F wave size as a monitor of motor neuron excitability: the effect of deafferentation

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SUMMARY F waves have been recorded from hand or leg muscles following surgical section or traumatic avulsion of dorsal roots. It has been found that under these conditions F wave size can still be changed by manoeuvres which influence motor neuron excitability but that the size and direction of the changes are variable and may be dependent on the resting level of that excitability.

The F wave is a late response recorded in the electromyograph (EMG) of a muscle following stimulation of its nerve supply. Although the response was originally thought to be a reflex, subsequent work showed that it can result from a recurrent discharge in motor neurons following their antidromic activation. Although its most frequent clinical use has been in determining conduction velocity in the axons of motor neurons, there has also been some interest in the possibility of using F wave size as a method of measuring changes in motor neuron excitability. In contrast to the results of Mayer and Feldman both McComas et al and Sica et al reported that, in the normal human subject, F wave size increases during voluntary manoeuvres which increase motor neuron excitability and Trontell reported that the occurrence of F waves recorded in single muscle fibres could be facilitated by Jendrassik’s manoeuvre or by weak voluntary motor neuron activation. There have been numerous reports that F wave size increases in spasticity and decreases when tone is pathologically reduced; attempts have also been made to use the F wave to monitor procedures carried out to relieve spasticity.

Despite the development of these practical applications there are conflicting reports about the nature of the relationship between F wave size and motor neuron excitability and there is still uncertainty about the physiological basis of the observed changes. Although it has been established that F waves can be purely the result of a recurrent discharge in motor neurons, some experiments indicate that, especially under conditions of motor neuron excitation, the response may also include reflex components. Any increase in the size of the late response might then result from increased reflex activity rather than from changes in the size of the F wave per se.

We report two groups of observations on the F wave. The first results, which were obtained from patients who had extensive dorsal root sections, show that F wave size can still change during voluntary muscle activation, even in the absence of a sensory input from the stimulated nerve. The nature of the relationship between F wave size and motor neuron excitability was then investigated further in a group of experiments on decerebrate cats. Some of these results have been briefly reported.

Material and methods

Patients

The first patient was a 41 year old woman in whom posterior rhizotomies of C5-T2 had been carried out for the relief of intractable pain in the left arm after a brachial plexus injury. Examination revealed complete anaesthesia from C5-T2 and grade 4 weakness throughout the left arm. During the investigation the patient sat with the forearm and hand lightly fixed, with the elbow semiflexed and the hand held in a vertical plane. A ring around the thumb was connected to a strain gauge which was arranged to measure abducing forces. The output from the strain gauge was displayed on an oscilloscope which could be seen by the patient.

EMG recordings were made using surface electrodes placed over the thenar eminence; the activity was amplified and displayed in the conventional way and recorded on magnetic tape for subsequent analysis. F waves were evoked by stimulating the median nerve at the wrist, using 0.1 ms pulses at an intensity 1.25 times that which gave a maximum M response: F waves were identified by eye and the size of each response was measured by electronic integration. Average F
wave size was calculated from the responses evoked by 50 consecutive stimulus presentations in the control and each experimental situation. Control F wave size was measured with the hand as relaxed as possible. The patient was then asked to make and maintain a weak abduction movement of the thumb. The force level was displayed to the patient on the oscilloscope and this enabled her to maintain a constant force despite the absence of a sensory input from the hand. This level of muscle contraction induced only a very small amount of background EMG activity: in order to ensure, however, that any apparent change in F wave size was not caused by the recording of background EMG activity from the hand muscles, the following procedure was adopted in control and experimental records: after the onset and end of the F wave had been identified and its size measured by integration, the activity in the same period before the stimulus was measured in the same way and subtracted from the measured F wave size.

The second patient was an otherwise healthy 22-year-old man who had suffered a unilateral traumatic avulsion of the third, fourth and fifth lumbar posterior roots and all sacral posterior roots with preservation of the ventral roots. The extent of the injury was confirmed at laminectomy. There was total sensory loss in the left leg, extending from L3 downwards and grade 4 weakness of the left ankle. For this investigation the patient sat comfortably in a chair with the foot supported. F waves were recorded using surface electrodes placed over tibialis anterior following stimulation of the lateral popliteal nerve at the popliteal fossa. Recordings were made with the leg at rest and during a weak, sustained dorsiflexion movement at the ankle. In order to maintain constant muscle tension, in this instance the movement was made against an inflated sphygmomanometer cuff. The patient could see the column of mercury and was asked to maintain it at a constant level. Measurement of average F wave size was then made in a manner similar to that used for the first patient.

Decerebrate animals

Results are reported from experiments on 11 cats weighing between 2.7 kg and 5.4 kg. The cats were anaesthetised with halothane and made decerebrate at the level of the superior colliculus. The cerebellum was exposed by a further craniectomy. In those experiments in which dorsal root section was carried out, a brief paralysis was induced with iv suxamethonium and positive pressure ventilation carried out. The spinal cord and spinal roots were exposed and dorsal roots L2 to S5 were cut on the left side.

Stimulating electrodes were placed on the right sciatic nerve and the nerve was cut distal to the electrodes. Stimulating electrodes were also placed on the left tibial nerve at the level of the ankle. Wire electrodes, insulated except for the final 3 mm, were inserted into the left plantar muscles and used to record EMG activity. After all surgery was completed, halothane was discontinued and an interval of approximately 2 hours was allowed for decerebrate rigidity to develop. EMG activity was amplified using conventional circuitry, displayed on an oscilloscope and recorded on magnetic tape for subsequent analysis.

F waves were evoked by 0.1 ms stimuli applied to the left tibial nerve at an intensity which was at least 1.25 times that necessary to evoke a maximum M response. Stimuli were delivered at a rate of 1 Hz. The right sciatic nerve was stimulated at a rate between 10 and 50 Hz. The intensity was adjusted until a crossed extensor response was observed and subsequent stimulation was carried out at an intensity just below this level. The cerebellum was stimulated by a pair of silver ball electrodes, separated by a distance of 3 mm. Stimulus rate varied between 30 and 200 Hz. Intensity was adjusted until a reduction in extensor tone could be detected by manual examination.

F waves were identified and average size calculated in the manner described for the two patients above. In order to ensure that repeated antidromic activation did not itself lead to a significant change in F wave size, the mean size of the response evoked by the first 10 stimuli was compared with that evoked by the last 10 stimuli in each of the control groups of 50 stimuli: there was no significant difference between the two.

F wave size is extremely variable and even the mean size, calculated from 50 stimulus presentations, can change during the course of an experiment (vide infra). For this reason, in the present experiments, control F wave size was measured before and after each experimental procedure: results were only included if the two values differed by not more than 7%.

Results

Patients with dorsal root section

In the patient with cervical dorsal root sections, F waves were recorded from the left (afferented) hand with a latency of 27–32 ms. Mean F wave size was determined in the left hand, (a) with the hand relaxed, and (b) with the thumb exerting a minimal abduction force. Mean F wave size, with the hand at rest, was defined as 100%; weak abduction of the thumb increased mean F wave size by 38% (p < 0.05). Following relaxation of the hand F wave size returned to the control level (fig 1a). The patient was then asked to make a fist with her right hand, contracting the hand and forearm muscles as vigorously as possible: at the same time she was asked to make no voluntary movements with her left hand (absence of detectable voluntary activity in muscles of the left thenar eminence was confirmed by inspection of the EMG records). During this manoeuvre mean F wave size increased by 67% (p < 0.05) and returned to control level following relaxation (fig 1b).

F waves were also recorded from the right (unaffected) hand. During minimal abduction of the right thumb mean F wave size increased by 81% (p < 0.05).

In the patient with lumbosacral root sections, F waves were recorded with latencies of 32–36 ms. Mean F wave size in the anterior crural muscles was measured with the leg relaxed and during weak dorsiflexion of the ankle. During dorsiflexion mean F wave size increased by 87% (p < 0.01) (fig 1c).

The procedure was repeated on the unaffected side.
During a weak dorsiflexion movement mean F wave size increased by 23% (p < 0.01).

**Decerebrate animals**
At low stimulus intensity a small M wave was recorded together with a variable late response with a latency of 8–10 ms. With increased stimulus intensity the M wave became larger and reached a maximum size. Two late responses could then be seen, the first had a latency of 8–10 ms and the second had a latency of 12–15 ms: we identify the first of the late components as the F wave and the later as a polysynaptic reflex response (fig 2).

**Spontaneous changes in F wave size**
Although in some animals mean F wave size (estimated from 50 consecutive stimulus presentations) stayed reasonably constant, in others the value changed during the course of the experiment. In order to measure this variability F wave size was measured in each of five animals on eight occasions over a 2–4 hour period under constant experimental conditions. The maximum change which any single value showed from the mean of the estimates varied between 12% and 78% (mean = 33%).

Because of this variability it was important to ensure that following each experimental procedure the mean F wave size returned to the control level (see Methods).

**The effect of cerebellar stimulation**
Stimulation of the anterior vermis of the cerebellum at 50 Hz and 2.5 volts induced a reduction in the extensor rigidity. At the intensity at which a change in clinically observed tone was noted, there was a reduction in F wave size (mean reduction = 58%, p < 0.01).

**The effect of contralateral sciatic nerve stimulation**
The contralateral sciatic nerve was stimulated at a rate and at an intensity just below that which would...
Recordings were also made in another animal in which “resting” F wave size changed during the course of the experiment. The effect of contralateral sciatic nerve stimulation in this animal differed at different times. In the early part of the experiment, contralateral sciatic nerve stimulation evoked a consistent decrease in mean F wave size (mean reduction of 29% on four separate tests, carried out over a 4 hour period). “Resting” F wave size then fell by 43% and contralateral sciatic nerve stimulation then evoked a 14% decrease in F wave size. A further reduction in F wave size (to 7% of the initial value) then occurred: contralateral sciatic nerve stimulation (identical stimulus parameters to those used in the earlier part of the experiment) then resulted in a facilitation of mean F wave size (mean increase = 47%). The effect was consistent with repeat testing over a 2 hour period. Figure 3 illustrates this result. These results suggest that when resting F wave size was small, contralateral sciatic nerve stimulation induced an increase in F wave size, but when resting F wave size was larger, contralateral sciatic nerve stimulation induced a decrease in F wave size.

The effects of contralateral sciatic nerve stimulation following deafferentation

The effects of contralateral sciatic nerve stimulation were variable. In six experiments increases in F wave size were seen during stimulation of the contralateral sciatic nerve at an intensity just below that which evoked a crossed extensor reflex (mean increase in F wave size = 47%, p < 0.01). In three experiments, however, stimulation of the opposite sciatic nerve, at the equivalent intensity, induced a decrease in F wave size (mean decrease = 26%, p < 0.01).
Discussion

The F wave following deafferentation

Our results confirm the observations that F waves can be recorded following deafferentation.\(^4\)\(^5\)\(^2\)\(^5\)\(^2\)\(^8\) This indicates that the F wave can be the result of a purely recurrent discharge following antidromic activation of motor neurons. Under resting conditions, relatively few neurons give this recurrent discharge\(^3\)\(^16\)\(^3\)\(^1\)\(^2\)\(^3\)\(^2\)\(^2\) and hence the F wave is very much smaller than the M wave.

Our results also confirm previous observations\(^16\)\(^17\)\(^3\)\(^3\)\(^3\) that when dorsal roots are intact F wave size increases during manoeuvres which increase motor neuron excitability. In addition, however, we have shown that, following deafferentation, F wave size still changes when motor neuron excitability is changed by weak voluntary contraction of the muscle under investigation, by vigorous contraction of contralateral muscles or by synaptic activation following stimulation of sensory nerves from the contralateral limb. Since the sensory input has been interrupted there can be no reflex contribution to the late response and therefore the changes in response size reflect changes in the size of the F wave itself.

Changes in mean F wave size, as recorded in our experiments, imply that individual motor neurons change their frequency of recurrent discharge following antidromic invasion and/or that there is a change in the total number of motor neurons giving a recurrent discharge.

It follows from the earlier work carried out in the lumbosacral cord of the cat that the occurrence of a recurrent discharge\(^3\)\(^1\)\(^2\)\(^3\)\(^2\) in an individual neuron depends on the level of motor neuron depolarisation:\(^3\)\(^4\) (a) when the neuron is relatively hyperpolarised, the antidromic action potential fails to pass from the axon hillock into the soma (and there can therefore be no recurrent discharge); (b) over a small range of depolarisation, soma invasion occurs after an interval which is sufficiently long for the initial segment to have passed through its refractory period and hence a recurrent discharge occurs; (c) further depolarisation of the soma allows antidromic invasion to occur very rapidly (that is, at a time when the initial segment is still refractory) and no recurrent discharge is seen.

Using the single fibre EMG technique, Schiller and Stalberg\(^3\)\(^2\) studied the responses of individual motor units in normal and spastic man; they showed that the frequency of F wave occurrence in individual units is consistent with its dependence on soma depolarisation, as observed by Eccles\(^3\)\(^4\) in his direct recordings from motor neuron cell bodies.

If we assume that the mean size of the F wave recorded in our experiments reflects both the frequency of recurrent discharge following antidromic invasion in individual neurons and the total number of individual neurons giving a recurrent discharge, then our results are consistent with those obtained by Schiller and Stalberg\(^3\)\(^2\) and can again be explained on the basis of Eccles’ observations; that is, when activation of the motor neuron pool results in an increased number of motor neurons reaching the critical level of depolarisation, there is an increase in mean F wave size; when motor neuron activation occurs against a background of already existing depolarisation then many neurons which previously gave a recurrent discharge will fail to give recurrent discharges and mean F wave size falls. Schiller and Stalberg\(^3\)\(^2\) suggest that although individual neurons respond very infrequently (so that F wave size is only a small percentage of M wave size) F waves, over a period of time, arise from a large part of the motor neuron pool. This implies that the whole motor neuron pool may behave in a relatively homogeneous way so far as F wave generation is concerned and hence an increase in mean F wave size (recorded from a whole muscle) may occur over only a relatively small range of synaptic activation applied to the motor neuron pool as a whole.

The dependence of the direction of size change on the number of neurons entering a small, critical level of depolarisation could also explain the fact that Upton et al\(^2\)\(^8\) saw no change in F wave size during voluntary activation in patients who had undergone posterior root section, while in our similar investigation F wave size increased. According to the hypothesis under consideration F wave size may or may not change, depending on the background level of depolarisation in the motor neurons comprising the motor neuron pool.

Combination of F waves and reflex components when dorsal roots are intact

In our experiments, acute deafferentation was associated with a reduction in mean (resting) F wave size. Deafferentation is followed by complex effects on motor neuron excitability\(^5\) and there are many factors that could contribute to our observed reduction in F wave size (for example, a reduction in ongoing synaptic activation of motor neurons or unintended damage to the cord and ventral roots). However, the observation would be consistent with the removal of a reflex component to the late response.

It is likely that when dorsal roots are intact some H waves will be recorded at the same time as F waves.\(^2\)\(^5\)\(^2\)\(^7\)\(^2\)\(^8\) Stimulation of a mixed nerve (supramaximal for motor fibres) results in activation of all alpha motor neurons and of the large fibre afferents. Antidromic conduction in motor fibres reaches the
initial segment and some impulses will reach the soma: some will induce recurrent discharges (vide supra). Orthodromic conduction in very fast sensory fibres arrives at the soma (via synapses) before any antidromic impulses. In some motor neurons this leads to an action potential: under conditions of rest, however, this will not lead to an H wave because the action potential will collide with the antidromic action potential travelling towards the cord. However, an H wave will occur in two circumstances: (a) when there is ongoing activity in the motor neuron; in this situation the “spontaneous” action potential will collide with the antidromic action potential, enabling the orthodromic H wave to pass through the whole length of the axon and (b) when orthodromic sensory activation is via medium-fast sensory fibres (that is, slower than the fastest conducting motor fibres). Synaptic activation via these synapses arises at the soma after any antidromic impulse (which in many instances will terminate at the initial segment): therefore, if synaptic activation is sufficiently intense an orthodromic action potential will be initiated in the motor neuron, giving rise to an action potential in the muscle fibres at approximately the time at which an F wave would be expected.

For these reasons, when the dorsal roots are intact, it might be more appropriate to describe the late response evoked by supramaximal stimulation of a peripheral nerve as an F–H complex rather than simply as an F wave, particularly under conditions of partial motor neuron activation.

Change in F wave size in spasticity

Since, under appropriate conditions, motor neuron activation may lead to an increase, a decrease or no change in mean F wave size, it is at first sight a little surprising that the F wave should have gained some acceptance as an indicator of spasticity and be capable of being used to monitor changes in spasticity. We believe that there are two explanations for this. First, it has been shown that even in moderately severe spasticity very little ongoing EMG activity can be recorded. This suggests that, in these patients, large numbers of motor neurons may be partially activated without reaching the level of generating action potentials. In this situation it seems not unlikely that large numbers of motor neurons may be within the critical level of depolarisation. Thus, mean F wave size would be higher in the spastic limb than in the control limb and operative procedures to reduce tone would also reduce the number of neurons in the critical depolarisation range. In addition, we have discussed above, in patients with intact posterior roots, the observed increase in “F wave” size may be only in part due to an increase in the number of neurons giving a recurrent discharge: in addition, we think it is likely that a reflex discharge contributes to the overall size, so that the observed increase in this situation reflects an increase in the F–H complex.

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F wave size as a monitor of motor neuron excitability: the effect of deafferentation

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