Electrodiagnostic Evaluation (24-Feb-2003)

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**Physiological Basis for Electrodiagnostic Studies**
- Resting Membrane Potentials
  - Action Potentials
    - Action Potentials in Single Cells
    - Compound Action Potentials
  - Postsynaptic Potentials

**Technical Aspects of Recording Electrical Activity**
- Differential Amplifier: Digital and Analog
- Volume Conduction and Electrode Types
- Volitional, Spontaneous and Evoked Activity
- Triggered and Non-triggered Signals
- Signal Averaging
- Calibration
- Audio Monitoring

**Electrical Activity in Muscle**
- Voluntary Activity in Muscle
  - Motor Unit Potentials
  - Interference Patterns
- Spontaneous Activity in Muscle
  - Miniature End-Plate Potentials
  - Insertion Potentials
  - Fasciculation Potentials
  - Fibrillation Potentials
  - Positive Sharp Waves
  - Complex Repetitive Discharges
  - Myotonic Discharges
  - Compound Muscle Action Potentials
  - Electrically Evoked
  - M wave
  - Nerve Conduction Velocity
  - F wave
  - Reflexively Evoked Potential
  - H wave
  - Single-Fiber Potentials

**Electrical Activity in Peripheral Nerves**
- Spontaneous Activity in Nerves
  - Electroneurography
  - Evoked Activity in Nerves

**Electrical Activity in the Central Nervous System**
- Spontaneous Activity in the Brain
  - Electroencephalography
  - Electroencephalogram (EEG)
- Evoked Activity in the Spinal Cord
  - Spinal Cord Evoked Potentials
  - Evoked Activity in the Brain
  - Brainstem Auditory Evoked Responses
  - Middle and Late Latency Auditory Evoked Responses
  - Somatosensory Evoked Potentials
  - Visual Evoked Potentials
  - Evoked Activity in the Retina
  - Flash Electroretinogram
  - Electroretinogram (ERG)
  - Oscillatory Potentials
  - Pattern Electroretinogram

Electrodiagnostic procedures have contributed to the certainty of diagnosis of a variety of neurological and neuromuscular diseases in animals. Widespread use of electrodiagnosis is limited by equipment costs and training of personnel. However, many of these procedures are used routinely in case work-ups in veterinary colleges or specialty practices. The purpose of this chapter is to present a brief review of the basic electrophysiology and methodology for a wide range of electrodiagnostic techniques. Examples of normal and abnormal recordings are presented, but the reader is referred to the literature for more specific information [1-22] or detailed descriptions of electrodiagnostic findings in specific neurological diseases. In addition, the American Association of Electrodiagnostic Medicine (www.aaem.net) provides instructional materials and courses on electromyography at both basic and advanced levels.
Action Potentials
When sufficiently intense stimuli are applied to excitable cells, either nerve or muscle, the membrane potential reverses (depolarization) and then spontaneously recovers (repolarization). These changes are brought about by the influx of sodium (depolarization) followed by the efflux of potassium (repolarization). Ion fluxes are initiated by alterations in membrane permeabilities associated with changes in specific ion channels located within the membrane. The tendency for sodium and potassium to travel down their electrochemical gradients through open channels is the basis for the action potential that is propagated along the axolemma (by continuous or saltatory conduction) or along the sarcolemma.

Compound Action Potentials
- When excitable cells are simultaneously active, a compound action potential may be recorded. The amplitude of a compound potential is a reflection of synchrony. Similar cells that discharge simultaneously will produce a brief duration whereas a long duration will be caused by dissimilar cells discharging synchronously or similar cells discharging asynchronously. In electrodiagnostic recordings, the terms potential or response may be used to refer to a recording of a single action potential, a compound action potential, or a combination of action potentials and postsynaptic potentials.

Postsynaptic Potentials
The usual means of communication between excitable cells is the synapse. A synapse between a neuron and a skeletal muscle cell is called the myoneural or neuromuscular junction. In response to neurotransmitters, postjunctional membranes in neurons may produce excitatory postsynaptic potentials (EPSP) or inhibitory postsynaptic potentials (IPSP). Postjunctional excitation in a skeletal muscle, in response to the release of acetylcholine by the motor axon terminal, is referred to as an end-plate potential (EPP). The EPP is a local, non-propagated potential. Postsynaptic potentials are also a source for bioelectric activity that can be recorded with surface or needle electrodes.

Technical Aspects of Recording Electrical Activity

Differential Amplifier: Digital and Analog
Because bioelectrical signals are so small, some form of amplification is required. Amplification of biological signals is commonly achieved with a differential amplifier. This type of amplifier has two inputs; the magnitude of the output represents the difference between the inputs. For many electrodiagnostic procedures, the inputs are provided by an active electrode and a reference electrode. The active electrode is placed near the activity to be recorded and the reference is placed in a distant inactive area. Because the differential amplifier attenuates activity that is common to both inputs, it helps to eliminate unwanted background electrical activity or "noise" which is a source of artifact. Bioelectric events are usually recorded in one of two forms, analog or digital. The output of an amplifier may be routed to a pen-writing recorder or oscilloscope; the display is an analog of the original physiological activity. Such a device presents the activity continuously in time. Discrete and discontinuous sampling of events at a predetermined rate is the first step toward recording information in digital form. One important advantage of the digital format is that high speed mathematical operations can be performed on the data during or after the recording. Digitally recorded potentials can be stored on computer and reconstructed later.

The frequency range over which an amplifier can amplify biopotentials without distortion is called its frequency response. High and low frequency filters allow the frequency response to be adjusted for optimal recording of the response. These filters attenuate unwanted noise with frequencies below and above the low and high frequency settings. For each type of electrodiagnostic procedure, the appropriate filter settings should be utilized consistently. Improper settings can alter the amplitude, shape and/or latency of responses. Differences in these settings among laboratories make comparisons of results more difficult.
Volume Conduction and Electrode Types
Many of the bioelectric events described in this chapter are recorded at a distance (far-field) from the generators of the actual activity. The generator is the source of the current, and the surrounding tissue and fluids are the volume through which it is conducted. Selection of the proper electrode is critical to successfully recording any bioelectric event. Surface electrodes can be difficult to apply to the skin of animals, although adhesive electrodes, metal disc electrodes and alligator clips have been used. Needle electrodes are commonly used. Needle electrodes can be placed subcutaneously or can be inserted deeper into muscle or placed near nerves. Monopolar electrodes are referenced to a second electrode at another site. With concentric electrodes, the active electrode is embedded in the core of the needle and insulated from the shaft which serves as the reference. Bipolar electrodes have both the active and reference electrode embedded within the core of the needle. Other specialized types of electrodes include contact lens electrodes for electroretinography.

The interface between the recording electrode and the tissue creates resistance to electrical current. Because of the types of circuits involved in electrodiagnostic recording systems, this type of resistance is more properly termed **impedance**. The impedance of the electrode-skin interface should be kept as low as possible and should be evenly matched between recording and reference electrodes in order to avoid **impedance mismatch**. This precaution, together with a high input impedance of the recorder, provide for the reliable recording of biopotentials.

Volitional, Spontaneous and Evoked Activity
Electrical activity recorded from excitable tissue can be voluntary, spontaneous or evoked. Voluntary activity occurs when an animal consciously performs some activity, such as moving a limb. Spontaneous activity can be recorded without voluntary participation or the use of an external stimulus, for example, electroencephalograms. Evoked responses (or "evoked potentials") represent the electrical response to an external stimulus, typically delivered at a specific intensity and rate (frequency). With such exceptions as testing of olfactory, visual, and auditory systems, most evoked responses are elicited by short pulses of electric current.

Triggered and Non-triggered Signals
For evoked potentials, amplifiers are triggered by the stimulus to begin recording for a preset period of time, termed the **analysis time**. In some protocols, a delay circuit is used to begin the recording at a fixed time after stimulus application. The time that the amplifier records activity is sometimes referred to as the **window**. A recording of spontaneous activity usually requires a wider recording window.

Signal Averaging
Many evoked responses are extremely small, with a poor signal-to-noise ratio. Signal averaging is a widely used technique to enhance the biopotential and reduce noise. If multiple responses are electronically averaged, the amplitude of the evoked response is increased in direct proportion to the number of samples. The background noise, which is random, is decreased by the square root of the number of responses. The number of repetitions that need to be averaged is determined by factors such as the response amplitude and the amount of noise. Although a set number of repetitions may be used in a protocol, it is up to the examiner to determine when an optimal response has been recorded. Higher numbers of repetitions do not equate with higher quality of recording. In some instances, the use of large numbers of repetitions can diminish the quality of the recording.

Calibration
The biopotentials discussed in this chapter are primarily rapidly occurring, low amplitude signals. Because many are far-field recordings, they are much smaller than the potentials recorded directly from single cells with microelectrodes. Most electrodiagnostic equipment is designed to record potentials in the millivolt (mV) and microvolt (µV) range. Time calibrations are usually in milliseconds. Most equipment provides on-screen cursors and computer programs that enable accurate measurements.

Audio Monitoring
For needle electromyographic (EMG) examinations, audio monitoring of signals is utilized. Biopotentials are taken from the system amplifier and fed to an audio amplifier and a speaker. Some specific EMG potentials, such as fibrillation potentials, have distinctive sounds by which they can be identified.

Electrical Activity in Muscle
Voluntary Activity in Muscle
Motor Unit Potentials - Electromyography (EMG) is the study of electrical activity in nerve and muscle. The basic functional
unit of normal skeletal muscle is the **motor unit**, which consists of a ventral horn cell (also termed a **lower motor neuron**, LMN) and the muscle cells (myofibers) which are innervated by its motor axon. When a LMN is activated, an action potential is propagated along its axon (motor nerve fiber), chemically recreated at end-plates, and then propagated along muscle cell membranes prior to muscle contraction. The composite electrical activity in muscle cell membranes in a motor unit is called a **motor unit potential** (MUP). Typical MUPs recorded from a dog with a monopolar electrode are shown in (Fig. 1). The size of a single MUP depends upon the type and size of the motor unit and the proximity of the unit to the recording electrode.

Electromyograms are often recorded in anesthetized or tranquilized animals to eliminate unwanted volitional activity and movement artifacts. Stoic animals and debilitated animals often will tolerate needle EMG examination provided the examiner is patient and handles the animal carefully. Volitional movement may be induced by reflexes or weight shifting. In some neurogenic diseases, MUPs can have an increase in duration and amplitude due to increased innervation ratios caused by collateral sprouting and reinnervation. These unusually large MUPs are referred to as **giant motor unit potentials**. The clinical interpretation of alterations in the duration, amplitude and shape of MUPs is part of the training for personnel who perform EMG. Recently, EMG has been incorporated into the technique for the administration of botulinum toxin (Botox). In these cases, EMG is used to pinpoint the site of botulinum toxin injection at the end plate region within the muscle [23].

**Interference Patterns** - Normal volitional muscle contraction is brought about by the activation of large numbers of motor units. **Recruitment** is the process of adding motor units to ones that are already active in order to increase the force of contraction. The pattern of muscle contraction during normal physiologic activity is called an **interference pattern** because the individual MUPs "interfere" with each other in a recording (Fig. 2).

Depending upon the intensity of muscle contraction, the interference pattern may be **complete or incomplete**. The interference pattern can be recorded from specific muscles with intramuscular monopolar needle electrodes or fine wire electrodes. Both types of electrodes are insulated except for the tip of the needle or wire. The characteristics of the interference pattern can aid the clinician in determining whether the disorder is myopathic or neuropathic. For instance, in peripheral neuropathies, the interference pattern tends to be reduced.

**Spontaneous Activity in Muscle**

Spontaneous activity in muscle, when it occurs, may be initiated in the LMN, the nerve root, the peripheral axon, the end-plate, or the muscle membrane itself. If skeletal muscle is not volitionally or reflexively activated, it is electrically quiescent. Most spontaneous activity is indicative of neuromuscular abnormalities.

**Miniature End-Plate Potentials** - Each skeletal muscle cell is innervated by a single branch of the LMN axon at a synapse referred to as the **end-plate**. In the absence of LMN activation, spontaneous activity in muscle is only recorded at locations within muscle where there is a high concentration of end-plates. These electrical discharges may be recorded by needle electrodes as **end-plate noise** which consists of large numbers of **miniature end-plate potentials** (MEPP). The electromyographer should be careful to distinguish between normal end-plate noise and fibrillation potentials.

**Insertion Potentials** - Other than end-plate noise, normal muscle membranes are electrically silent if there is no LMN activity. However, when a needle electrode is inserted into or moved in a normal healthy muscle, it is accompanied by electrical activity called **insertion potentials**. Insertion potentials are caused by the mechanical stimulation of muscle fibers and usually cease when needle movement ceases. As described below, insertion potentials may be prolonged in neuropathic or myopathic disorders and mixed with other abnormal potentials such as positive sharp waves and fibrillation potentials. Insertion potentials may be reduced in severely atrophied muscle or muscle with fibrosis.

**Fasciculation Potentials** - **Fasciculation** is the spontaneous twitch that occurs when motor units or parts of neighboring motor units discharge. Electrically, fasciculations have durations, amplitudes and other characteristics similar to MUPs.
Fasciculations are likely caused by ephaptically activated muscle fibers ("cross-talk") as a result of discharge in pacemaker fibers in either nerve or muscle. Fasciculations can sometimes be observed through the skin. Fasciculation can be seen in a variety of diseases affecting nerve and muscle, and infrequently in degenerative diseases affecting the spinal cord gray matter.

**Fibrillation Potentials** - Fibrillation potentials (FP) are spontaneous bi- or triphasic potentials that occur in neurogenic and myopathic disorders (Fig. 3). Fibrillation potentials represent the discharge of single muscle fibers. The sound of these potentials from a loudspeaker has been likened to "eggs frying" or "rain on a tin roof".

This potential is a consistent electrical hallmark of partially or completely denervated muscle. The amplitude of fibrillation potentials ranges from 50 - 350 µV with durations of 1 - 2 msec. In cases of nerve damage, FPs do not occur immediately after denervation. Instead, FPs appear in the denervated muscle after a latent period that is proportional to the length of remaining axons distal to the site of a nerve lesion. Their onset may be preceded by periods of increased insertional activity. Once these potentials appear in denervated muscle, their rate of occurrence increases over a period of several weeks, and they persist until muscle is reinnervated or until no viable muscle fibers remain. Fibrillation potentials are also seen in myopathic disorders such as muscular dystrophies, polymyositis, and dermatomyositis. Their origin is related to oscillating membrane changes or irregular prepotentials caused by membrane instability. In neuropathies characterized by demyelination rather than axonal degeneration (Wallericn degeneration), FPs tend to be absent.

**Positive Sharp Waves** - Positive sharp waves (PSWs) are characterized by an initial positive phase followed by a more gradual negative-going phase (Fig. 4). Although these potentials make a lower pitched sound than fibrillation potentials and usually have a lower discharge rate, they are currently considered to represent a type of fibrillation potential.

**Complex Repetitive Discharges** - Complex repetitive discharges (formerly named bizarre high frequency discharges or pseudomyotonic discharges) consist of polyphasic potentials that discharge spontaneously at a high frequency. Within the train of discharges, each potential may have the same morphology (Fig. 5).

Such behavior suggests the presence of pacemaker muscle fibers that oscillate. The onset is often associated with needle movement and the discharges start and stop abruptly. These potentials can occur in a variety of neuromuscular disorders and suggest that the animal has a chronic condition. Although these potentials were referred to as pseudomyotonic potentials at one time, they do not wax and wane in amplitude and frequency as do true myotonic potentials. From the loudspeaker of the electromyograph, these discharges have continuous high-pitched motor-like sounds.

**Myotonic Discharges** - Myotonic potentials occur in muscle as a result of abnormal permeability in muscle fiber membranes. Muscles continue to be electrically activated even after the cessation of volitional contraction. These high frequency (100 to 200/sec) potentials spontaneously wax and wane in amplitude and rate in an EMG pattern that has become the electrical signature of myotonia. In addition to normal presynaptic nerve activity, the onset may be precipitated mechanically such as with percussing the muscle or by EMG needle movement. Spontaneous activity may last for a second or more. In some types of myotonia, the repetitive discharges may be explained by altered chloride conductance in muscle membranes while in other types, the malady may be related to a disorder in sodium conductance. Audio monitoring of myotonic potentials reveal a
characteristic EMG sound, referred to as *dive-bomber potentials*.

**Evoked Activity in Muscle**
Skeletal muscle activity is usually evoked by electrical stimulation of motor nerves with intramuscular needle or surface electrodes as recording electrodes. In other evoked responses, receptors are physiologically stimulated and muscles are reflexively activated. Muscle activity may also be produced by transcranial electrical or magnetic stimulation of the motor cortex.

**Compound Muscle Action Potentials**

*Electrically Evoked* - When the motor nerve to a muscle is supramaximally stimulated with electrical current, motor units are activated as their nerve fibers reach threshold. When many fibers are simultaneously active, a compound muscle action potential (CMAP) can be recorded.

This potential is also referred to as the muscle response (**M response** or **M wave**). Depending on the specific muscle and recording electrodes, the amplitude of the M wave in dogs can range from a few to over a hundred millivolts (mV) and is proportional to the number and size of the discharging fibers. Figure 6 illustrates a latency period followed by the M wave in an interosseous muscle. The latency of the M wave is proportional to the distance between the muscle and the stimulating electrode location along the peripheral nerve. The duration is a reflection of synchrony, i.e., how closely muscle fibers discharge in time. For any given nerve, the further away from the muscle its motor nerve is stimulated, the longer the duration of the M wave and the lower the amplitude.

If a peripheral motor nerve is stimulated at two predetermined locations and CMAPs recorded for each stimulus, the **nerve conduction velocity** (NCV) can be calculated (Fig. 7).

| Table 1. Estimates of Motor Nerve Conduction Velocities (mean, meters per second) in Dogs and Cats at Different Ages |
|------------------|------------------|------------------|------------------|
|                  | Sciatic-tibial Nerve | Ulnar Nerve |
| **Age**          | **Dog** | **Cat** | **Dog** | **Cat** |
| 3 months         | 37      | 70      | 42      | 62      |
| 6 months         | 53      | 95      | 54      | 84      |

Dividing the difference (in mm) between the proximal and distal stimulation sites by the difference (in msec) between proximal and distal CMAP latencies gives the NCV (in mm/msec or m/sec). Using this technique in dogs, NCV range from approximately 50 - 90 m/sec, depending on the peripheral nerve tested. In addition, cranial nerves can be evaluated with EMG techniques [24].

Normal values for NCV are age-dependent. Adult values for NCV are attained by approximately 6 - 9 months of age in dogs and begin to decline in dogs over approximately 8 years of age (Table 1). Each laboratory should establish that their normal values are in accord with values reported in the literature [20].
When electrical current is applied to peripheral nerves, large nerve fibers reach threshold more easily than small fibers. The greater cross-sectional area of larger fibers offers less resistance to current flow than smaller fibers. In addition, large peripheral nerve fibers are capable of discharging at a faster rate than small fibers. Fiber size, myelination, and internodal distance are the key factors in determining conduction velocity—the larger the fiber, the faster the velocity. Nerve conduction velocity is always determined by the large fibers, even if there are fewer than normal present. For this reason, it is not unusual to find normal NCV during the early phases of demyelination, incomplete demyelination, or axonal degeneration. The distal stump of a completely transected axon will continue to conduct electrical impulses for a period of time that is roughly proportional to the distance between the injury and the muscle. During the interval of several days between damage and cessation of function, the CMAP duration will increase and the amplitude will decrease. The amplitude and duration of the CMAP may also be altered in any abnormality of the neuromuscular junction such as botulism. An extensive amount of data on CMAPs are available in the literature [1,6,13,21].

If a peripheral nerve is stimulated repetitively, the resultant CMAP will maintain its amplitude as long as the stimulation rate is not too high. In myasthenia gravis, a disease that affects the neuromuscular junction, the CMAP will show a decrement even at low rates of stimulation. The electrodiagnostic support for myasthenia gravis is a decrement in the CMAP of 10% or more using a stimulation rate of 2 - 3/sec.

When a peripheral nerve is stimulated electrically, nerve fibers conduct impulses in both directions from the point of stimulation. Orthodromic conduction in motor nerve fibers will produce a CMAP. Antidromic conduction may re-excite the lower motor neuron. When this happens, a second volley of nerve impulses will produce a second smaller CMAP referred to as an **F response** or **F wave**. The latency of the F wave will depend upon the distance from the point of stimulation to the CNS and the distance from the participating LMN to the muscle. The F wave requires that the peripheral nerve proximal to the point of stimulation and ventral roots be functional. Analysis of the F wave can aid in the diagnosis of radiculopathy [25]. Various equations have been suggested to assess F waves, but the most straightforward method is to determine F wave latency with the stimulating needle at a standardized position and compare the latency to the normal range for dogs with similar limb length.

Central pathways that innervate lower motor neurons can be evaluated by stimulation of the motor cortex and recording **motor evoked potentials (MEPs)** from the spinal cord, peripheral nerves, or skeletal muscles. Direct stimulation has been accomplished with transcranial electrical current (Fig. 8) or electromagnetic pulses.

<table>
<thead>
<tr>
<th>Age</th>
<th>Scatic-tibial Nerve</th>
<th>Ulnar Nerve</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Dog</td>
<td>Cat</td>
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<tr>
<td>1 - 8 years</td>
<td>62</td>
<td>95</td>
</tr>
<tr>
<td>9 years</td>
<td>57</td>
<td>94</td>
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<td>14 years</td>
<td>48</td>
<td>80</td>
</tr>
<tr>
<td>16 years</td>
<td>39</td>
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</tr>
</tbody>
</table>

Modified from: Swallow JS and Griffiths IR. [20] and Pillai et al. [34].

- For details, including mean and standard deviation values and ranges, consult the above references.
- Individuals should confirm these values in healthy animals in their own laboratories in order to establish their normal range.

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![Figure 8](image-url)
Whereas the somatosensory evoked potential (see below) primarily monitors activity in the dorsal columns, MEPs utilize areas of the spinal cord that have a different blood supply. Cortical stimulation may cause bilateral responses in nerve and muscle, but the contralateral response has the lower threshold. Studies in animals and human beings have revealed that MEPs may be more sensitive than somatosensory potentials for assessing acute or chronic spinal cord injury.

**Reflexively Evoked Potential** - An electrical stimulus delivered to a peripheral nerve will excite sensory fibers, especially the large IA afferent fibers from muscle spindles. Impulses in these fibers monosynaptically excite the LMN, thus producing a second smaller CMAP which is called the H reflex or H wave. This is equivalent to elicitation of a myotatic reflex such as the patellar reflex. The latency of the H reflex is similar to the F wave but requires functional dorsal roots in addition to ventral roots and proximal peripheral nerve. By stimulating a peripheral nerve at two locations and dividing the interelectrode distance by the difference in H reflex latencies, one can calculate NCV of these fast-conducting sensory fibers. Because these proprioceptive fibers are as large (and sometimes larger) as the motor fibers innervating skeletal muscle, this type of sensory NCV will be in the same range as that in motor fibers. However, H waves are not reliably reproduced in all muscles, and their application to clinical veterinary electrodiagnostics remains limited at this time.

**Single-Fiber Potentials** - The discharge of a single muscle fiber is also of interest, especially in the diagnosis of junctionopathies. With a specially designed needle electrode, the electrical activity of single myofibers can be recorded as a part of a procedure called single-fiber EMG (SF-EMG). Single-fiber potentials are recorded and used to trigger the recording amplifier, or in some protocols, electrical stimuli are used as the trigger. When a fiber is found that is linked to a triggering event, then it is possible to measure its discharge time relative to the first potential (Fig. 9).

![Figure 9. Sequential action potentials recorded from a single muscle fiber in response to an electrical axonal stimulation. Traces show normal latency variation or jitter (upper traces) and increased latency variation in a dog with myasthenia gravis (lower traces). (SA, stimulus artifact.) (From: Hopkins AL et al., [35]). (Included with permission from: M. H. Sims. In: Electrodiagnostic evaluation. K.G. Braund, 2nd ed. Clinical syndromes in veterinary neurology. St Louis: Mosby, 1994; 349-368.). - To view this image in full size go to the IVIS website at www.ivis.org . -](image)

Any variability in latency is called jitter and is due to a variation in synaptic delay between the end-plates. In some neuromuscular disorders, such as myasthenia gravis, the jitter value may increase or the second SF potential may be blocked altogether (Fig. 9). Although widely used in human electrodiagnostics, this technique is not frequently used in veterinary electrodiagnostics. A method has been reported in dogs in which electrical stimulation was substituted for the standard voluntary muscle activation used in the human patient.

**Electrical Activity in Peripheral Nerves**

**Spontaneous Activity in Nerves**

**Electroneurography** - This is the study of electrical activity in neural tissue such as peripheral nerve. When muscles contract volitionally, action potentials appear asynchronously in peripheral motor nerve fibers. This activity is mixed with action potentials in sensory neurons from peripheral receptors thus making it impossible to distinguish one type from the other. In addition, the action potential amplitudes are so low as to make a recording of this type of activity clinically impractical. Evoked activity in peripheral nerves, however, provides more usable information by synchronizing activity in either motor or sensory fibers.

**Evoked Activity in Nerves**

Because peripheral nerve fibers conduct impulses bidirectionally, it would not be possible to simply stimulate a mixed nerve and record a compound nerve action potential that reflected activity in only sensory or motor fibers. For this reason, motor NCV is determined as described above. Sensory NCV, however, can be determined by stimulating a purely sensory nerve, or its cutaneous receptors, and recording from the parent nerve at a more proximal site or sites. Cutaneous areas exclusively innervated by nerves of interest are called autonomous zones and have been established for the major peripheral nerves in dogs. Sensory compound nerve action potentials (SNAP) are small and signal averaging is usually necessary. However, near field recordings are practical. With a needle recording electrode carefully placed adjacent to the superficial radial nerve, for instance, signal averaging is not required. As with other evoked potentials, amplitude and duration are important variables for interpretation. The measurement of sensory NCV provides objective data to explain loss of sensory or reflex function and to assist in the diagnosis of acquired or congenital sensory neuropathies. With the more recent availability of relatively inexpensive electrodes, microneurography will likely be adapted in veterinary medicine in the near future.
Electrical Activity in the Central Nervous System

Spontaneous Activity in the Brain

Electroencephalography - If electrodes are attached to the scalp overlying the cerebral hemispheres, activity in the brain can be recorded in awake, sedated or anesthetized animals. A record of this type of activity is called an electroencephalogram (EEG). The EEG provides important diagnostic information in certain neurological cases, and the reader is referred to the literature for more detailed information [5,8]. However, with the availability of newer imaging techniques such as computerized tomography, magnetic resonance imaging, and other types of scanning, the role of EEG is being revised such that EEG may not be included in the work up of many neurological cases. Rather, its importance may lie in work up of specific disorders such as epilepsy [26,27]. In a case where the scalp-recorded EEG was normal in a dog with intractable epilepsy, the electrocorticogram was recorded with electrodes implanted on the dura mater [37].

Visual interpretation of the EEG requires considerable expertise of the clinician, beyond what is needed for the training in other electodiagnostic techniques. In addition to evaluating amplitude and frequency, the interpretation is based on evaluating factors such as symmetry, mental status, types and frequency of artifacts, identification of specific waveforms, and overall pattern. Some electroencephalographers record from awake animals, while others insist on tranquilization or anesthesia in order to reduce artifacts and to decrease the amount of preparation time. While it is true that sedatives and anesthetics alter normal patterns, some prefer these alterations to those produced by awake but uncooperative patients. The initial difference between the two techniques is seen in the low-voltage, short duration waves in the awake animal as a product of desynchronization. This is contrasted with higher voltage, longer duration synchronized wave characteristics of a sedated or asleep animal. The ability to evaluate both awake and drowsy pattern in an animal may provide a higher diagnostic yield.

A common recording technique consists of a montage of small needle electrodes placed subcutaneously in the scalp. Activities from preselected electrode pairs are fed to multiple amplifiers and printed on a strip-chart recorder. Although the time-favored approach to EEG analysis is the visual subjective method, computer-enhanced electroencephalographic records provide user-defined data analysis including power spectrum analysis and cortical mapping capabilities. Quantitative analysis of the EEG has been used in veterinary anesthesiology for purposes such as assessing depth of sedation [38,39].

Most abnormalities consist of high-voltage, high-frequency activity, high-voltage, slow-wave activity, spikes, spindles, or any combination of these. The first question answered by the EEG is whether abnormal activity is diffuse or focal. Focal abnormalities can be further defined by triangulation, a process that helps to localize the lesion. Commonly identified EEG abnormalities are the high-voltage, slow-wave patterns characteristic of hydrocephalus and the high-voltage, spiky waves associated with encephalitis.

Evoked Activity in the Spinal Cord

Spinal Cord Evoked Potentials - Electrical stimulation of peripheral nerves will result in recordable volleys of activity in the spinal cord [28]. These complex potentials, referred to as spinal cord evoked potentials (SCEP), are usually polyphasic and tend to undergo temporal dispersion as recording electrodes are located more rostrally (Fig. 10).

Figure 10. Evoked potentials recorded from (top to bottom) cortex, thoracic spinal cord, sacral spinal cord, and peripheral nerve in a dog as a result of electrical pulses applied to the tibial nerve. Horizontal division = 5 msec; vertical division = 5 µV for nerve action potential, 2.5 µV for both spinal cord evoked potentials (SCEP), and 1.25 µV for the somatosensory evokes potential (SEP) from the cortex. (Included with permission from: M. H. Sims. In: Electrodiagnostic evaluation. K.G. Braund, 2nd ed. Clinical syndromes in veterinary neurology. St Louis: Mosby, 1994; 349-368.). - To view this image in full size go to the IVIS website at www.ivis.org . -

Cord dorsum potentials can be recorded percutaneously from the lumbar enlargement after stimulation of nerves in the pelvic limb or tail and from the cervical enlargement after forelimb nerve stimulation. Conduction times and conduction velocities can be calculated for spinal cord tracts in the same way as peripheral nerves. SCEPs are particularly indicated for determining the location and severity of spinal cord lesions or lesions affecting the dorsal roots [29]. However, SCEP should not be used for determining prognosis, especially if only measured on one occasion. For instance, in dogs with herniated intervertebral disks, the SCEP may be absent initially and later return as the animal recovers.

Evoked Activity in the Brain

Brainstem Auditory Evoked Responses - Electrical potentials that are produced in response to auditory stimulation are called
auditory evoked responses (AER). One of the principle means for assessing auditory function in animals is the brainstem auditory evoked response (BAER). Short-duration auditory stimuli in the form of clicks are delivered to the external auditory canal and signal-averaged responses are recorded from subcutaneous scalp electrodes. In small animals, BAER occur within the first 10 msec after stimulus application and consist of 6 - 7 waves with amplitudes in the microvolt or submicrovolt range (Fig. 11).

Figure 11. Brain stem auditory evoked response (BAER) in response to clicks (intensity = 90 dB nHL) delivered at a rate of 11.4/sec. Each trace is an average of responses to 1000 clicks alternating between condensation and rarefaction. Roman numerals indentify positive BAER peaks. Horizontal division = 1 msec; vertical division = 0.61 µV. (Included with permission from: M. H. Sims. In: Electrodiagnostic evaluation. K.G. Braund, 2nd ed. Clinical syndromes in veterinary neurology. St Louis: Mosby, 1994; 349-368.). - To view this image in full size go to the IVIS website at www.ivis.org . -

Generally, the peaks of the BAER are produced by the auditory nerve and brainstem portions of the auditory pathway, but individual peaks cannot be correlated with specific nuclei in the auditory pathway. As with most of the electrodiagnostic tests, the responses change during maturation and in geriatric animals compared to the normal adult. The clinician must be aware of the age at which responses attain normal adult values and use age-appropriate comparisons [30]. In cases of severe cochlear damage or hereditary agenesis, a flat-line recording may result (Fig. 12). This is a common finding in a large number of breeds of dogs with hereditary deafness and forms the basis for screening for inherited deafness in litters of puppies of certain breeds around 5 weeks of age. Based on behavior alone, deafness may be suspected in puppies or adult dogs. However, the BAER is an objective method for confirming partial or total deafness, and for identifying animals that are unilaterally deaf. In dogs with suspected brainstem disorders, BAER may also be used to assess lesions in the brainstem that do not necessarily affect hearing. Poncelet et al reported a method for estimating audiograms from brainstem tone-evoked potentials in puppies [40].

Figure 12. Brain stem auditory evoked responses recorded from the left side (bottom trace) and right side (top trace) of a dog with a hereditary cochlear dysfunction on the left side. Each trace is an average of 1000 responses to click stimuli at an intensity of 90 dB nHL and a rate of 11.7/sec. Horizontal division = 1 msec; vertical division = 0.61 µV. (From Sims MH [36]). (Included with permission from: M. H. Sims. In: Electrodiagnostic evaluation. K.G. Braund, 2nd ed. Clinical syndromes in veterinary neurology. St Louis: Mosby, 1994; 349-368.). - To view this image in full size go to the IVIS website at www.ivis.org . -

Middle and Late Latency Auditory Evoked Responses - In contrast to the short-latency response described above, extending the analysis time on the amplifier will produce AER that occur later and more rostrally in the neuroaxis. Middle-latency AER components occur at a latency of 10 - 50 msec (Fig. 13) and late-latency AER are found in the 50 - 250 msec range. These potentials are not as clearly defined as the short-latency BAER, and therefore have not been used as extensively in veterinary medicine, although their implications for the examination of dogs with neurological disorders is being studied [31].

Figure 13. A middle-latency auditory evoked response in a cat in response to clicks at an intensity of 90 dB nHL at a rate of 4.7/sec. Components of the middle latency response are labeled Po, Na, Pa, Nb, and Pb. The peak labeled V is wave V of the brain stem auditory evoked response. Each trace is an average of responses to 2000 stimuli. Horizontal division = 6 msec; vertical division = 0.762 µV. (From Sims MH [36]). (Included with permission from: M. H. Sims. In: Electrodiagnostic evaluation. K.G. Braund, 2nd ed. Clinical syndromes in veterinary neurology. St Louis: Mosby, 1994; 349-368.). - To view this image in full size go to the IVIS website at www.ivis.org . -

Somatosensory Evoked Potentials - When sensory receptors are stimulated at specific locations in the body (soma), the arrival of impulses in the somatosensory cortex can be monitored with strategically placed electrodes. These complex potentials are called somatosensory evoked potentials (SEPs). Some authors refer to these as cortical potentials or cortical evoked potentials because components of the waveform are believed to arise from the cortex. Many SEPs are initiated by the electrical stimulation of mixed peripheral nerves (Fig. 14). With multi-channel recording, ascending volleys can be tracked at different levels in the periphery and CNS to provide information about lesion localization (Fig. 10). Miko et al. recently reported on the use of recording electrodes placed in the nasopharynx and trachea, with stimulation of the median nerve. They concluded that potentials recorded with nasopharyngeal and tracheal electrodes are suitable for intraoperative neurophysiologic monitoring in anesthetized dogs [41].
Visual Evoked Potentials - A variety of light stimuli will produce cortical responses that are referred to as *visual evoked potentials* (VEPs). Stroboscopic flashes and light-emitting diodes have been used to record VEPs in cats and dogs (Fig. 15). These cortical potentials are important in distinguishing between visual problems that originate in the eye and those that are due to lesions in the visual pathway distal to the eye. The clinician should be aware that the VEP tends to be contaminated by the electroretinogram, the waves of which can be recognized by their early latencies or by simultaneous recording of VEP and ERG (see below).

Oscillatory Potentials - *Oscillatory potentials* (OPs) are small wavelets appearing on the ascending and descending slopes of the b-wave of the ERG (Fig. 17). Filter settings can be varied to enhance or eliminate the OPs. The OPs are thought to arise from negative feedback circuits in the retina with major contributions from the amacrine cells. Because OPs are sensitive to changes in retinal blood supply, these potentials have been used to assess visual disorders caused by circulatory dysfunction. Possible applications in veterinary medicine include evaluation of diabetic retinopathies or elevated intraocular pressures caused by glaucoma.
Figure 17. Oscillatory potentials recorded from a cat (top) and a dog (bottom) in a response to a single white stroboscopic flash after dark adaption. Frequency bandpass = 100 to 500 Hz. Positive peaks are labeled 01 through 04 or 05 for the cat and dog, respectively. Horizontal division = 25 msec; vertical division = 12.2 µV (top) and 9.76 µV (bottom). (Arrow, flash discharge). (Included with permission from: M. H. Sims. In: Electrodiagnostic evaluation. K.G. Braund, 2nd ed. Clinical syndromes in veterinary neurology. St Louis: Mosby, 1994; 349-368.). - To view this image in full size go to the IVIS website at www.ivis.org . -

Pattern Electroretinogram - The use of a more complex visual stimulus, such as alternating patterns of light and dark bars, will produce an ERG that is called a pattern ERG or PERG (Fig. 18).

Figure 18. Pattern electroretinogram (PERG) recorded from a dog in response to visual stimulation with a vertical grating pattern at a spatial frequency of 0.06 cycles per degree of visual angle. Each trace is an average of 512 responses. Negative (N) and positive (P) peaks are labeled for the major PERG peaks. Traces are replicates. Horizontal division = 50 msec; vertical division = 0.61 µV. (Included with permission from: M. H. Sims. In: Electrodiagnostic evaluation. K.G. Braund, 2nd ed. Clinical syndromes in veterinary neurology. St Louis: Mosby, 1994; 349-368.). - To view this image in full size go to the IVIS website at www.ivis.org . -

The waveform of this complex potential has some resemblance to the FERG. However, whereas the FERG is a diffuse response of retinal photoreceptors to light, the PERG is thought to arise from more proximal portions of the retina such as ganglion cells. The PERG has been evaluated as an indicator of increased intraocular pressure in dogs [33].


References

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