ELECTROPHYSIOLOGIC STUDIES OF NEUROMUSCULAR TRANSMISSION

Single Fiber Electromyography

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I. Introduction

Single fiber electromyography (SFEMG) is a sensitive method for extracellular recording of single muscle fiber action potentials (MFAPs). The selective recording of individual MFAPs relates to the small recording surface (25 micrometers) of the SFEMG electrode (Figure 1). The technique was first reported by Ekstedt and Stalberg; since the initial reports, the technique has been used to study a variety of physiologic and pathologic conditions of neuromuscular transmission and muscle fiber density. The most popular application relates to the evaluation of neuromuscular transmission in patients with suspected myasthenia gravis.

II. Electromyographic Jitter

With practice, it is possible to record from two MFAPs from the same motor unit during minimal volitional activation in about 25% of SFEMG electrode placements. The recordings are very sensitive to position and substantial patient cooperation is required. When such MFAPs are simultaneously recorded, small variations can be observed in the timing of the action potentials (Figure 2). This variation or variability is called jitter. Experimental studies have demonstrated that most of this variability relates to small differences in the time required for an endplate potential to reach threshold.

The measure used to quantitate jitter is the mean consecutive interpotential difference (MCD), which is calculated by a variety of formulas, depending upon the recording paradigm. Most digital electromyography equipment is capable of automatically calculating the MCD (jitter). The equation for calculating the MCD from the interpotential intervals (IPIs) is:

\[\text{MCD} = \frac{(\text{IPI}_1 - \text{IPI}_2) + (\text{IPI}_2 - \text{IPI}_3) + \ldots + (\text{IPI}_{n-1} - \text{IPI}_n)}{n-1}\]

Jitter can be thought of as a measure of the safety factor of neuromuscular transmission. When the safety factor is large (e.g. the endplate potential is well above threshold for generation of a MFAP), jitter values are very small, indicating little variability in the timing of MFAP discharge. When the safety factor is small (e.g. the endplate potential is just above the threshold for generation of a MFAP), jitter values are very large, reflecting great variability in MFAP discharge. Figure 3 demonstrates a SFEMG recording from a patient with mild myasthenia gravis, demonstrating a mild increase in jitter. If neuromuscular transmission is sufficiently impaired, an individual endplate potential may fail to reach the threshold and a MFAP is not generated. This is referred to as blocking. The decremental response recorded in patients with myasthenia gravis during repetitive motor nerve stimulation is related to blocking of individual MFAPs.
FIGURE 1: Schematic illustration comparing a conventional concentric EMG needle recording (top recording) of a motor unit action potential with two SFEMG electrode recordings (middle and lower records). The middle recording represents a SFEMG recording of a single muscle fiber action potential (MFAP). The lower recording represents a SFEMG recording of two MFAPs from the same motor unit.

Because of the normal variability in jitter among pairs of MFAPs in normal subjects, as least 20 potential pairs are studies for any muscle, and the results expressed both as the average jitter for the 20 pairs, the percentage of fiber pairs having jitter above a 3 standard deviation upper limit, and the percentage of fiber pairs demonstrating intermittent blocking. Representative normal values for adults 15 to 60 years of age for the UMMC EMG Laboratory are shown in Table 1.

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Normal MCD Avg. 20 Pairs (microseconds)</th>
<th>Upper Limit for Individual Pair MCD (microseconds)</th>
<th>Pairs Exceeding Upper Limit (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDC</td>
<td>&lt;33</td>
<td>55</td>
<td>10</td>
</tr>
<tr>
<td>Orbicularis Oculi</td>
<td>&lt;32</td>
<td>45</td>
<td>10</td>
</tr>
<tr>
<td>Biceps Brachii</td>
<td>&lt;30</td>
<td>40</td>
<td>10</td>
</tr>
</tbody>
</table>
A given study is considered abnormal if either of the two criteria are exceeded; e.g. if the average jitter exceeds the upper limit of the average MCD, or greater than 10% of fiber pairs have a jitter exceeding the absolute upper limit of normal for that muscle.

The utility of SFEMG is the evaluation of neuromuscular transmission is related to the sensitivity of this measure. The sensitivity is demonstrated by the frequent identification of abnormality (increased jitter) in muscles that are clinically normal and have no evidence of a decremental response on repetitive motor nerve stimulation studies.

III. **SFEMG in Myasthenia Gravis**

SFEMG is the most sensitive clinical electrodiagnostic test capable of demonstrating abnormal or defective neuromuscular transmission in patients with myasthenia gravis. Most patients with myasthenia gravis demonstrate some MFAP pairs within a given endplate region with normal jitter, while other potential pairs demonstrate excessive jitter and/or intermittent blocking. The MCD is calculated from potential pairs that do not demonstrate blocking. Like repetitive stimulation studies, it is recommended that anticholinesterase medications be withheld for at least 12 hours prior to testing, if clinically safe.

SFEMG studies cannot be performed in isolation. Rather, conventional nerve conduction studies including repetitive motor nerve stimulation should be completed first, together with conventional needle electromyography. Abnormal jitter is not diagnostic of a specific disease, such as myasthenia gravis. Abnormal jitter does reflect defective neuromuscular transmission, but it can be from any etiology including that seen during active reinnervation.

The standard SFEMG protocol is to initially evaluate jitter for the EDC muscle. This muscle is easily activated, fiber pairs are easily found, and the muscle is relatively free of age-related changes. The EDC muscle commonly demonstrates abnormality in patients with myasthenia gravis and generalized symptoms and signs (Table). It is also abnormal in a surprising number of myasthenic patients with only ocular symptoms and signs.

In patients with predominant ocular or bulbar involvement in whom the EDC studies are normal, the frontalis or orbicularis oculi muscles may be examined. By testing a second muscle, virtually all (99%) of patients with known myasthenia gravis demonstrate an abnormal SFEMG study. The muscle selected depends upon the symptoms and signs of weakness and fatiguability in the individual patient. The incidence of abnormality on SFEMG, conventional repetitive motor nerve stimulation studies, and acetylcholine receptor antibody studies is shown in Table 2 for patients with mild generalized and ocular myasthenia gravis, as well as for myasthenic patients in clinical remission.
TABLE 2

LABORATORY DIAGNOSIS OF MILD MYASTHENIA GRAVIS
PERCENT ABNORMAL STUDIES IN 78 PATIENTS*

<table>
<thead>
<tr>
<th></th>
<th>Remission</th>
<th>Ocular</th>
<th>Mild Generalized</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repetitive Stimulation</td>
<td>14</td>
<td>21</td>
<td>71</td>
</tr>
<tr>
<td>SFEMG (1)</td>
<td>71</td>
<td>86</td>
<td>94</td>
</tr>
<tr>
<td>Ach R Ab (2)</td>
<td>57</td>
<td>62</td>
<td>82</td>
</tr>
</tbody>
</table>

* University of Michigan Medical Center; diagnoses secure in all patients.
1. SFEMG of EDC and frontalis muscles, when appropriate.
2. Ach R Ab = acetylcholine receptor antibody levels.

Summary

SFEMG is a very sensitive indicator of defective neuromuscular transmission, and the most sensitive electrodiagnostic study able to detect abnormality in patients with myasthenia gravis. The studies form one component of the overall electrodiagnostic evaluation, and the studies are not performed in isolation. If unequivocal abnormalities are demonstrated on repetitive stimulation of motor nerves, SFEMG studies may not be necessary to establish the diagnosis. The specific muscle tested may depend upon the distribution of weakness, although the majority of myasthenic patients demonstrate abnormality in the EDC muscle. Because neuromuscular transmission may be abnormal in a variety of conditions, an abnormal SFEMG study is not diagnostic for myasthenia gravis. However, if the SFEMG studies are normal in a clinically weak muscle, the etiology of the weakness is not myasthenia.
Single-fiber electromyography (SFEMG) is a selective recording technique in which a needle electrode with a small recording surface in the side is used to identify action potentials from individual muscle fibers. The SFEMG parameters of greatest clinical use are fiber density (FD) and neuromuscular jitter. FD reflects the local organization of muscle fibers within the motor unit; jitter reflects the safety factor of neuromuscular transmission at individual neuromuscular junctions. SFEMG can be of great value in demonstrating or excluding abnormalities in mild or questionable disease of nerve, muscle, or the neuromuscular junction. The neuromuscular jitter may be measured during nerve stimulation, which is particularly useful in uncooperative patients or when it is desirable to control the firing rate precisely, or during voluntary muscle activation, which is less subject to technical artifact. The SFEMG findings may not be specific to a particular disease, but they frequently increase understanding of the disease process by demonstrating abnormal neuromuscular transmission or rearrangement of muscle fibers within the motor unit, which complements information from more conventional EMG examinations.

Key words: single-fiber electromyography • electromyography • myasthenia gravis • neuropathy • myopathy • neuromuscular transmission
of the muscle fiber topography in the motor unit. It is increased in neurogenic conditions but also in myopathies.

MEASURING FIBER DENSITY
Fiber density (FD) measurements require an electromyograph with a 500-Hz low-frequency filter, a signal-triggered oscilloscope, and delay line. Measurements are made by observing the signals on the oscilloscope screen. As the patient voluntarily activates the muscle, the electrode is positioned to record with maximum amplitude the AP from one muscle fiber. This AP triggers the oscilloscope sweep and is delayed for display so that the number of synchronized APs with amplitude exceeding 200 μV can be counted. For example, if no AP other than the triggering potential appears at a constant position on the screen, this is counted as one AP (Fig. 1). If one potential other than the triggering AP appears at a constant position, this is counted as two APs, and so forth. Care must be taken to count as separate potentials, APs that are partially obscured by other APs. If there is a clear "notch" between two such potentials, they are counted as separate APs even if the amplitude of the smaller is less than 200 μV. APs are recorded thus at 20 separate sites within a muscle, usually via three separate insertion sites, and the FD is the mean number of APs, including the triggering AP, counted at these 20 sites. The normal FD is different among different muscles and increases over the age of 60, especially in distal muscles (Table 1).

NEUROMUSCULAR JITTER
When APs elicited by nerve stimulation are recorded with an SFEMG electrode (called stimulation SFEMG), the latency from stimulus to response varies (Fig. 2). This variation is the neuromuscular jitter at the end-plate, most of which is produced by fluctuations in the time it takes for end-plate potentials at the neuromuscular junction to reach the AP threshold. When the SFEMG electrode is positioned to record from two or more muscle fibers in one voluntarily activated motor unit, the neuromuscular jitter is seen as variations in the time intervals between pairs of APs from these fibers (Figs. 3-6). This paired jitter represents the combined jitter in two end-plates.

Jitter is a sensitive measure of the safety factor of neuromuscular transmission. It becomes increased whenever the ratio between the AP threshold and the end-plate potential becomes increased. When neuromuscular transmission is sufficiently impaired, nerve impulses fail to elicit muscle APs, and SFEMG demonstrates intermittent impulse blocking (Fig. 6). When blocking occurs in many end-plates in a muscle, there is clinical weakness. Jitter varies among different end-plates in a muscle and from muscle to muscle.5 In diseases of abnormal neuromuscular transmission, jitter may be increased in muscles that are clinically normal and that show no decrement to repetitive nerve stimulation.8

The variation in intervals can be expressed as the standard deviation (SD) of a series of intervals. However, the intervals may slowly increase or decrease due to electrode movement, changes in the AP propagation velocity along muscle fibers, or other factors, in which case the SD is not an accurate measure of jitter. To minimize the effects of such slow trends, the jitter is expressed as the mean value of consecutive differences (MCD) of successive interpotential intervals (IPIs), calculated from the following formula:

\[
\text{MCD} = \frac{|IPI_1 - IPI_2| + |IPI_2 - IPI_3| + \ldots + |IPI_{n-1} - IPI_n|}{n-1}
\]

where \(IPI_i\) is the interpotential interval (or, when nerve stimulation is used, the stimulus–response interval).

In certain situations, the IPI may be influenced by the preceding interdischarge interval (IDI), which
Table 1. Fiber density reference values: 95% upper confidence limits.*

<table>
<thead>
<tr>
<th>Muscle</th>
<th>10 years</th>
<th>20 years</th>
<th>30 years</th>
<th>40 years</th>
<th>50 years</th>
<th>60 years</th>
<th>70 years</th>
<th>80 years</th>
<th>90 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frontalis</td>
<td>1.67</td>
<td>1.67</td>
<td>1.68</td>
<td>1.69</td>
<td>1.70</td>
<td>1.73</td>
<td>1.76</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tongue</td>
<td>1.78</td>
<td>1.78</td>
<td>1.78</td>
<td>1.78</td>
<td>1.78</td>
<td>1.79</td>
<td>1.79</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sternocleidomastoid</td>
<td>1.89</td>
<td>1.89</td>
<td>1.90</td>
<td>1.92</td>
<td>1.96</td>
<td>2.01</td>
<td>2.08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deltoid</td>
<td>1.56</td>
<td>1.56</td>
<td>1.57</td>
<td>1.57</td>
<td>1.58</td>
<td>1.59</td>
<td>1.60</td>
<td>1.62</td>
<td>1.65</td>
</tr>
<tr>
<td>Biceps</td>
<td>1.52</td>
<td>1.52</td>
<td>1.53</td>
<td>1.54</td>
<td>1.57</td>
<td>1.60</td>
<td>1.65</td>
<td>1.72</td>
<td>1.80</td>
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<tr>
<td>Extensor digitorum</td>
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<td>1.80</td>
<td>1.83</td>
<td>1.90</td>
<td>1.99</td>
<td>2.12</td>
<td>2.29</td>
<td>2.51</td>
</tr>
<tr>
<td>Communis</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Abductor digiti minimi</td>
<td>1.99</td>
<td>2.00</td>
<td>2.03</td>
<td>2.08</td>
<td>2.16</td>
<td>2.28</td>
<td>2.46</td>
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<td></td>
</tr>
<tr>
<td>Quadriceps</td>
<td>1.93</td>
<td>1.94</td>
<td>1.96</td>
<td>1.99</td>
<td>2.05</td>
<td>2.14</td>
<td>2.26</td>
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<td></td>
</tr>
<tr>
<td>Tibialis anterior</td>
<td>1.94</td>
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<td>1.96</td>
<td>1.98</td>
<td>2.02</td>
<td>2.07</td>
<td>2.15</td>
<td>2.26</td>
<td></td>
</tr>
<tr>
<td>Soleus</td>
<td>1.56</td>
<td>1.56</td>
<td>1.56</td>
<td>1.57</td>
<td>1.59</td>
<td>1.62</td>
<td>1.66</td>
<td>1.71</td>
<td></td>
</tr>
</tbody>
</table>

may introduce an additional variation due to changes in the velocity of action potential propagation in the muscle fibers.28 This is not a factor with stimulation jitter studies using a constant stimulus rate if the first 10 intervals of each train are excluded from the jitter calculation, since the effect of preceding depolarizations becomes constant at that point, provided there is no impulse blocking to produce an irregular discharge rate. The effect of variable firing rates when jitter is measured during voluntary activation can be minimized by sorting the IPIs according to the length of the preceding IDI and then calculating the mean of the consecutive IPI differences in the new sequence. The result is called the mean sorted-data difference (MSD). If the ratio MCD:MSD exceeds 1.25, then variations in the firing rate have contributed to the jitter, and the MSD should be used to represent the neuromuscular jitter. The MCD is used to express the jitter if the MCD:MSD ratio is less than 1.25.

**ACTIVATION AND RECORDING TECHNIQUE**

**Electrical Stimulation.** Stimulation jitter studies are particularly useful in patients who have difficulty maintaining constant voluntary activation of the muscle, when there is a tremor, in children too young to cooperate, or when it is desirable to control the firing rate precisely, as when assessing the effect of firing rate on jitter. The motor nerve may be stimulated proximal to its entry into the muscle, or individual motor nerve branches may be stimulated within the muscle. The former technique is ideal for activating facial muscles since individual branches of the facial nerve can be stimulated with a monopolar needle electrode inserted lateral to the orbicularis oculi muscle. Many motor units are usually activated if a surface electrode is used for stimulation, making it difficult to identify the responses of single muscle fibers. Some jitter may be introduced by variations in the intensity of the stimulus that reaches the individual motor nerve fibers, especially when surface stimulation is used.

For limb muscles, intramuscular axonal stimulation is delivered by a monopolar needle electrode inserted near the motor end-plate zone (Fig. 2). Another needle electrode or surface electrode is used as the anode.

With each of these stimulus techniques, stimulation is delivered at 2–10 Hz, and the stimulus intensity is adjusted to produce a slight twitch of the mus-
FIGURE 3. Single-fiber EMG recording technique for jitter studies during voluntary muscle activation. (A) The recording position of the SFEMG electrode (e). (B) Consecutive discharges of one pair of potentials recorded at a slow oscilloscope sweep speed. (C) The same potentials have been delayed and recorded at a faster sweep speed and displayed in a rastered mode, with the oscilloscope triggered by the first potential. (D) The same potentials as (C), displayed superimposed, to demonstrate the neuromuscular jitter. (From Stålberg and Trontelj.25)

cle. The SFEMG electrode is inserted into the twitching portion of the muscle and positioned to record clearly defined single-fiber APs. As the stimulus intensity is increased, increasing numbers of single-fiber APs are elicited, initially with high jitter and intermittent blocking due to liminal stimulation. The jitter is measured between stimulus and individual APs when a further increase in stimulus intensity no longer decreases the jitter. Jitter can be measured in all clear, distinct APs at each recording site. Stimulation at 10 Hz is usually used to approximate physiologic activation rates, and at least 50 stimuli are analyzed for each AP. The recording electrode is moved to several different sites in the muscle to minimize the possibility of recording APs more than once from the same muscle fiber. For optimal sampling of each muscle, APs should be measured from at least 30 end-plates.

APs elicited by nerve stimulation have jitter greater than 5 μs, whereas jitter is less when the muscle fiber is stimulated directly (Fig. 2). Liminal stimulation and other technical factors, however, can produce variability in the stimulus–response interval.

FIGURE 4. Single-fiber EMG recordings from normal extensor digitorum communis muscle. The oscilloscope is triggered by the rising phase of the first action potential and 10 oscilloscope traces are superimposed. Jitter is seen as slight variability in the position of the second action potential and is normal (MCD 19 μs). Bars indicate the time windows and voltage level used to identify the beginning and end of the interpotential intervals to be measured.

FIGURE 5. Single-fiber EMG recordings from the extensor digitorum communis muscle of a patient with myasthenia gravis; 55 oscilloscope traces are superimposed. Jitter is markedly increased, and there is occasional blocking.
Jitter can be calculated most precisely if the IPIs are measured directly with an interval counter or clock. Many electromyographs have this capability and calculate MCD directly. To ensure that acceptable signals are being acquired, feedback should be provided to the operator during data acquisition. Some systems electronically store and redisplay the waveforms for review so the operator can exclude unacceptable signals before making the final calculations. In most systems, the operator sets a threshold level to select the APs of interest and to exclude undesired signals. In some systems, the same threshold level is used to select APs and to measure IPIs. In more flexible systems, independent threshold levels are used for AP selection and for interval measurements. Some systems use a peak detecting algorithm to identify APs automatically. No system can reliably distinguish true blocking from spurious signals; the operator must make this distinction and should be able to record this information in the analysis record. In some machines interdischarge intervals are also measured, which permits calculation of the MSD and demonstration of the effect of firing rate on jitter. Some systems display the IPI values graphically, which permits easy visualization of the data distribution and trends (Fig. 7).

It is useful to present the results of jitter measurements in each muscle as (a) the mean or median value of the MCD values in all the pairs or end-plates measured (mean or median MCD); (b) the percent-

Voluntary Activation. Usually, jitter measurements are performed during voluntary activation of the muscle, since this technique is less subject to technical problems that lead to misinterpretation of results, but it requires more patient cooperation. As the patient slightly contracts the muscle, the SFEMG electrode is inserted into the muscle near the end-plate zone and positioned to record two (or more) time-locked APs from the same motor unit (Fig. 3). The amplitudes of the APs are optimized by slightly adjusting the electrode position; in the best recording position for jitter measurements, all APs of interest should have sharply rising phases and adequate amplitude. This may not be the position where the amplitude of any single AP is maximal, and thus, differs from the position used for FD measurements. The trigger point for IPI measurements should be located on a stable portion of the AP. A constant recording position is maintained while at least 50 discharges are recorded. APs should be measured from 20 potential pairs recorded from different portions of the muscle, using 3-4 skin insertions.

JITTER ANALYSIS

Jitter can be calculated most precisely if the IPIs are measured directly with an interval counter or clock. During direct muscle stimulation which can be difficult to distinguish from neuromuscular jitter. Experience and careful technique are necessary to avoid misinterpretation when increased jitter is seen during axonal stimulation.

FIGURE 6. Single-fiber EMG recordings from the extensor digitorum communis muscle of a patient with myasthenia gravis; 36 traces are superimposed. Jitter is markedly increased and there is frequent blocking in the second action potential, whereas jitter is normal between the first and third potentials.

FIGURE 7. Graphical display of the interpotential intervals (IPIs) measured during jitter analysis. Top: sequential histogram of IPI values centered around the mean interpotential interval (MIPI). The thickness of the line of data reflects the variability in IPI, that is, the jitter. Bottom: nonsequential histogram of the same IPI values, demonstrating that they have a Gaussian distribution. Any deviation from this pattern would suggest that spurious data may have been acquired.
age of paired potentials or end-plates in which block-
ing was seen (percent blocking); and (c) the percent-
age of pairs or end-plates in which jitter exceeds the normal limit for that muscle (percent abnormal pairs or end-plates.) The mean MCD may exceed normal limits when a few individual jitter values are extremely high. To avoid this, jitter values greater than 150 \( \mu s \) may be excluded from the mean MCD calculation or the median MCD may be used to express the central tendency of the data. In normal muscle, the mean and median MCD values are the same. The interpretation of jitter studies is facilitated if the results are presented graphically (Fig. 8).

The measurement of jitter cannot be completely automated since the operator selects the signal to be analyzed and determines the quality of that signal. There is more variation among the results obtained by different operators using the same technique than between results obtained by the same operator using different equipment. Selection of the recording position of the electrode and the epoch to analyze has more effect on the jitter results than does the equipment. Even so, these differences are small, as demon-

![Graphical display of results of single-fiber EMG jitter studies in the extensor digitorum communis muscle. Top: normal; bottom: patient with myasthenia gravis. Each symbol represents the jitter value from one pair of potentials. The vertical lines indicate the upper limit of normal for jitter in individual potential pairs. Filled symbols indicate that there was blocking in that pair of potentials. Jitter values greater than 170 \( \mu s \) are listed. Summary data are recorded for each study.](image-url)

FIGURE 8. Graphical display of results of single-fiber EMG jitter studies in the extensor digitorum communis muscle. Top: normal; bottom: patient with myasthenia gravis. Each symbol represents the jitter value from one pair of potentials. The vertical lines indicate the upper limit of normal for jitter in individual potential pairs. Filled symbols indicate that there was blocking in that pair of potentials. Jitter values greater than 170 \( \mu s \) are listed. Summary data are recorded for each study.

Long-Term Recordings. Sometimes it is desirable to monitor the jitter in one pair of potentials or in one end-plate for prolonged periods, such as when determining the effect of drugs, ischemia, temperature, etc., on neuromuscular transmission. Some electromyographs can measure jitter in several hundred IPIs, but to analyze jitter over more prolonged periods, the data must be divided into distinct epochs. To facilitate this, the EMG signals can be recorded on magnetic tape, from which selected epochs can be played for analysis. The system should be capable of making recordings with accurate time relationships and a frequency range of 300 Hz to 10 kHz. Audio quality reel-to-reel recorders and digital audio tape recorders are ideal for this purpose. SFEMG signals can also be recorded accurately on the audio channels of VCRs capable of "Hi-Fi" sound recording. Also, pulse code modulators can be used to convert analog EMG signals into video signals that can be recorded with great accuracy on standard

Table 2. Reference values for jitter measurements in healthy subjects during voluntary muscle activation (μs); 95% confidence limits for upper limit of mean MCD/95% confidence limits for MCD values of individual fiber pairs.

<table>
<thead>
<tr>
<th>Muscle</th>
<th>10 years</th>
<th>20 years</th>
<th>30 years</th>
<th>40 years</th>
<th>50 years</th>
<th>60 years</th>
<th>70 years</th>
<th>80 years</th>
<th>90 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frontalis</td>
<td>33.6/49.7</td>
<td>33.9/50.1</td>
<td>34.4/51.3</td>
<td>35.5/53.5</td>
<td>37.3/57.5</td>
<td>40.0/63.9</td>
<td>43.8/74.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Orbicularis oculi</td>
<td>39.8/64.6</td>
<td>39.8/64.7</td>
<td>40.0/64.7</td>
<td>40.4/54.8</td>
<td>40.9/55.0</td>
<td>41.8/55.3</td>
<td>43.0/55.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Orbicularis oris</td>
<td>34.7/52.2</td>
<td>34.7/52.7</td>
<td>34.9/53.2</td>
<td>35.3/54.1</td>
<td>36.0/55.7</td>
<td>37.0/58.2</td>
<td>38.3/61.8</td>
<td>40.2/67.0</td>
<td>42.5/74.2</td>
</tr>
<tr>
<td>Tongue</td>
<td>32.8/48.6</td>
<td>33.0/49.0</td>
<td>33.6/50.2</td>
<td>34.6/52.5</td>
<td>36.8/54.3</td>
<td>39.5/62.0</td>
<td>44.0/70.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sternocephalodastoid</td>
<td>29.1/54.5</td>
<td>29.3/54.8</td>
<td>29.8/46.8</td>
<td>30.8/48.8</td>
<td>32.5/42.4</td>
<td>34.9/58.2</td>
<td>38.4/62.3</td>
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<tr>
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<td>32.9/44.6</td>
<td>33.0/44.8</td>
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<tr>
<td>Biceps</td>
<td>34.9/55.2</td>
<td>29.6/55.2</td>
<td>29.6/55.2</td>
<td>29.6/55.7</td>
<td>30.1/46.2</td>
<td>30.5/46.9</td>
<td>31.0/48.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extensor digitorum communis</td>
<td>34.9/50.0</td>
<td>34.9/50.1</td>
<td>35.1/50.5</td>
<td>35.4/51.3</td>
<td>35.9/52.5</td>
<td>36.5/64.4</td>
<td>37.7/57.2</td>
<td>39.1/61.1</td>
<td>40.9/66.5</td>
</tr>
<tr>
<td>Abductor digit minimi</td>
<td>44.4/63.5</td>
<td>44.7/64.0</td>
<td>45.2/65.5</td>
<td>46.4/66.6</td>
<td>48.2/73.9</td>
<td>51.0/82.7</td>
<td>54.8/96.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quadriceps</td>
<td>35.9/47.9</td>
<td>36.0/48.0</td>
<td>36.5/48.2</td>
<td>37.5/48.5</td>
<td>39.0/49.1</td>
<td>41.3/50.0</td>
<td>44.6/51.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tibialis anterior</td>
<td>49.4/60.0</td>
<td>49.3/79.8</td>
<td>49.2/79.3</td>
<td>48.9/78.3</td>
<td>48.5/76.8</td>
<td>47.9/74.5</td>
<td>47.0/71.4</td>
<td>45.8/67.5</td>
<td>44.3/62.9</td>
</tr>
</tbody>
</table>

VCRs. Audio quality cassette recorders have too much speed variability to record SFEMG signals accurately.

**NORMAL JITTER VALUES**

Reference jitter values have been determined for many muscles in a multicenter collaborative study (Table 2). With increased age, there is a slight increase in jitter in normal subjects. Note that these reference values are valid only for interspike intervals up to 4 msec; erroneously high jitter values may be obtained from recordings with long interspike intervals, particularly if the firing rate is irregular. Using the MSD calculation, as described above, does not completely compensate for the effects of AP velocity variations in recordings with long interspike intervals, especially if there are also slow trends in the intervals.

A study is abnormal if either of the following criteria is met:

A. The mean (or median) jitter exceeds the upper limit for the muscle; or
B. More than 10% of pairs or end-plates have increased jitter.

In most studies, the conclusions from both criteria are concordant. Occasionally the mean MCD is increased in myasthenia gravis (MG) when fewer than 10% of potential pairs have increased jitter. The converse is rarely true.

Jitter of 5 μs or less is seen rarely in voluntarily activated SFEMG studies in normal muscles and more often in myopathies. These low values probably result from recordings made from split muscle fibers, both branches of which are activated by a single neuromuscular junction. These values should not be included in assessments of neuromuscular transmission.

The MCD value measured during axonal stimulation is less than that measured during voluntary activation of the same muscle, since the jitter measured during axonal stimulation comes from only single end-plates. The theoretical relationship between values obtained by these two techniques is expressed by the formula:

\[
\text{Mean MCD (vol activation)} = \frac{\text{Mean MCD (axonstim)}}{\sqrt{2}}
\]

Reference values for jitter during axonal stimulation have been determined for the extensor digitorum communis (EDC) and orbicularis oculi muscles (Table 3). For other muscles, the normative values for stimulation jitter can be obtained by multiplying the values obtained by voluntary activation (Table 2) by a conversion factor of 0.8, which approximates the theoretical relationship expressed in the formula above. MCD values of 4 μs or less obtained during stimulation SFEMG indicate that the muscle fiber is being directly stimulated (Fig. 2); these values should not be used for assessment of neuromuscular transmission.

**TECHNICAL CONSIDERATIONS**

The electrodiagnostic medicine consultant must have considerable experience with SFEMG to be able

**Table 3. Reference stimulation jitter values.**

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Upper limit of normal for MCD values of individual fiber pairs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extensor digitorum communis</td>
<td>Mean MCD (μs)</td>
</tr>
<tr>
<td>Orbicularis oculi</td>
<td>25</td>
</tr>
</tbody>
</table>

The MCD value of 25 μs obtained during axonal stimulation is not abnormal (Fig. 2).
Jitter was abnormal in the EDC in 85% of all MG patients. Jitter recordings can be made in one muscle in about 5 min and requires an electromyograph with a signal-triggered delay line to display APs. Jitter recordings can be made in one muscle in less than 30 min in most patients. The time it takes to analyze the results depends upon the analysis technique used. Many EMG machines incorporate automated jitter analysis techniques that can greatly reduce analysis time.

The condition of the SFEMG electrode is critical in making good recordings. The tip should be sharp and free of hooks that can tear the muscle fibers. The recording surface must be clean and have a low impedance to maximize the signal-to-noise ratio.

Most adult patients are able to cooperate for adequate SFEMG studies. Patient discomfort rarely limits the use of this test, even when several muscles must be examined. Most patients report that SFEMG is less uncomfortable than repetitive nerve stimulation, especially when the latter requires stimulation of facial or proximal muscles.

If the patient has a tremor, it may be impossible to make adequate recordings from distal arm muscles during voluntary activation. In such cases, recordings can usually be made from facial or more proximal arm muscles. Alternatively, recordings of jitter can be made during axonal stimulation.

Children above the age of 8 can usually cooperate well enough for adequate studies. In uncooperative children, jitter studies can be performed during axonal stimulation, with sedation.

The potential complications of SFEMG are those of needle electromyography in general, i.e., a very slight risk of hemorrhage or infection. The only complications the authors have encountered have been occasional small hematomas at the insertion site.

**SFEMG IN MYASTHENIA GRAVIS**

The following conclusions are based on SFEMG studies performed in more than 900 patients with acquired MG (D.B. Sanders, J.F. Howard, J.M. Massey—unpublished). In patients with MG, jitter is greater in weak muscles but is usually increased even in muscles with normal strength.

The EDC muscle is usually tested first if the patient has weakness or symptoms involving oropharyngeal or any limb muscles. Most patients can activate this muscle easily and it is relatively free of age-dependent changes that affect more distal limb muscles. Jitter was abnormal in the EDC in 85% of all MG patients during their initial electrophysiologic evaluation. In patients with normal jitter in the EDC, a second muscle (usually the frontalis) was tested and was abnormal in 85% of those patients. In a few patients, jitter was normal in both the EDC and frontalis, in which case a third muscle (usually the orbicularis oculi) was tested, and was abnormal in most.

When the EDC and frontalis muscles were both examined during the initial evaluation, results were concordant in the two muscles in 76% of patients (Table 4). In 21% of these patients, jitter was abnormal in the frontalis but normal in the EDC. The converse was true in 4% of patients. Rarely, when only a few limb or axial muscles are weak, jitter may be increased in these muscles when it is normal in the EDC.

Jitter is usually abnormal even when the patient is taking cholinesterase inhibitors. However, in rare patients with ocular or mild limb weakness, jitter is increased only after cholinesterase inhibitors have been discontinued. Although the authors do not feel it is necessary to withhold cholinesterase inhibitors before SFEMG studies in all patients, the diagnostic yield of SFEMG will be higher if this is done in patients with mild disease. If jitter is normal while the patient is taking these medications, the studies should be repeated after they have been withheld for at least 24 h.

In summary, SFEMG demonstrates increased jitter in virtually all patients with MG. Although no one muscle is more abnormal in every patient with MG, the EDC is abnormal in most. The EDC muscle is usually tested first unless the symptoms or weakness is limited to the ocular muscles, in which case the orbicularis oculi or frontalis may be first. If the EDC is normal, usually the frontalis or orbicularis oculi is tested. If the first of these facial muscles is normal, the other should be tested before excluding the diagnosis of MG. If any limb muscle is weak, it also should be tested before concluding that the patient does not have MG. Jitter is also increased in diseases of nerve and muscle; these diseases must be excluded by other electrophysiologic and clinical examinations before concluding that the patient has MG. If neuronal or myopathic disease is present, increased jitter does not indicate that MG is also present; however,

<table>
<thead>
<tr>
<th>Extensor Digitorum Communis</th>
<th>Frontalis</th>
<th>Abnormal</th>
<th>Normal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abnormal</td>
<td>72%</td>
<td>21%</td>
<td></td>
</tr>
<tr>
<td>Normal</td>
<td>4%</td>
<td>4%</td>
<td></td>
</tr>
</tbody>
</table>
Table 5. Results of SFEMG studies of jitter in the extensor digitorum communis muscle in 788 patients with myasthenia gravis (D. B. Sanders, J. F. Howard, J. M. Massey—unpublished).

<table>
<thead>
<tr>
<th>Disease class</th>
<th>Remission</th>
<th>Ocular</th>
<th>Generalized</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of patients*</td>
<td>21</td>
<td>107</td>
<td>660</td>
</tr>
<tr>
<td>%, studies abnormal</td>
<td>52%</td>
<td>61%</td>
<td>88%</td>
</tr>
<tr>
<td>Mean MCD (μs)*</td>
<td>40</td>
<td>41</td>
<td>88</td>
</tr>
<tr>
<td>Pairs with blocking</td>
<td>4%</td>
<td>5%</td>
<td>28%</td>
</tr>
<tr>
<td>Normal pairs†</td>
<td>82%</td>
<td>83%</td>
<td>48%</td>
</tr>
</tbody>
</table>

*Data for patients in remission were obtained after treatment. Data for other classes were obtained at the first electrodiagnostic evaluation.
† Mean values for each class.

...if jitter is normal in a muscle with definite weakness, the weakness is not due to MG.

**COMPARISON OF JITTER WITH DISEASE SEVERITY**

Jitter is more often increased in any given muscle in patients with more severe disease (Table 5, Fig. 9). However, jitter varies markedly among patients with similar weakness and disease severity cannot be inferred from the amount of jitter alone.

**Ocular Myasthenia.** In 16% of patients with MG, weakness is confined to the ocular muscles. Jitter is less abnormal in these patients than in those with generalized disease (Table 5, Fig. 9). The study found abnormal jitter in the EDC in 60% of patients with ocular myasthenia, confirming that the physiologic abnormality is more widespread than indicated by the clinical findings.

**EFFECT OF PROLONGED ACTIVITY AND FIRING RATE ON JITTER**

The abnormality of neuromuscular transmission in MG is exacerbated by prolonged or high-frequency activation of the motor unit. In some potential pairs, jitter increases significantly as measurements are made over a period of several minutes. In some recordings, jitter that is initially within the high normal range (> 40 μs in the EDC) becomes abnormal during prolonged activation. Jitter does not become abnormal during prolonged activation in normal muscle.

In MG, it is frequently possible to demonstrate greater jitter (and blocking) in a pair of potentials when the motor unit is firing rapidly than when it is firing at a slower rate. This effect cannot be demonstrated in all potential pairs, however. In presynaptic neuromuscular abnormalities, such as Lambert-Eaton myasthenic syndrome and botulism, jitter and blocking typically decrease as the firing rate increases (Fig. 10). Jitter and blocking decrease at high firing rates in some potential pairs also in patients with neuropathy or MG. The effect of firing rate on jitter is best assessed using nerve stimulation but may also be assessed by measuring jitter from one pair of potentials while the patient maintains a low activation rate, and again at a higher rate.

**SERIAL SFEMG STUDIES IN MYASTHENIA GRAVIS**

In most patients with MG, changes in disease severity correlate with changes in jitter measurements. The mean MCD increases by at least 10% in the tested muscle in two thirds of patients who become worse between SFEMG studies. Conversely, in over 80% of instances in which the mean MCD falls by at least 10% between two studies, there has been definite clinical improvement. Thus, there is a strong correlation between overall clinical improvement in patients with MG and a fall of at least 10% in mean jitter in any muscle. Serial SFEMG studies may be of value in predicting changes in disease severity under certain circumstances. For example, when the jitter values in one muscle have been constant for several months, any subsequent increase in jitter usually accompanies or heralds clinical deterioration. If serial studies are performed on patients taking cholinesterase inhibitors, the effects of these medications on jitter must be taken into account when interpreting the results. Follow-up studies should be performed at a constant time after a dose of medication, if possible. In MG patients receiving immunosuppressive therapy, the
FIGURE 10. The results of stimulation jitter studies in 32 endplates in myasthenia gravis (MG) and 23 in Lambert-Eaton myasthenic syndrome (LEMS). Mean values and ranges between the 5th and the 95th percentile are shown. In MG, jitter increases with increasing rates up to 10 Hz, and falls at higher rates. In LEMS, there is facilitation even from the lowest stimulation rates. (Modified from Trontelj and Stålberg.32)

jitter in a given muscle decreases as the disease improves, but is usually increased even after strength becomes normal. Thereafter, jitter typically continues to fall toward normal as long as immunotherapy is adequate. Any deviation from this expected pattern suggests that treatment may not be adequate to suppress the immunologic abnormality. Although therapeutic decisions should always be based on clinical considerations, jitter measurements may be useful in providing one part of the clinical picture.

COMPARISON WITH OTHER DIAGNOSTIC TECHNIQUES IN MYASTHENIA GRAVIS

Repetitive nerve stimulation (RNS) demonstrates a decrementing pattern in up to 85% of patients with MG when many muscles are tested. In a group of patients with MG who had RNS tests performed in a hand and a proximal arm muscle, an abnormal decrement was found in at least one muscle in 76% of patients, whereas jitter was abnormal in some muscle in 99% (Fig. 9) (D.B. Sanders, J.F. Howard, J.M. Massey—unpublished).

When abnormal neuromuscular transmission has been demonstrated by RNS, the finding of abnormal jitter does not add to the diagnosis, although it may be useful to have baseline jitter values for comparison with subsequent studies. SFEMG is most valuable clinically in the patient with suspected MG in whom other tests of neuromuscular transmission and anticholinesterase receptor antibody measurements are normal.

The “double-step” RNS test involves prolonged stimulation of a muscle in the hand before and after ischemia of the limb. This test was found to be only slightly more sensitive than RNS of the trapezius muscle alone and only 60% as sensitive as SFEMG of a hand muscle. Increased jitter and blocking are frequently found in muscles in which there is no decrement to RNS, but the converse is not seen.

Antibodies to the acetylcholine receptor are found in the blood in 70–90% of patients with MG and are much less likely to be elevated in patients with ocular MG (Fig. 9). SFEMG can be particularly useful in confirming or excluding the diagnosis of MG in patients in whom these antibodies are not found.

SFEMG IN THE LAMBERT-EATON MYASTHENIC SYNDROME

The jitter measured by SFEMG is markedly increased in Lambert-Eaton myasthenia syndrome (LEMS), frequently out of proportion to the severity of weakness, with frequent impulse blocking. In many endplates, there is a characteristic effect of firing rate, the jitter and blocking decreasing as the firing rate increases (Fig. 10). However, this pattern is not pathognomonic for LEMS, since jitter and blocking may also decrease at higher firing rates in some endplates in patients with MG.

SFEMG IN NEUROPATHY

Reinnervation of denervated muscle fibers takes place by collateral sprouting of intramuscular nerve fibers and regeneration from the ends of transected nerve fibers. Collateral sprouting produces remodeling of the motor unit and a greater number of muscle fibers per motor unit. On muscle biopsy, this is seen as type grouping and increased terminal innervation ratio. With SFEMG, this is seen as increased FD. FD may be increased 3–4 weeks after nerve injury, long before changes of reinnervation can be seen on muscle biopsy or conventional needle EMG. Thus,
increased FD may be the earliest and most subtle evidence of reinnervation. Neuromuscular jitter is increased in neuropathies during the reinnervating process. As reinnervation becomes established, and FD increases, the jitter becomes less (Fig. 11). This implies that neuromuscular transmission is uncertain or impaired in immature synapses. Neurogenic blocking may also be seen during early reinnervation, indicating that there is transmission failure in the terminal axon branching sites. This is seen in voluntary SFEMG recordings as concomitant blocking of two or more components when three or more spikes are recorded (Fig. 12). Jitter may also be increased during acute denervation, e.g., within days after onset of Guillain–Barré syndrome or following nerve injury.

**Peripheral Neuropathy.** In diabetic neuropathy, a variable pattern of SFEMG findings has been reported. In some patients, FD and jitter are normal in the EDC, indicating that there is little axonal loss, but more demyelination, in nerves to that muscle. In a study of the tibialis anterior in diabetic patients with and without clinical neuropathy, jitter was increased equally in both groups, whereas FD was increased more in those with signs of neuropathy, suggesting that the neuropathy in these patients was primarily axonal. As in other neuropathies, the abnormalities are most marked in distal, lower extremity muscles.

FD and jitter are normal in some patients with uremic neuropathy, indicating that there is little axonal loss. In other patients, jitter has been found to be increased despite normal FD; these abnormalities improved after a year of hemodialysis. This pattern could result from peripheral nerve twig demyelination, although abnormalities of the muscle membrane or neuromuscular junction could produce similar findings. FD and increased jitter are found in many motor units (MUs) in alcoholic neuropathy, indicating that there is axonal loss and reinnervation.

In Guillain–Barré syndrome (GBS), jitter may be increased within days after onset. If conduction block is the only abnormality, recovery of strength is not accompanied by increased FD. In most cases of GBS, there is some axonal loss, and FD increases later as reinnervation occurs with collateral sprouting.

**Motor Neuron Disease.** In most muscles in patients with amyotrophic lateral sclerosis, FD and motor unit action potential (MUAP) size are increased to similar degrees, indicating that reinnervation is distributed homogeneously throughout the MU. In some muscles in which strength is normal or only slightly decreased, however, FD may be increased in the absence of increased MUAP size. Increased jitter may be the earliest electromyographic abnormality seen in some muscles, suggesting that neuromuscular transmission is abnormal during neuronal degeneration. In the early stages of disease, FD and MUAP size increase while strength remains normal or only slightly weak, indicating that loss of MUs is adequately compensated by reinnervation. The highest values of FD and MUAP size are seen in muscles with moderately severe weakness, indicating that reinnervation is maximum but is not sufficient to compensate for the loss of MUs at this stage of the disease. FD and
MUAP size are not as great in muscles that have severe weakness, indicating that the MUs in these muscles cannot maintain maximum reinnervation as the disease progresses. Jitter and blocking are greatest when the disease is most rapidly progressive. FD is highest in chronic, slowly progressive motor neuron disease, such as spinal muscular atrophy (Fig. 11).

In patients who have had poliomyelitis, FD is increased in most muscles and is not correlated to the age of the patient or the length of time since the polio. Jitter is also increased in many muscles, even in patients who have no symptoms of progressive weakness. The greatest jitter is seen in MUs with the highest FD values. These observations suggest that MUs achieve stable reinnervation after acute poliomyelitis and later undergo deterioration, perhaps as part of the normal aging process.

In syringomyelia, there is increased FD and occasional increased jitter, with marked variability among different muscles. The greatest jitter is seen in muscles with the most marked recent progression.

**Age.** FD increases with age, especially after the age of 70 (Table 1), especially in distal muscles. In men whose occupation involves chronic muscle use, these changes are more marked, suggesting that age and chronic use produce mild denervation and reinnervation. Jitter also increases slightly with age in asymptomatic subjects.

**Summary.** SFEMG can be of great value in demonstrating or excluding abnormalities in patients with mild or questionable neuronal disease. In peripheral neuropathies, abnormalities are most marked in distal muscles. A patchy distribution of abnormality is seen in diseases such as syringomyelia or motor neuron disease. By testing multiple muscles with SFEMG, the distribution of neuronal abnormality can be demonstrated, even when the disease is mild or subclinical. The stage of neuronal disease and completeness of reinnervation can be inferred from the combination of jitter and FD findings. Increased FD with stable MU components indicate that reinnervation is complete. Most neuropathies are progressive, however, and increased jitter and blocking in these conditions may be seen at all stages, perhaps due to ongoing denervation as well as reinnervation.

**SFEMG IN MYOPATHY**

SFEMG demonstrates abnormalities in muscle disease that are not apparent by other electromyographic techniques. Although these findings may not be specific to a particular disease, they frequently increase our understanding of the disease process by demonstrating the presence of abnormal neuromuscular transmission or rearrangement of muscle fibers within the MU. This information complements the findings from more conventional needle EMG examinations. Below is a brief review of typical findings in some muscle disorders (Table 6).

**Duchenne, Becker, and Limb-Girdle Muscular Dystrophy.** FD is increased in Duchenne, Becker, and limb-girdle muscular dystrophy, but is usually much higher in Duchenne dystrophy than in the others, frequently being greater than 3.0 or as high as 6.0 in the EDC. Recordings of up to 16 spike components may be seen. In late stages, the FD may decrease but still remains above normal. In Becker and limb-girdle dystrophy, FD values are most often between 2.0 and 3.0, although normal values may also be found. The duration of multiple spike recordings tends to be quite long, about 10 ms on average, often with most or all spikes separated by long IPIs. The duration of multiple potentials is less increased in Becker and limb-girdle dystrophies, but it is common to find at least some long potentials even in muscles that are clinically little affected in these two conditions.

Jitter is moderately increased in about 20–40% of recordings in Duchenne dystrophy, and about 5–10% show intermittent blocking. The tendency for the later components in a complex potential to have larger jitter is much less pronounced than in neurogenic disorders and the very late components may be remarkably stable. Long complex potentials often show a pronounced interdischarge interval-dependent jitter, seen usually as a progressive shortening of the whole complex as the discharge rate

### Table 6. SFEMG Findings in Myopathy.

<table>
<thead>
<tr>
<th>Disease</th>
<th>FD</th>
<th>Jitter</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dystrophy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Duchenne</td>
<td>↑</td>
<td>↑</td>
<td>Very long, complex potentials; pronounced VRF; Frequent low jitter (&quot;split fibers&quot;).</td>
</tr>
<tr>
<td>Limb-girdle</td>
<td>↑</td>
<td>↑</td>
<td>Similar to Duchenne, but less marked</td>
</tr>
<tr>
<td>FSH</td>
<td>±↑</td>
<td>↑</td>
<td>Only minimally abnormal. Frequent extra discharges (SFEMG may show the earliest/oldest EMG abnormalities.)</td>
</tr>
<tr>
<td>Myotonic dystrophy</td>
<td>↑</td>
<td>↑</td>
<td></td>
</tr>
<tr>
<td>Polymyositis</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acute</td>
<td>NI</td>
<td>↑ /BI</td>
<td></td>
</tr>
<tr>
<td>Chronic</td>
<td>↑</td>
<td>↑</td>
<td></td>
</tr>
<tr>
<td>Oculocraniosomatic</td>
<td>NI</td>
<td>↑</td>
<td>Similar to mild MG.</td>
</tr>
</tbody>
</table>

FD, fiber density; BI, impulse blocking; VRF, velocity recovery function; FSH, facioscapulohumeral; NI, normal; MG, myasthenia gravis.

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increases and vice versa, the changes being progressively more pronounced in the later components (the so-called "accordion effect"). This phenomenon is evidently caused by pronounced variability in the muscle AP propagation velocity, which differs considerably among muscle fibers with different diameters.

Jitter less than 5 µs can frequently be measured between spike components in complex potentials in these diseases, probably from APs from split muscle fibers.

Concomitant large jitter with blocking is occasionally seen, involving two or more spike components in a multiple potential. This could be due to an abnormal axonal branch supplying the muscle fibers involved, as may be seen in some neurogenic disorders. However, in muscle diseases, this is more likely to be due to a split muscle fiber with an abnormal motor end-plate; this is proven when the jitter is less than 5 µs between the APs in a blocking pair.

Becker and limb-girdle muscular dystrophy show similar, but considerably less pronounced abnormalities as described for Duchenne dystrophy.

Facioscapulohumeral Dystrophy. The SFEMG findings in facioscapulohumeral dystrophy tend to be considerably less pronounced than in other dystrophies. Even in weak muscles, the FD tends to be normal or only slightly increased, up to 2.5. Similarly, the mean duration of complex potentials is less abnormal. Jitter is increased in a small percentage of recordings but is usually within normal limits, even in facial muscles that are significantly involved by the disease process. These findings correlate well with the rather normal findings on conventional needle EMG.

Myotonic Dystrophy. In myotonic dystrophy, the FD and jitter are abnormal to a similar degree as in limb-girdle dystrophy; however, the myotonic discharges represent a distinguishing feature. The myotonic discharges consist of single-fiber APs and are similar in all myotonic conditions. Spontaneous activity of all types is usually less pronounced in SFEMG recordings than in concentric needle EMG, possibly because the SFEMG electrode records over a smaller distance and because the recording surface is distant from the tip of the needle, where spontaneous activity is generated by movement of the electrode through the muscle. The amplitude and duration of the APs in myotonia change continuously, with an initial shortening followed by a prolongation of the rise time and sometimes the appearance of a notch. Similarly, the amplitude of the AP initially increases and then decreases, occasionally to less than half the original amplitude.

The FD can be considerably increased in clinically most affected and atrophic muscles, and the jitter is abnormal in about 25% of the recordings.

Myotonia Congenita. In myotonic congenita, FD is usually normal, but jitter may be increased in about 10% of the recordings and some blockings may appear. In some patients with myotonia congenita, the amplitude of APs recorded with SFEMG electrodes may decrement markedly during stimulation of the intramuscular nerves at frequencies as low as 2 Hz. In other patients, however, this finding has not been seen, even when there was a marked decrement of compound muscle APs recorded from the tested muscle.

Polymyositis. The SFEMG picture in polymyositis varies considerably, depending not only on the severity of weakness but also on the stage of the disease. In the early stage, the FD is usually only slightly or moderately increased. The jitter, however, is increased in many components and blocking is frequent. Occasional concomitant blocking of two or several spike components suggests involvement of the motor axons or, more likely, immaturity of newly grown axonal sprouts. This may also account for the finding of very large jitter with little or no blocking in some spike components that may be seen in polymyositis.

Later when the disease becomes more or less arrested, the FD becomes more increased and may be very high in muscles with little atrophy and good recovery of strength. At the same time, the frequency of blocking becomes reduced, and the jitter becomes less abnormal.

SFEMG findings in polymyositis overlap considerably with those in other disorders, particularly muscular dystrophies. The proportion of recordings with abnormal jitter and particularly the frequency of blocking and, to a lesser extent, the FD values, can be used to monitor changes in the disease process and the extent and effectiveness of regeneration.

Congenital/Metabolic Myopathies. During attacks of hypokalemic periodic paralysis, jitter is increased with blocking and the FD may be decreased, presumably because some muscle fibers may not be excitable. Between attacks the SFEMG findings are normal. Later in life the FD tends to increase slightly.

FD is moderately increased in patients with central core disease. In mitochondrial myopathy, FD may be slightly increased and jitter increased. These findings may result from collateral reinnervation of mus-
Oculocraniosomatic Myopathy. In oculocraniosomatic myopathy, which usually presents as chronic progressive ophthalmoplegia, most patients have increased jitter, usually more marked in the facial than in arm muscles. FD is usually normal. Since this is also the pattern characteristic of MG, SFEMG findings may not distinguish these two conditions.

Summary. SFEMG findings can support the diagnosis of a muscle disorder and may be helpful in distinguishing between myogenic and neurogenic disorders, since in muscles of similar weakness, the FD tends to be much lower in myopathies than in neuropathies. Jitter is less useful in making this distinction.

The increase in FD in myopathies suggests that there is focal grouping in some areas and probably loss of fibers in other parts of the MU territory. The focal increase in FD is partly due to muscle fiber splitting. Other mechanisms include innervation of regenerated muscle fibers, packing of muscle fibers due to atrophy, and ephaptic recruitment of muscle fibers of other MUs. The increased jitter may be due to uncertain conduction in immature motor axons, transmission across immature or degenerating motor endplates, and threshold ephaptic transmission.

The SFEMG findings in some myopathies may occasionally resemble those of MG, although it is usually not difficult to distinguish between these conditions. In MG, jitter is typically greater in facial muscles, whereas most myopathies spare these muscles. It should be emphasized that although individual SFEMG findings are not specific for any disease, the relative degrees of abnormality of individual parameters, the distribution of abnormalities among different muscles, and their combination frequently assist in making the correct diagnosis, when correlated to the clinical picture and the results of other diagnostic techniques.

OTHER USES FOR SFEMG
Since SFEMG identifies the electrical activity from individual muscle fibers and thus from individual MUs, the technique can be used to "mark" MUs in a number of situations. This can be used for so-called spike-triggered averaging in macro EMG, surface recording of single MUs, and twitch studies of individual MUs. SFEMG can also be used to study axonal conduction and late responses (H-reflexes, F-waves, A-waves) from individual neurons.

REFERENCES