11 The H-Reflex and F-Response

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Introduction

Common electrophysiological recording modalities applied in the surgical setting include somatosensory evoked potentials (SSEPs), motor evoked potentials (TcMEPs), and electromyography (EMG). Central function is traditionally monitored with SSEPs and TcMEPs. Spinal nerve and nerve root function can be more easily assessed with EMG. While generally accepted to provide complete spinal cord protection, SSEPs are specific for the dorsal white matter tracts and the vascular territory of the posterior spinal arteries. The TcMEP is specific for monitoring descending white matter pathways of the lateral and anterior columns, but is also distinct in being the only routinely applied modality to monitor the integrity of the spinal gray matter. While useful in detecting gross changes in motor function as a result of spinal cord injury, TcMEPs do not monitor more complex spinal circuits including multisegmental, interneuronal, and propriospinal circuitry responsible for the control of voluntary movement. Furthermore, TcMEP monitoring has some contraindications and typically causes considerable patient movement and the risk of bite injury. Two other modalities, the Hoffmann reflex (H-reflex) and the F-response, have been proposed as valuable adjuncts to SSEPs and TcMEPs for monitoring spinal cord integrity during neurosurgical spine procedures [1].

The eponymously named Hoffmann reflex (H-reflex) is an electrical analogue of the tendon tap reflex. The H-reflex was first described in the early 1900s by Piper [2] and then further elaborated by Hoffmann [3], who described a long-latency muscular contraction in the triceps surae muscle in response to submaximal electrical stimulation of the posterior tibial nerve. The reflex was further studied in a series of papers in the 1950s by Magladery and colleagues, who first named this response for Paul Hoffman [4]. The H-reflex is still used in laboratory settings to assess neuronal organization and to interrogate the plasticity of spinal cord circuitry and in clinical practice to assess spinal reflexes, peripheral conduction velocity, and spasticity [5, 6].

Physiology of the Stretch and H-Reflex

The H-reflex is an electrically evoked response that operates via the same neuronal circuitry as stretch reflexes. In order to understand H-reflexes, it is best to review the basic physiology and

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anatomy of the standard monosynaptic stretch reflex (Fig. 11.1a). Monosynaptic stretch reflexes, sometimes referred to as deep tendon reflexes, are evoked by clinicians during standard reflex testing and can be generated at multiple points on the body by performing a tendon tap with a small rubber mallet. When the muscle is stretched via a tendon tap, stretch-responsive sensory neurons termed Ia afferents are activated. The cell bodies of these Ia afferent neurons are located in the dorsal root ganglion. The central process of these neurons sends a collateral that terminates on

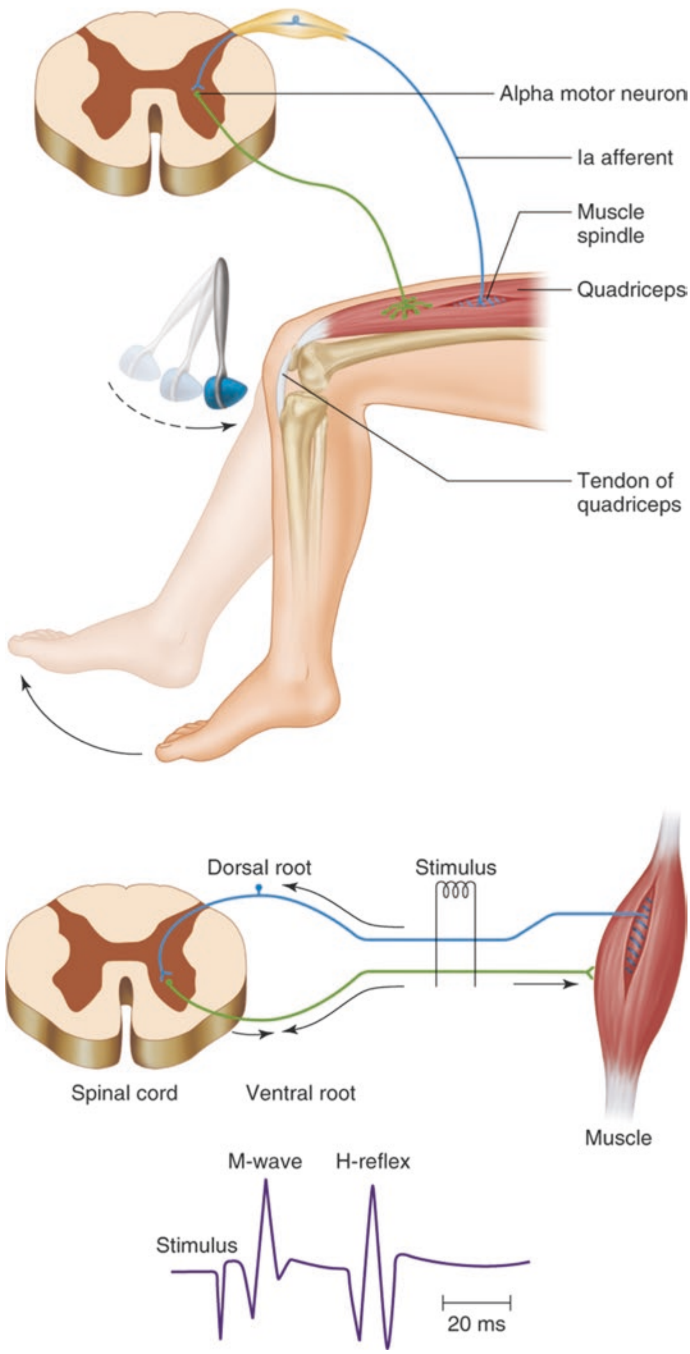

Fig. 11.1 The monosynaptic stretch reflex. (**a**) In response to rapid stretch, sensory Ia afferents activate alpha motoneurons in the ventral horns of the spinal cord, resulting in a delayed contraction of the muscle that was stretched. Clinicians make use of this response to test spinal cord reflexes. (**b**) The same pathways can be assessed intraoperatively using the H-reflex. A peripheral nerve is electrically stimulated, producing two responses that can be recorded with EMG. An early response, known as the M-wave, is elicited by direct activation of the muscle via motor axons. A later response, the H-reflex, is the result of activation of sensory Ia afferents, similar to what occurs when the muscle is stretched

alpha motor neurons in the ventral horn of the spinal cord gray matter. This synapse evokes a delayed contraction in the muscle from which the tendon reflex was initiated. The presence of a delayed muscular contraction in response to tendon tap as well as the latency of the muscular response can be evaluated in order to confirm the integrity of spinal cord reflexes. From a gross clinical perspective, the reflex is considered normal if an involuntary muscle contraction is observed after a slight delay following the tendon tap. The noticeable delay, or latency of the response, is a result of the fact that the signal must travel along sensory axons toward the spinal cord, synapse in the spinal cord, and then travel along motor axons back to the muscle before finally evoking a muscular response.

Electrically Evoked Responses

Unlike the stretch reflex that is detected by visual observation, EMG is used to record the M-wave, H-reflex, and F-response. In EMG testing, muscle contractions are recorded as compound muscle action potentials (CMAPs). Electrophysiological recordings afford the clinical scientist the opportunity to make precise measurements of latency, amplitude, and morphology (Fig. 11.1b).

Two physiological differences distinguish the H-reflex from the stretch reflex: (1) the H-reflex is evoked by electrical stimulation of a mixed motor and sensory nerve rather than by muscular stretch and (2) the H-reflex is activated proximal to the muscle and avoids entirely the muscle spindle fibers which, along with gamma motor neurons, play a role in modulating stretch-reflex gain. These factors make the H-reflex well suited to assessing spinal cord excitability [7].

The H-Reflex

Electrical activation of a mixed peripheral nerve creates an action potential that propagates in both directions along both sensory and motor axons (i.e., both ortho- and antidromically in afferent and efferent axons). The stimulation threshold for the H-reflex is typically low, and the reflex response is characterized by consistent latency between trials and simple morphology, leading to the conclusion that the reflex is mediated by large-diameter, monosynaptic Ia afferent fibers [5]. Despite this, there is some evidence for oligosynaptic components to the H-reflex response [6].

In humans, the CMAP response evoked by the lowest intensity stimulation is likely to be the H-reflex. The stimulus intensity where the H-reflex is first recorded is near or below the motor threshold, and therefore, an orthodromic motor response (M-wave) may not be recorded.

The H-reflex response is most like the muscle stretch reflex as it is evoked by the same process whereby a signal travels orthodromically along Ia sensory afferents toward the spinal cord, crosses the synapse onto alpha motor neurons, and then travels orthodromically along efferent motor axons to the muscle where it evokes a delayed muscular contraction [5]. Because of this similar route, it shares a similar characteristic delay with the stretch reflex. H-reflexes evoked at the popliteal fossa and recorded at the *soleus* muscle typically have a latency of ~30 ms, while those evoked at the cubital fossa and recorded at the *flexor carpi radialis* muscle have a latency of ~18 ms [8]. As with the stretch response, this delay is due to the longer route that this signal must take.

The M-Wave

As stimulation intensity is gradually increased, a shorter latency CMAP begins to appear in the recording. This response is termed the M-wave and is activated not through a reflex circuit but via the direct orthodromic transmission of an action potential along the motor axon to the neuromuscular junction. The stimulus intensity where the M-wave is first recorded is the termed the motor threshold. The M-wave response has the shortest latency because it is the simplest physiologically, being the result of the direct activation of the motor axon and subsequent transmission of an action potential to the neuromuscular junction, producing a contraction of the postsynaptic muscle. As stimulus intensity increases further, the H-reflex will peak in amplitude and then begin to decline as the M-wave increases. Near supramaximal stimulation intensities, the M-wave dominates the recording as its amplitude peaks and the H-reflex disappears altogether.

The F-Response

By the time stimulus intensity becomes supramaximal, a third CMAP response appears on the EMG recording with a similar latency to the H-reflex. Termed the F-response, this response is not a reflex but is generated by an action potential that travels first antidromically and then orthodromically along motor axons. As just explained, the initial orthodromic action potential generated by electrical stimulation will generate a short-latency response, the M-wave. However, the same motor axons will also generate antidromic action potentials that travel toward the spinal cord along the same axons. When the antidromic action potential reaches the motor neuronal pools, the majority of these action potentials will be abolished. However, some of these signals will survive to depolarize the cell body causing an orthodromic action potential to form and travel back down the same motor axons. This "backfiring" of the motor neuron results in a CMAP response in the EMG recording. The population of motor units recruited to produce an F-response will vary from trial to trial yielding variable amplitude, latency, and morphology. This is one way in which the F-response can be distinguished from the H-reflex [9].

Ordered Responses Explained

The H-reflex, M-wave, and F-response are recruited in an ordered manner by electrical stimulation of increasing intensity. This occurs because the excitability of axons when evoked by electrical current is directly related to their diameter and input resistance; the largest axons will be recruited by the lowest stimulus intensity [10]. The largest diameter axons in a mixed peripheral nerve are the Ia afferent axons responsible for carrying the sensory action potential which initiates the H-reflex. The second largest group of axons are those of the alpha motor neurons, especially those that innervate larger, fast-twitch fatigable motor units in skeletal muscle. There is some overlap in the diameters of these axons, which explains why there is also some overlap in the intensities at which the M-wave and H-reflex are recorded. Nevertheless, the H-reflex is typically first noted at stimulus intensities that are subthreshold for the M-wave.

Advantages of the H-Reflex

Because H-reflexes are single-sweep and do not require averaging they offer a real-time test, similar in this respect to TcMEPs. They are also like TcMEPs in that they involve spinal cord circuitry in the gray matter; however, unlike TcMEPs they can be run without having to pause or interrupt the surgery as they produce little or no detectable movement. Furthermore, they have been shown to be stable with anesthetic regimens commonly employed to allow intraoperative monitoring [11].

Perhaps the greatest physiological advantage of H-reflexes is that they can be used to assess not just the nerve roots through which the afferent and efferent signal travels but complex suprasegmental, propriospinal, and interneuronal circuitry that affects the reflex arc both pre- and postsynaptically [6]. When evoked by stimulation of the posterior tibial nerve at the popliteal fossa, or the median nerve at the cubital fossa, H-reflexes can be minimally understood to be providing information about the integrity of S1 and C6/C7 nerves and nerve roots, respectively. However, the potential advantage of H-reflex monitoring is that it may provide a way of monitoring the integrity of a much larger network of suprasegmental spinal cord circuitry. Leppanen has speculated that the loss of H-reflexes following spinal cord trauma may have to do with uncoupling of the central pattern generator in humans and the disruption of inputs onto segmental afferents, yielding a change in reflex gain [8]. Although this is an intriguing hypothesis, it is difficult to be certain about the specific mechanisms of H-reflex suppression in humans following spinal cord trauma.

Two reports using H-reflexes in the operating room have described H-reflexes as being remarkably sensitive to intraoperative events. Standard surgical maneuvers such as hammering with a mallet, distraction, and derotation of the spine resulted in transient decreases in H-reflex amplitude [12, 13]. This decrease in H-reflex amplitude was repeatedly observed across multiple procedures and was correlated with stressful spinal manipulations and perturbances of the spinal cord. The authors of this chapter have observed similar decreases in H-reflex amplitude correlated with spinal corrections or EMG bursts observed during posterior decompressions (Fig. 11.2). A more recent case study involving severe scoliosis correction reported loss of both TceMEP and H-reflex signals following a hypotensive event [14]. The physiological signals recovered following re-establishment of baseline mean arterial pressure.

Practical CONSIDERATIONS

Anesthesia

As with other intraoperative modalities, H-reflex and F-response data can be compromised by anesthetic regimens that are not optimized to provide the best environment for achieving valid neurophysiological results. Critically, H-reflexes and

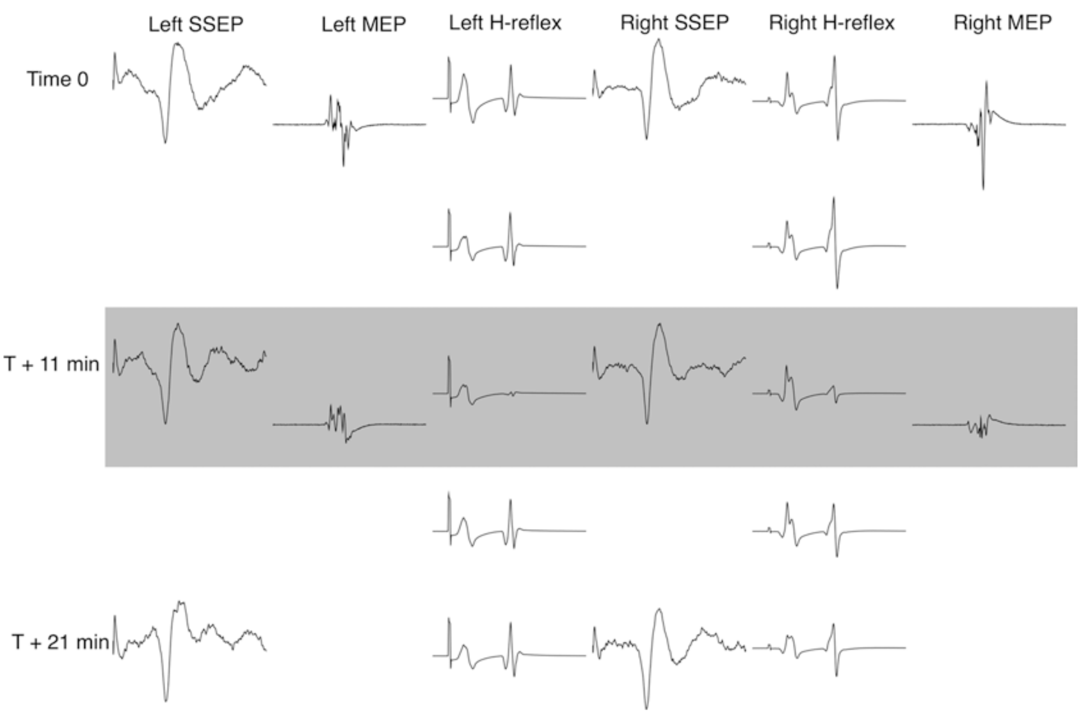

Fig. 11.2 The H-reflex is sensitive to spinal irritation. Displayed signals were gleaned during a complex scoliosis correction in an 18-year-old male. SSEP and H-reflex tests were gathered at regular intervals, while the TcMEP was run as often as practical, in communication with the surgical team. Pictured signals include bilateral cortical SSEPs evoked from the posterior tibial nerve, bilateral H-reflexes recorded at the *soleus* muscle, and bilateral TcMEPs recorded at the *abductor hallucis* muscle. During osteotomy, a large EMG burst (not shown) was observed across multiple lower limb muscles bilaterally in response to a distinct hammer strike upon the osteotome. The surgical team noted the same response as a brief but large patient spasm and requested TcMEPs to be tested. H-reflexes were significantly diminished for a period of approximately 5 min bilaterally. SSEPs remained undiminished while TcMEPs were diminished in amplitude but remained present in all recorded muscles bilaterally. Both H-reflexes and TcMEPs were determined to be unchanged from baselines at close and the patient awoke with no deficit

F-responses rely upon accurate recordings of muscular contraction via EMG. As such, they are strongly affected by paralytics applied during surgery. Neuromuscular blocking agents will diminish or even abolish the CMAP responses evoked as H-reflexes or F-responses. Interpretation of H-reflexes and F-responses should take into account the degree of neuromuscular blockade.

H-reflexes are modified by complex multisegmental, propriospinal, and interneuronal spinal networks [6]. Commonly applied anesthetics can alter the excitability of these networks, potentially yielding invalid results. H-reflex and F-response amplitudes are diminished significantly by the use of inhalants such as isoflurane and nitrous oxide [15]. Furthermore, H-reflex amplitudes show a concentration-dependent suppression in response to sevoflurane or propofol anesthesia [16, 17]. The same authors argue that both propofol and sevoflurane cause an increase of presynaptic Ia inhibition, a likely cause of H-reflex suppression [18, 19].

Previous authors have made suggestions regarding the limits of various anesthetic regimes whereby H-reflexes and F-responses are likely to remain valid [8]. The authors of this chapter can attest that H-reflexes and F-responses can be readily evoked by most anesthetic regimens that are appropriate for EMG, SSEP, and TcMEP monitoring, including total intravenous anesthetic, a mixture of volatile inhalants and propofol/remifentanil, or the use of up to 1.0 MAC of volatile inhalants. Although H-reflexes and F-responses are suppressed by these regimens to one degree or another, the stability of the H-reflex with stable anesthetic conditions has been established [11].

Stimulation Characteristics

Intraoperative H-reflexes are primarily evoked from *soleus* and *flexor carpi radialis* muscles in response to popliteal fossa and cubital fossa stimulation, respectively (Fig. 11.3). Stimulation can be achieved using needles or pads in a bipolar configuration or by placing the cathode in the popliteal/cubital crease with the anode placed on the opposite side of the joint [20]. The authors of this chapter have had considerable success with the latter, cross-joint stimulation configuration and prefer it, although it typically requires a higher stimulus intensity to evoke a H-reflex. The H-reflex is optimally activated by single pulses with relative long stimulus pulse widths of 0.5–1.0 ms. The stimulus pulse is typically monophasic and relatively low intensity. Although the first H-reflex response can often be elicited at a stimulus intensity below 10 mA, it is difficult to prescribe a specific stimulus intensity due to variables related to the individual patient and the selection of needle or pad electrodes for stimulation. Nevertheless, it can be said that the stimulus intensity to elicit a maximal H-reflex response should be near or even below the motor threshold.

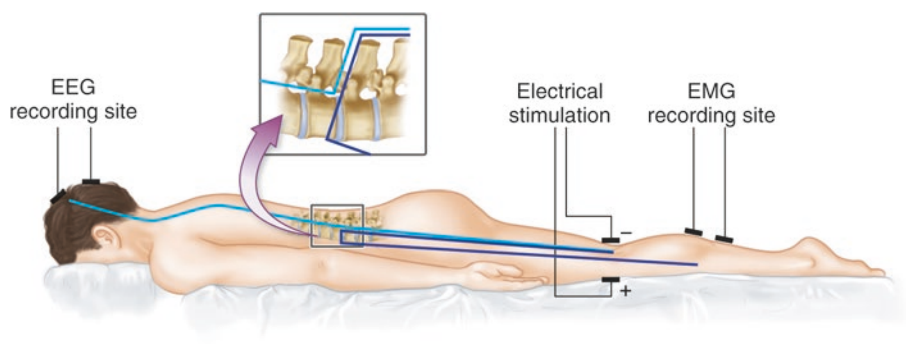

Fig. 11.3 Configuration of H-reflex testing. H-reflexes are most easily recorded from soleus muscle but can be recorded from multiple lower limb muscles in response to stimulation of the posterior tibial nerve at the popliteal fossa. Recording is typically bipolar at the soleus muscle. Stimulation can be bipolar at the popliteal fossa or monopolar across the joint as pictured above

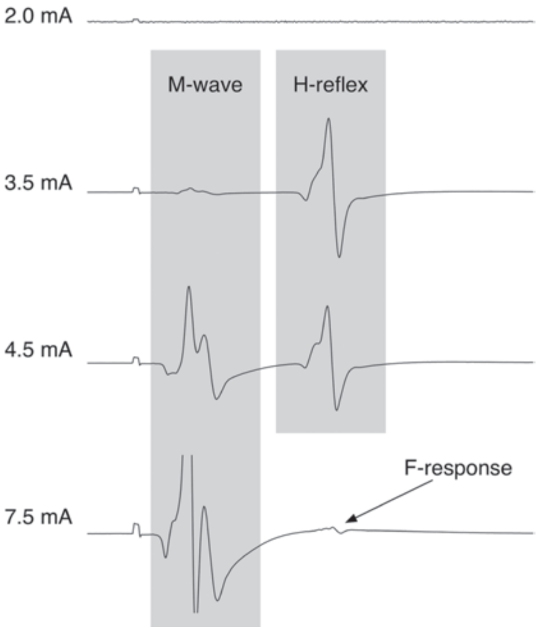

Fig. 11.4 Optimizing the H-reflex response. H-reflex amplitude will be affected by changing stimulus intensity. At low intensities the M-wave will be absent and a small H-reflex will appear. As stimulus intensity is gradually increased the H-reflex will peak in amplitude before declining as the M-wave comes to dominate the recording. F-responses can be noted at a similar latency to the now absent H-reflex

As stimulus intensity is increased, the H-reflex will reach maximal amplitude and then decline as the M-wave increases to its maximum (Fig. 11.4). Stimulus intensity should be chosen at the beginning of a procedure in order to maximize the H-reflex amplitude. Multiple H-reflex trials should be attempted in order to determine the stimulus intensity at which the H-reflex amplitude is maximized. Individual pulses should not be applied at intervals less than 1 pulse every 2.0 s (0.5 Hz stim rate). Some authors have even suggested that H-reflexes may be depressed by stimulating more often than once every 10 s [5, 21].

Recording Characteristics

In diagnostic or research settings, the soleus muscle is often selected for recording the lower limb H-reflex [7]. Commonly, one electrode is placed at the mid-calf, just distal to the bifurcation of the medial and lateral lobes of the *gastrocnemius* muscle. However, the medial gastrocnemius is also often targeted with bipolar needle electrodes over the medial aspect of the upper one-third of the calf [8]. We often use a referential EMG configuration with one needle over the *medial gastrocnemius* muscle and one over the *soleus* muscle. Recordings for the lower limb are single-sweep with a total sweep time of 50–100 ms. The medial gastrocnemius H-reflex response typically has a latency of ~30 ms, measured from the stimulus pulse onset, while the M-wave latency is closer to 15 ms or less. These numbers can vary with patient height or with conditions that affect peripheral conduction velocity. Since the M-wave, H-reflex, and F-response are recorded by EMG as CMAPs, the filter settings are similar to those used for free-running or triggered EMG. The high- and low-pass filters should be 3–30 Hz and 3–10 kHz, respectively. Notch filters to remove 60 Hz mains noise should generally be avoided.

Recognizing the H-Reflex

When reviewing an EMG recording for potential H-reflex responses, the neurophysiologist should keep in mind the characteristics of the H-reflex. The H-reflex response should be of appropriate latency as discussed above, have a short duration, simple morphology, high amplitude relative to the M-wave, and should be characterized by stability across multiple trials. After consideration of the latency and amplitude of the recorded CMAP, the M-wave should be immediately distinguishable from the H-reflex. In contrast, the F-response may be confused with the H-reflex due to their similar latencies. However, the F-response differs in a number of key ways. Firstly, the amplitude of the F-response is typically considerably less than that of the H-reflex. Secondly the F-response is less stable than the H-reflex with respect to latency, amplitude, and morphology. Finally, the amplitude of the corresponding M-wave CMAP recorded along with the F-response is much larger than that which would typically be recorded with a H-reflex. This indicates supramaximal stimulation of the nerve, a condition that typically precludes the recording of H-reflexes. Other authors have noted that the H-reflex response at its peak will typically reach 50–100% of the M-wave amplitude [22].

Assessing the H-Reflex

While sometimes used intraoperatively, there are no universally accepted criteria for interpreting H-reflex data. In addition, only a handful of primary papers have been published containing intraoperative H-reflex data [11–13, 23, 24]. This makes the establishment of alarm criteria difficult. Factors that can be monitored for change include peak-to-peak amplitude, latency of the response, and the ratio of the maximal H-reflex to maximal M-wave amplitude [25]. Although these elements can all be monitored, no objective criteria have been described relating to what would constitute an alarming alteration of these values. Nevertheless, the H-reflex has been described as remarkably stable given stable anesthetic conditions [11, 12]. As such, the authors of this chapter recommend that H-reflexes be established at the beginning of a procedure and monitored for changes throughout the operation. Lacking any objective criteria, a decrease in amplitude of greater than 50% and an increase in latency of greater than 10% are reasonable and accepted criteria to use when deciding whether or not to communicate a change to the surgical staff. H-reflex changes correlating with changes of either SSEP or TcMEP are particularly alarming. Currently, the clinical utility of the F-response remains under investigation.

Troubleshooting the H-Reflex

As mentioned above, H-reflexes are recorded as an EMG response and are not recordable in the presence of neuromuscular blocking agents. Accordingly, a train-of-four test should be used to inform the neurophysiologist of the level of paralysis. If H-reflexes prove unobtainable at any point during the procedure, a train-of-four can eliminate neuromuscular blockade as a cause of signal loss.

It is not uncommon for the optimal stimulation intensity to vary during a surgical procedure. If the amplitude of the H-reflex or the maximal H-reflex to maximal M-wave ratio should decrease during the procedure, the first step should be to increase or decrease the stimulus intensity through multiple trials in order to optimize the H-reflex CMAP amplitude. The goal when testing H-reflexes should be to adjust the stimulus intensity to produce the maximal H-reflex response. The optimal stimulation intensity can drift by a few milliamps and may need to be retested. This could simply be due to a change in resistance of the stimulating electrodes.

Conclusion

The H-reflex is a useful tool for monitoring spinal cord excitability in the surgical suite. It can be run without disturbing the surgical staff, it does not require placing any electrodes beyond those commonly placed for more routine spinal cord monitoring modalities, and the response appears to be effected by anesthesia similarly to SSEP and TcMEP monitoring. Nevertheless, H-reflexes and F-responses are one of the least well-studied modalities applied intraoperatively. Unfortunately, only a handful of papers containing primary data exist. Moving forward, it will be necessary to further characterize these responses intraoperatively in order to continue to assess their value and to establish reliable alarm criteria for transmitting a warning to the surgical staff.

Review Questions

1. What are the characteristics allowing for recognition of the H-reflex recording in humans?
2. When is the physiological basis for the F-response?
3. What advantages might intraoperative H-reflex monitoring offer to the clinician?
4. At what thresholds are the M-wave, H-reflex, and F-response evoked?

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