rate of postoperative transient VF paralysis and paresis over intermittent intraoperative RLN mapping alone has already been published.[24]

During vagal schwannomas excision, the LAR allows continuous monitoring of the vagal nerve and functional assessments of the sensory and motor fibers spread over the tumor's capsule. Thus, mapping the sensory fibers of the vagus nerve is possible for the first time through the LAR.[25-27]

The LAR has been proven helpful in monitoring the vagus nerve and the reflexive medullary pathways in complex posterior fossa surgery, both in children and adult populations.[22,28] In a multicenter study involving 53 patients, the LAR presented a monitorability of 94% and a good correlation between the intraoperative LAR signals and the postoperative outcomes. When the LAR amplitude decreased by more than 50%, the surgeon was informed, and different corrective maneuvers were applied, such as a surgical pause or a change in the resection angle. The cases with permanent decrement or loss of the LAR R1 response correlated with postoperative laryngeal dysfunction, including vocal palsy, dysphonia, pharyngeal hypoesthesia, or more-severe problems like aspiration, pneumonia, or permanent swallowing problems, requiring tracheostomy. On the other hand, the patients with stable LAR throughout the surgery or with a transitory decrement of the amplitude that recovered after the corrective maneuvers presented with normal sensory and motor laryngeal function.[28]

In summary, the LAR is a valuable tool for monitoring the laryngeal nerves, the vagus nerve, and the brainstem structures involved in the reflex in all those surgeries where they are at risk of iatrogenic damage. It allows us to continuously assess the sensory and motor pathways without inducing movement in the surgical field and has shown a strong correlation with postoperative outcomes. Combining the LAR with the other classical modalities used for IOM (cranial nerve mapping and corticobulbar evoked potentials) increases the patient's safety in these surgeries.

The trigeminal hypoglossal reflex

The trigeminal hypoglossal reflex (THR) is a brainstem reflex mediated by trigeminal afference and hypoglossal efference involved in tongue movement coordination during complex oromotor behaviors. These include mastication, swallowing, vocalizing, and breathing.[29-36] The THR results from polysynaptic pathways that involve interneurons of the perihypoglossal area.[37] This area receives trigeminal afferences (as well as vagal, hypoglossal, and reticular afferences) and projects hypoglossal efferences.[32,38] However, THR is only one part of the complex brainstem network that results in tongue activation. This network also includes somatic afferences.[39]

The net final movement of the tongue, in response to trigeminal stimulation, results from the summating excitatory and inhibitory postsynaptic potentials that arrive at the tongue. Protractive or retractive muscles of the tongue respond to the stimulation of the different trigeminal branches. In that sense, there are multiple reflexes of trigeminal afference, which depend on the branch being stimulated; for example, the lingual reflex and the masseteric reflex,[40] the inferior alveolar reflex,[41] the jaw-hypoglossal reflex,[42] and the jaw-tongue reflex.[43] Despite this, there is a stronger physiological preference for a resultant tongue retraction than tongue protraction.

Methodology

The THR can be elicited under general anesthesia using a train stimulation paradigm (pulses 2–4 of 0.2–0.5 ms pulse width, at a repetition rate of 0.4–0.7 Hz and interstimulus interval of 2 ms).[44] The stimulation should be done using isolated 18-mm needle electrodes placed percutaneously with the cathode and anode placed under the zygomatic arch (1.5–2 cm apart) and 0.5 cm anteriorly to the temporomandibular joint.[45,46] Given the resultant potential movement of the tongue, isolated 13-mm needles should be placed in both the styloglossus (retractive) and genioglossus (protractive) muscles to allow for the recording of the reflex in the case of tongue protraction or retraction following trigeminal stimulation. The THR usually presents a polyphasic component with a latency of around 40 ms (Fig. 3). The reflex can also be recorded using direct trigeminal nerve stimulation using a handheld probe in the surgical field.[39,44]

THR application during surgery

The THR can be recorded in 82.1% of cases if the methodology is followed accurately.[44] The tongue retraction pattern of the reflex is more prevalent than the tongue protraction. Despite only showing limited data, the same authors reported that the disappearance of the THR could be related to trigeminal or hypoglossal deficits postoperatively, but further studies are necessary to confirm this correlation.

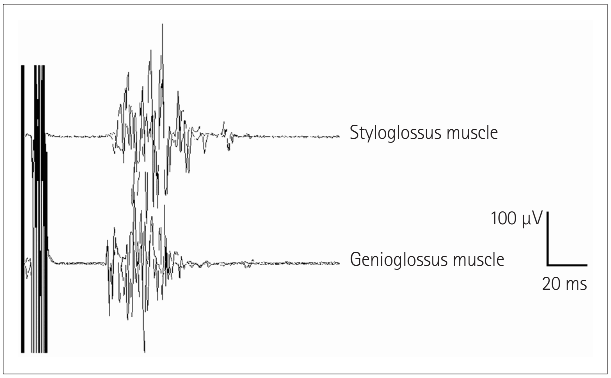

Fig. 3. Several trials presented in superimposed mode. The trigeminal hypoglossal reflex depicted here was recorded in the styloglossus and genioglossus muscles.

H reflex of the masseter muscle

The masseter H reflex is a monosynaptic trigeminal-trigeminal reflex that reflects conduction through the midbrain and pons. It involves proprioceptive fibers originating from the masseter muscle spindles (fibers Ia), whose cell bodies are located in the mesencephalic nucleus of the trigeminal nerve. These fibers serve as the afferent pathway, descending to the trigeminal motor nucleus in the midpons and forming monosynaptic excitatory synapses to activate the jaw-closing motoneurons of the ipsilateral masseter (efferent pathway).[47-49]

The masseter proprioceptive fibers also establish heteronymous connections with the ipsilateral temporalis muscle, indicating a synergistic behavior between these muscles. When the masseteric nerve is electrically stimulated, it elicits both an M response and a homonymous H response on the masseter muscle, whereas only a heteronymous H response is observed on the ipsilateral temporalis muscle.[49-51]

The masseter H reflex fulfills all three criteria of an H reflex: it can be elicited below the M threshold, its amplitude progressively increases until an M response is present, and it decreases from that point onwards when higher intensity stimuli are applied.[49] However, the heteronymous H reflex may reach a plateau and persist even at more potent stimuli.[51]

Methodology

TIVA with propofol and remifentanil is the preferred anesthetic regimen when monitoring brainstem reflexes. However, due to the monosynaptic nature of the masseter H reflex, the inhibitory effects of general anesthesia may have a milder impact than polysynaptic pathways.

Various stimulation and recording techniques have been described in the literature for both clinical[45,50-52] and intraoperative settings.[46]

Direct electrical stimulation of the masseteric nerve using a pair of monopolar electromyography (EMG) (as described by Ulkatan et al.[46]) or twisted monopolar isolated needles (Spes Medica, TFDN453731, 150 cm length, 26 G, 37-mm uninsulated tip) is considered the optimal method to ensure specific stimulation of the masseteric nerve. In awake subjects, inserting needle electrodes can cause discomfort and pain that might make the procedure uncomfortable for patients. However, percutaneous needle stimulation is preferred under general anesthesia as pain is no longer a limitation.

The needles are inserted about 1.5 cm in depth right under the zygomatic arch, with the cathode between the condyle and the coronoid process and the anode about 2 cm apart. A handheld stimulator can be used to pass a low-intensity current through the needles while being inserted to ensure specific stimulation of the masseteric nerve (through the visual confirmation of masseter contraction) and avoid facial nerve (needle placed too superficial) or deep temporal nerve (needle placed too deep) co-stimulation.

A twisted pair of subdermal monopolar needles are inserted on the masseter and the temporalis muscles to record these muscles' M and H responses. For the masseter, the anterior and inferior portions of the muscle belly have been found to be the ideal point for recording as the anterior portion of the temporalis muscle. Voluntary contraction (closing the jaw tight) can be requested from the patient prior to intubation, allowing to highlight the points of maximal contraction and signal them with a skin marker for future reference during the setup.

A single pulse of 0.2 ms duration is applied for stimulation, progressively increasing in intensity from zero until an H reflex is elicited and additionally increased until an M response is visible (Fig. 4). The lack of antidromic volleys influencing the excitability of the temporalis motoneurons produces a temporalis H reflex without an M wave. For this reason, measuring the temporalis H reflex can be easier than the masseter H when getting obliterated by the masseter M wave.

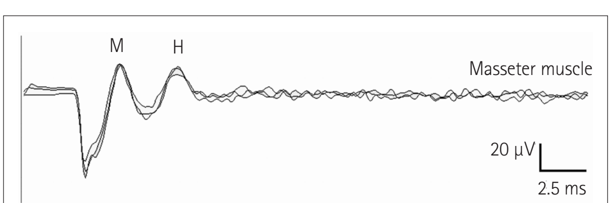

Fig. 4. The masseter H reflex. For low-intensity electrical stimulation both the H reflex and M response are visible. When the stimulation intensity is increased to a supramaximal level, the M response peaks and the H reflex disappears.

Amplitudes, latencies, and stimulation intensity values do not significantly differ between the surgical and the clinical contexts.[46,50,53] Normative values subtracted from clinical experience could be hypothetically applied to interpret the operating room's elicited M and H waveforms. However, further studies would be needed to verify this point, given the scarce intraoperative data published.

Muscle vibration and voluntary contraction have facilitated the masseter H reflex during wakefulness, increasing its elicitability rate.[45,53,54] In the operating room, a similar facilitatory effect can be obtained by placing a bite block between the molars to passively keep the mouth in a semi-open position (the same already used to prevent bite injuries during transcranial evoked potentials). This mild tension in the mouth, preventing the mouth from fully relaxing, would activate the Ia fibers from the muscle spindles on the masseter muscle.

Masseter H reflex application during surgery

Both intra- and extra-axial lesions involving the midbrain and midpons can be susceptible to benefit from monitoring the masseter H reflex.

To our knowledge, no studies have examined the relationship between masseter H reflex changes and postoperative outcomes for this muscle. A warning criterion has not been, therefore, established. However, an irreversible loss of a previously present reflex could theoretically represent an indirect sign of injury to any structures involved in the reflex arc. Further systematic analyses are needed to establish more-accurate correlations.

SPINAL REFLEXES

H reflex of the soleus muscle

The H reflex, initially described by Paul Hoffmann, is a spinal reflex involving impulses originating from direct stimulation of sensory nerve fibers innervating muscle spindles.[49,55] These fibers enter the spinal cord through the dorsal root and dorsal horn and synapse monosynaptically with the second motoneuron at the anterior horn nuclei. The efferent conduction occurs through the motor portion of the peripheral nerve to generate the reflex. The soleus H reflex has been extensively used in studying the effects of anesthetics and other drugs on the excitability of spinal motoneurons. However, the effects of anesthetics like propofol on the H reflex have been debated.[56,57]

Methodology

To elicit H reflexes and M responses from the soleus muscle, the tibial nerve is electrically stimulated using surface electrodes with a rectangular pulse of 0.5–1 ms duration in the popliteal fossa. The stimulus intensity is gradually increased from below the H reflex threshold up to the maximal M response. The recording is done with active electrodes positioned 2 cm distal to the gastrocnemius muscle, while the reference electrode is placed 3 cm further distal. In the operating room, subdermal needles are used to record the soleus muscle's activity. It should be noted that the recorded H reflex amplitude and waveform can vary depending on the type and placement of the recording electrodes. The recorded signals are filtered within a frequency range of 20 Hz to 2.5 kHz.[58]

As the stimulus intensity increases, the amplitude of the H reflex initially increases until the onset of the M wave, after which it declines. Conversely, the M wave increases until reaching its maximum amplitude, while the H reflex disappears (Fig. 5). Potential reasons for the attenuation of the H reflex at higher intensities include the collision of antidromic activity with the reflex impulse in the alpha motoneuron refractoriness of the axon hillock following the antidromic impulse, and Renshaw inhibition of motoneuron axon collaterals mediated by internuncial cells and neighboring alpha motoneurons.[49,59,60]

Soleus H reflex application during surgery

The soleus H reflex is a valuable measure of nerve conduction along the tibial and S1 pathways, providing insights into proximal nerve segments such as the plexus and roots.[55] This test has been employed in various studies to investigate spinal trauma, assess motoneuronal function and excitability, and monitor the functional integrity of the spinal cord and its reflex pathways during surgical procedures under general anesthesia. It proves particularly useful in spinal cord manipulation surgeries or when there is potential for spinal cord or adjacent structure injury.

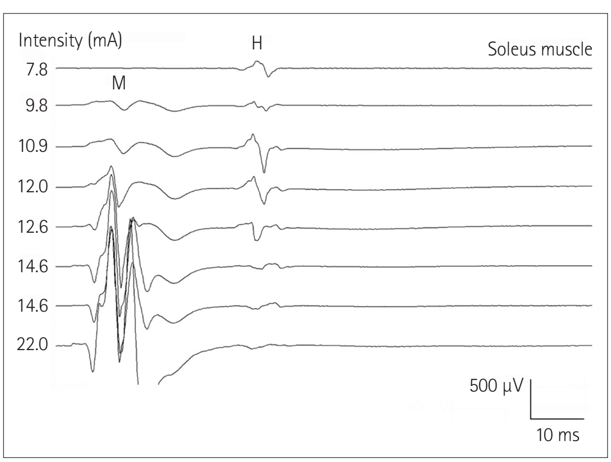

Fig. 5. The soleus H reflex. H reflex and M responses of the soleus muscle are presented on a cascaded screen. The intensity of the electrical pulses is gradually increased from the H reflex threshold until the M response becomes supramaximal.

Posterior root muscle reflexes

Posterior root muscle (PRM) reflexes are spinal responses elicited through electrical stimulation of the lumbar and upper sacral posterior roots, and their corresponding recordings can be observed in lower limb muscles.[61,62] The posterior roots can be stimulated by needle electrodes placed in the posterior epidural space or transcutaneously by surface electrodes. A single electrical stimulus elicits PRM reflexes that can be recorded bilaterally in nearly all lower limb muscles.[63,64] PRM reflex assessment offers several advantages in intraoperative neurophysiological monitoring, including evaluating motoneuronal excitability and the integrity of motor roots and peripheral nerves in the lower limbs. This review paper focuses on the PRM reflexes elicited through transcutaneous surface electrodes.

Methodology

To elicit PRM reflexes, various configurations of surface electrodes have been employed. These electrode montages generate flow currents, targeting the neural structures within the spinal canal. Typically, the cathode, which is of smaller dimensions (1–5 cm×1–5 cm), is positioned paravertebrally at the center between the T11 and T12 vertebrae, although it can also be placed more caudally along the cauda equina. The larger anode is positioned over the lower abdomen or the anterior superior iliac spine. In order to enhance the total electrode surface area for abdominal electrodes, a periumbilical electrode is created by connecting a pair of surface electrodes, each measuring 8 cm×13 cm.[62] This monopolar-like setup is preferred as it exhibits lower response thresholds compared to bipolar arrangements, where the cathode and anode are longitudinally positioned over the spine.[65-67]

For the recording of PRM reflexes, a pair of subdermal needles are inserted into various lower limb muscles, including the rectus femoris, vastus medialis, vastus lateralis, tibialis anterior, peroneus longus, medial hamstring, biceps femoris, medial gastrocnemius, lateral gastrocnemius, soleus, extensor digitorum brevis, flexor digitorum brevis, and gluteus maximus.[62,68,69]

The onset latencies of PRM reflexes are typically shorter in proximal lower limb muscles compared to distal ones due to variations in the lengths of the respective reflex arcs' efferent limbs. On average, midthigh responses have onset latencies ranging from 9 ms to 12 ms, while mid-lower leg respons-

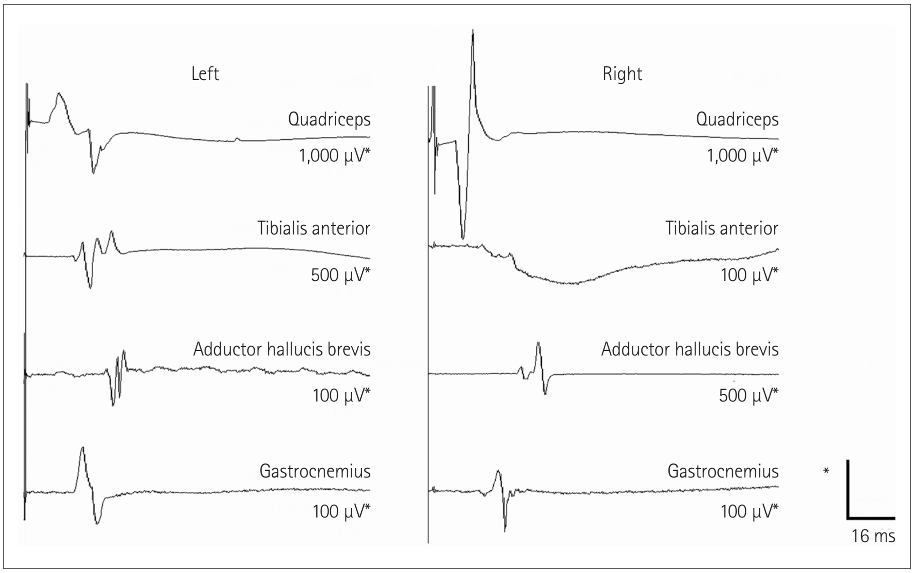

Fig. 6. Posterior root muscle (PRM) reflexes. A single stimulus of electrical stimulation is delivered to simultaneously elicit the PRM reflex in all muscles of the lower extremities.

es range from 18 ms to 21 ms (Fig. 6). These latencies also correlate with the height of the tested individuals.[62]

Compared to the H reflex, PRM reflexes benefit from a shorter distance traveled by electrically evoked action potentials in the afferent limb of the reflex arc. This reduces the temporal dispersion of afferent volleys reaching the spinal level, leading to more-efficient summation processes of postsynaptic potentials at the motoneurons. Additionally, potential heteronymous facilitation may contribute to these reflexes, which explains why PRM reflexes can be elicited in muscles such as the tibialis anterior, where H reflexes are not easily evoked without voluntary facilitation.

When transcutaneous electrical stimulation is applied with an active electrode positioned caudally over the cauda equina, posterior and anterior roots can be recruited in multiple lower limb muscles. The body position also influences the evoked responses by altering the transversal location of the spinal cord within the spinal canal and changing the excitation thresholds of posterior and anterior roots.

PRM reflexes have been elicited in various body positions, including supine, prone, sitting, standing, and during treadmill stepping. However, it is important to note that the reliable stimulation of posterior root fibers can be compromised in a prone position. In the prone position, stimulation can elicit direct motor responses in the anterior roots in addition to PRM reflexes. Consequently, the responses must be interpreted carefully when performing transcutaneous spinal cord stimulation in a prone position.

PRM reflexes application during surgery

Examples of the application of PRM reflexes in IOM include neurophysiological monitoring during neurostimulator placement for the lumbar spine, which is essential for precise electrode positioning over specific spinal cord segments' dorsal root entry zones. PRM reflexes are also helpful in complex hip surgeries to assess the functional integrity of the sciatic and femoral nerves.

Overall, PRM reflex assessment offers several advantages, including simultaneous evaluation of motoneuronal excitability and the integrity of motor roots and peripheral nerves in the lower limbs.

Sacral reflexes

Sacral reflexes, including the bulbocavernosus reflex (BCR) and anal reflexes, can be utilized to assess the integrity of the sacral spinal cord. A non-nociceptive stimulus elicits the BCR. Electrical stimulation and EMG recording have shown differences in reflex responses between the dorsal nerve of the clitoris/penis and the perianal skin in the external anal sphincter. This review focuses on the BCR, discussing its clinical significance and intraoperative applications with support from relevant literature.

Bors and Blinn[70] first described the BCR in 1959. EMG of the BCR was initially performed by Rushworth[71] in 1967 and has since been recognized as a clinically helpful examination. Deletis and Vodusek[72] demonstrated intraoperative BCR monitoring in patients under general anesthesia in 1997. This breakthrough allowed for intraoperative BCR monitoring in various neurosurgical conditions such as tethered spinal cords, spinal cord tumors, and spinal decompression and fusion.

The BCR is a polysynaptic spinal reflex arc that is mediated by the pudendal nerve. The reflex arc consists of three types of neurons: sensory neurons, motoneurons, and interneurons. The afferent somatic sensory pathway of the BCR comprises the dorsal penile nerve, the pudendal nerve, the sacral plexus, and the S2, S3, and S4 sacral roots. The efferent somatic motor pathway comprises the neurons in Onuf's nucleus, sacral roots S2, S3, and S4, the pudendal nerve, the sacral plexus, the deep branch of the pudendal nerve, and the bulbocavernosus muscle. When the penis/clitoris is stimulated, the sensory neuron sends action potentials to the spinal cord that travel up to the ventral horn where they synapse with the motoneuron. The motoneuron then sends action potentials to the bulbocavernosus muscle induce contraction. The BCR is elicited by mechanical or electrical stimulation of the penis/clitoris.

Methodology

Intraoperative BCR monitoring involves placing surface or needle electrodes in the perineal region to stimulate the pudendal nerve. Stimulation is carried out using anode and cathode electrodes positioned on the distal and proximal areas of the penis/clitoris, respectively. A train stimulation paradigm, often with double trains, enhances the BCR response.[73] Needle electrodes are inserted into the external anal sphincter for recording the BCR (Fig. 7). Changes in BCR characteristics such as in its latency, amplitude, and waveform shape are compared with baseline measurements to identify potential nerve injury or dysfunction, with particular attention given to the stable early component (with a latency of around 30 ms). Unlike somatosensory evoked potentials and MEPs, there were no established criteria for determining alarm thresholds during intraoperative BCR monitoring until recently.[74] Loss of the BCR can be used as a predictor of adverse postoperative urinary function. A threshold of >75% for the BCR amplitude reduction may be a useful warning criterion. Notable reductions in waveform complexity, such as a decreased duration or turn count, may indicate an imminent signal loss or an incomplete conduction block within the reflex circuit.

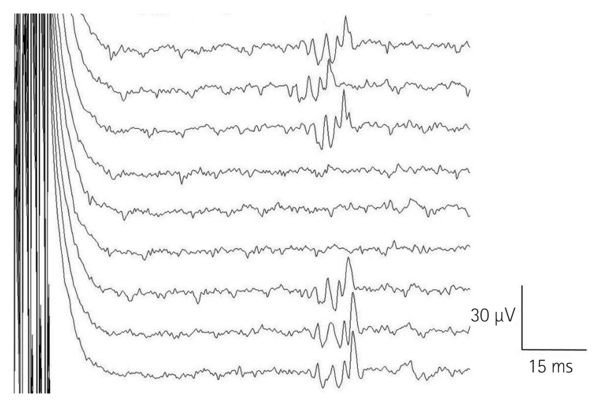

Fig. 7. Intraoperative bulbocavernosus reflex (BCR) monitoring during posterior lumbar decompression and fusion surgery. The BCR on the left side disappears during decompression, but the waveform recovers after warm-saline irrigation, retractor release, and intravenous methylprednisolone administration, and then remains stable until the end of the surgery.

Pudendal motoneurons mediate the BCR, and the anesthetic requirements for BCR monitoring are aligned with those for acquiring MEPs. It is generally advised to avoid inhaled agents and instead prefer a propofol/narcotic induction and maintenance approach. Muscle relaxation should be minimized, except for intubation or when the surgeon specifically requests a brief relaxation period for initial exposure.

BCR application during surgery

Deletis and Vodusek[72] conducted a groundbreaking study in 1997 that introduced intraoperative BCR monitoring in patients under general anesthesia. Subsequent studies focused on applying intraoperative BCR monitoring, specifically in untethering surgeries for infants and young children. Researchers such as Sala et al.,[75] Hwang et al.,[76] Cha et al.,[77] Morota,[74] and Shinjo et al.[78] highlighted the importance of BCR monitoring in these procedures. A recent study by Choi et al.[79] examined the effectiveness of intraoperative BCR monitoring in 63 adult patients undergoing lumbosacral spinal tumor surgery. That study investigated the correlation between intraoperative BCR changes and postoperative voiding function and found that patients with a maintained BCR had significantly better voiding-function outcomes, while all patients without a BCR experienced voiding difficulties postoperatively. The sensitivity, specificity, positive predictive value, and negative predictive value were all 100% when using intraoperative BCR monitoring to predict voiding function at 6 months after surgery. This indicates that the BCR is a reliable predictor for assessing and monitoring voiding function during lumbosacral spinal tumor surgery. Another study by Choi et al.[80] evaluated the efficacy of intraoperative BCR monitoring in predicting postoperative voiding dysfunction among 153 adult patients undergoing posterior lumbar fusion surgery. That study found that patients with a preserved BCR had lower rates of voiding difficulties at discharge and follow-ups, while BCR loss was associated with an increased risk of voiding dysfunction. These study findings indicate that intraoperative BCR monitoring can provide valuable reference data for predicting the outcome of voiding function following spinal surgery.

CONCLUSION

The development and optimization of neurophysiological monitoring techniques using the various human reflexes as summarized in this review have progressed steadily. Some reflexes, such as the BR, LAR, and BCR, have recently been demonstrated to have significant clinical relevance for postoperative neurological outcomes, and so further applications of these tools worldwide can be expected. However, the usefulness of monitoring has been reported for only small numbers of cases, and so further studies are needed to validate the clinical significance of certain reflexes and to establish reliable and precise methodologies and warning criteria. The advancement and refinement of monitoring techniques by utilizing human reflexes will expand the application of intraoperative neurophysiological monitoring and further contribute to safer and more-successful surgical interventions.

Availability of Data and Material

Data sharing not applicable to this article as no datasets were generated or analyzed during the study.

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Conflicts of Interest

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