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The H-reflex to Magnetic Stimulation of Lower-Limb Nerves

Yu Zhu, MD; Arnold Starr, MD; Su Hwan Su, MD; K. George Woodward, MD; Scott Haldeman, MD

• We elicited H-reflexes by magnetic and electrical stimulation of several different nerves in 10 healthy subjects and two patients with S-1 radiculopathy. The posterior tibial nerve at the popliteal fossa and the femoral nerve at the inguinal ligament were tested with both electrical and magnetic stimulation; the proximal sciatic nerve was tested only with magnetic stimulation. Muscle activity was recorded from the soleus muscle for posterior tibial and sciatic nerve stimulation and from the vastus medialis muscle for femoral nerve stimulation. No significant difference was found between the latency of H-reflexes evoked by magnetic or electrical stimulation. With magnetic stimulation, the mean (\pm SD) Ia sensory fiber conduction velocity in the proximal segment of the sciatic nerve was 72.4 ± 3.3 m/s, while the motor nerve fiber conduction velocity in the same portion of the nerve was significantly slower, at 60.6 ± 2.0 m/s. In two patients with unilateral S-1 radiculopathy, the latency of the H-reflex from the soleus muscle to both magnetic and electrical stimulation of the posterior tibial nerve was absent or prolonged on the affected side. Magnetic stimulation can be used to study the H-reflex and Ia fiber conduction velocity and is particularly advantageous when testing deeply located nerve trunks.

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Hoffmann¹ originally described the electrically induced monosynaptic reflex (H-reflex) occurring in calf muscles of humans on stimulation of the posterior tibial nerve at the popliteal fossa. The afferent limb of the reflex is mediated by group I sensory fibers of muscle origin, with the lowest threshold to electrical stimulation.² Magladery and

McDougal³ reported that afferent Ia fibers had a 10% faster conduction velocity than those of motor efferent axons. The H-reflex has subsequently been used to measure the conduction time in the proximal segment of the peripheral nerve and to study the excitability of motor neurons in the spinal cord.^{4,7} With the recent development of magnetic stimulation as a method to stimulate nerves,⁸ numerous studies of magnetic activation of motor fibers within mixed nerves in the upper limbs⁹⁻¹⁴ and motor nerve roots at the cervical or lumbar regions have been conducted.^{15,16} The extremely short duration of the magnetic stimulus has been assumed to be inadequate for direct Ia fiber excitation.^{12,14,17} We tested Ia fiber responsiveness in nerves of the lower extremity to magnetic stimulation with the use of H-reflexes.

SUBJECTS AND METHODS

Ten healthy subjects (six men and four women; age range, 29 to 44 years; height, 157 to 192 cm) participated in the study after giving informed consent. For soleus muscle H-reflex testing, the subjects lay relaxed in a prone position with a pillow placed under the ankles to maintain the knee joint at 120°. The skin temperature was maintained above 34°C. Recording electrodes were Ag/AgCl disks (8 mm in diameter) placed 3 cm apart over the soleus muscle belly, with their lead wires twisted together to reduce the amplitude of the stimulation artifact from the magnetic coil. The potentials were amplified with a bandwidth of 15 Hz to 1.5 kHz.

In all subjects, H-reflexes were elicited from stimulation of the posterior tibial nerve at the popliteal fossa with magnetic or electrical stimulation. Electrical stimulation was performed with bipolar electrodes placed 2.5 cm apart with the cathode proximal. The duration of the rectangular pulse was 1 millisecond. Magnetic stimulation was delivered with a Cadwell MES-10 magnetic stimulator (Cadwell Laboratories, Inc, Kennewick, Wash). The edge of a circular coil with a focal point at its tip having a dimension of 9.5 cm or

5.5 cm (hereafter referred to as the "9-cm coil" or the "5-cm coil") was placed tangentially to the skin overlying the posterior tibial nerve. The middle of the contacting edge of the coil was placed at the site of the electrical cathode. A brief, 0.07-millisecond pulse, up to 3000 V at maximal output, was passed through the coil by the discharge of capacitors. The changing magnetic field induced electrical currents within the tissue. Peak magnetic flux intensity at the center of the coils is approximately 2.0 T.¹⁸ The intensity of the magnetic stimulus was raised until a maximal H-reflex was elicited. The onset latency of the H-reflex and the M wave was defined to the initial deflection. Peak-to-peak amplitudes of the potentials were measured. The maximal amplitudes of the H-reflex (H_{max}) were defined with magnetic and electrical stimulation. The maximal amplitude of the M wave (M_{max}) was defined with electrical stimulation but could not be achieved with magnetic stimulation, even with 100% output.

A comparison of soleus muscle H-reflexes with the use of magnetic coils 9 and 5 cm in diameter was performed in six subjects. In a comparison of magnetic and electrical stimulation, the 9-cm coil was used in all 10 subjects. The effect of the direction of current flow in the 9-cm coil on the latencies and amplitudes of the M waves or H-reflexes was studied in four subjects with the edge of the coil placed tangentially to the skin overlying the posterior tibial nerve at the popliteal fossa. The current flow in the section of the edge of the coil covering the nerve was defined as either rostral or caudal.

In two of the subjects, electrical stimulation with very short durations of 0.1, 0.07, 0.05 and 0.04 milliseconds was also applied to the posterior tibial nerve at the popliteal fossa to compare the thresholds of the H-reflex and the M wave response as a function of stimulus duration. The effect of vibration on the soleus muscle H-reflex was studied in two subjects during magnetic stimulation. Vibration was produced by activating a rod that had a 4-cm diameter ring at its tip. The ring was applied onto the Achilles tendon. The frequency of the vibration was 60 Hz.

In two patients with unilateral S-1 radiculopathy confirmed by magnetic resonance imaging or during operation, the soleus mus-

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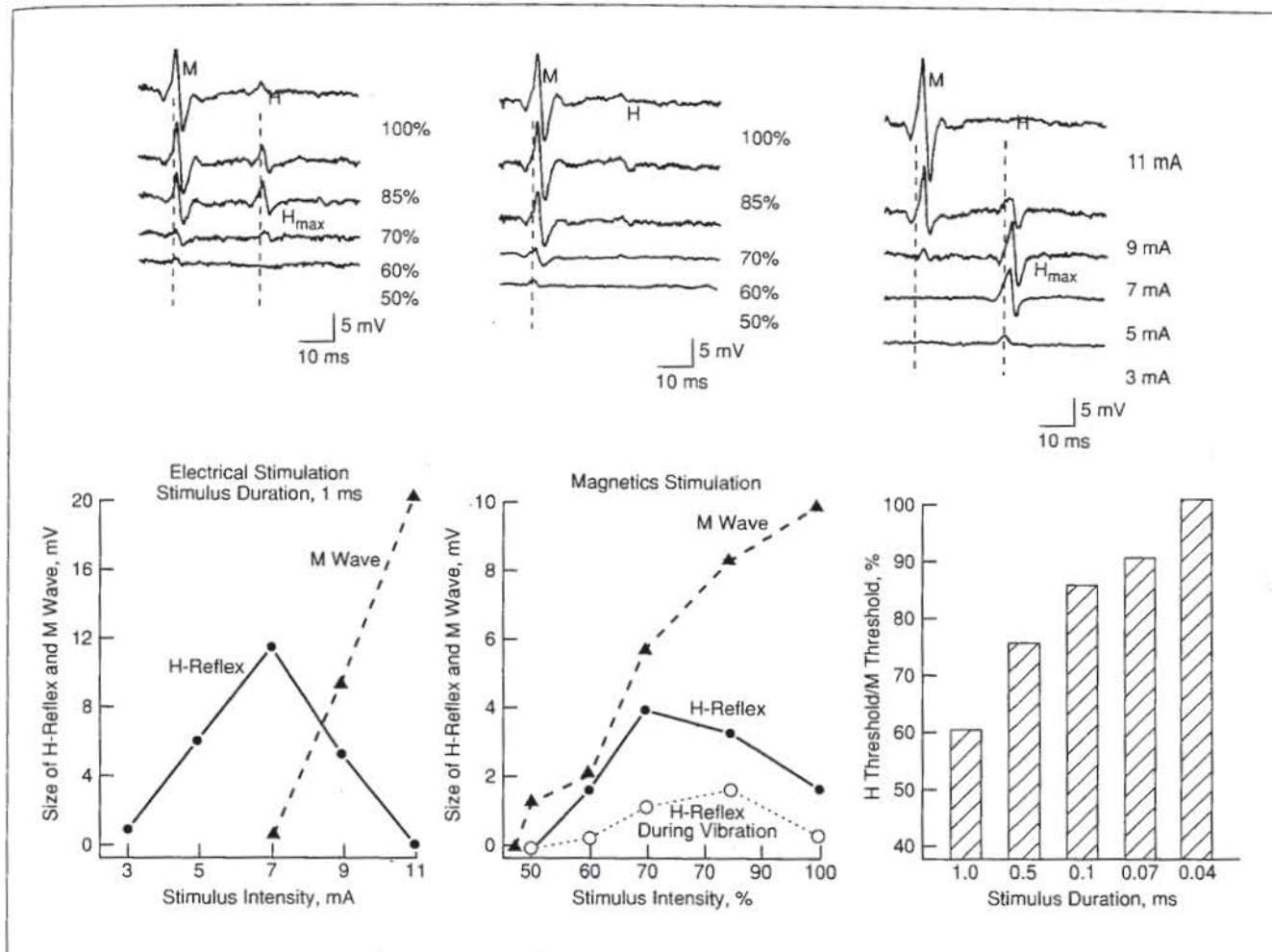


Fig 1.—H-reflexes from soleus muscle in a healthy subject elicited by magnetic stimulation (top left) and by electrical stimulation (top right) to the posterior tibial nerve at the popliteal fossa. The responses to progressively increasing stimulus intensities were recorded. The maximal amplitude of the M wave (M_{max}) was not obtained by magnetic stimulation at maximal stimulus output. Vibration at 60 Hz to the Achilles tendon significantly decreases the amplitude of the H-reflex (top middle). The maximal amplitude of the H-reflex (M_{max}) obtained by the two forms of stimulation have different amplitudes and different associations with the occurrence of the M wave response (bottom left, bottom middle). The stimulus duration shows a significant influence on the H-reflex threshold/M wave threshold ratio (bottom right). Negativity at grid 1 of the amplifier for compound muscle action potentials is displayed upward in this and all subsequent figures.

cle H-reflex was tested on both sides.

In five subjects, the H-reflex from the quadriceps muscle was tested with magnetic and electrical stimulation to the femoral nerve in the inguinal region. The subjects were relaxed and in the supine position. The femoral nerve was stimulated with a 9-cm coil for magnetic stimulation and with a pair of surface electrodes for electrical stimulation. The recording disk electrodes were placed 1.5 cm apart over the vastus medialis muscle.

In seven subjects, magnetic stimulation at several points along the sciatic/tibial nerve extending from the low back down to the midcalf was performed to elicit the H-reflex. The sciatic/tibial nerve was stimulated at the first sacral vertebra, the midpoint of the gluteal fold, the posterior thigh between the gluteal fold and the popliteal fossa, the popliteal fossa, and the belly of the gastrocnemius.

For stimulation of the S-1 nerve root, the edge of the coil was placed over the first dorsal sacral foramen on the side tested, which was about 2 cm from the median sacral crest. The distances between the stimulation sites were measured with a tape. The conduction velocities of Ia sensory fibers and motor nerve fibers at the segment between the popliteal fossa and the S-1 level of the spinal column were calculated. For the calculation of Ia sensory fiber conduction velocity (IaCV), the distance from the stimulus site at the popliteal fossa to the first dorsal sacral foramen was divided by the peak latency difference of the soleus muscle H-reflexes recorded from stimulation of the sciatic nerve at the popliteal fossa and the first dorsal sacral foramen. For the calculation of motor nerve fiber conduction velocity (MCV), the same distance between the two stimulation sites was divided by the difference be-

tween the onset latency of soleus muscle M waves obtained from the two stimulating sites.

RESULTS

9-cm Coil vs 5-cm Coil

With both coils, magnetic stimulation of the posterior tibial nerve at the popliteal fossa evoked an H-reflex in the soleus muscle in six subjects tested (Fig 1, top left). The H-reflex threshold was $55\% \pm 2.6\%$ for the 9-cm coil and $66\% \pm 2.5\%$ for the 5-cm coil ($P < .05$). There was no significant difference between the latencies of the soleus muscle H-reflexes evoked by the two magnetic coils (29.5 ± 1.7 milliseconds for the 9-cm coil vs 29.6 ± 1.8 milliseconds for the 5-cm coil).

Direction of Current Flow in the Coil

The direction of current flow in the coil affected the amplitude of the M wave and H-reflex responses but not their latencies (Fig 2). In five subjects studied, the M wave had a significantly higher amplitude when current flow in the coil was directed rostrad rather than caudad ($15.0\% \pm 3.2\%$, $P < .05$). The latency of both the M wave and the H-reflex was not affected by the direction of current flow. A rostrad current flow was used in all subsequent studies.

Stimulation Intensity and the Amplitude of the H-reflex and the M Wave

When the magnetic coil was placed over the posterior tibial nerve at the popliteal fossa, the stimulus strength necessary to produce an H-reflex was slightly higher than that to produce an M wave response (Fig 1, top left). In 10 subjects, the threshold for soleus muscle H-reflex from stimulation of the posterior tibial nerve at the popliteal fossa was $55\% \pm 2.6\%$ of the maximal output compared with $48.5\% \pm 2.8\%$ of the maximal output for the threshold of the M wave response ($P < .05$). It is apparent from Fig 1, top left, that with just suprathreshold stimulation, only a minimal M wave response occurred at a latency of 6 milliseconds before the appearance of the H-reflex. With progressively stronger stimulation, the M wave increased and the H-reflex appeared. Further increases in stimulus intensity were accompanied first by a progressive increase in the amplitude of both M wave and H-reflex responses and then by a decline in the H-reflex amplitude, while the M wave continued to increase. The H_{max} usually appeared at a stimulus intensity approximately 70% to 85% of the maximal output. The H-reflex decreased in amplitude with further increases in the stimulus output (Fig 1, bottom middle). In contrast, H-reflex thresholds were consistently lower than M wave thresholds with electrical stimulation pulse durations of 1.0 milliseconds (Fig 1, top right and bottom left). In two of the subjects tested, H-reflex thresholds were also lower than M wave thresholds with electrical stimulus durations of 0.5, 0.1, and 0.07 milliseconds, while at a stimulus duration of 0.04 milliseconds, the M wave and H-reflex responses appeared at the same threshold (Fig 1, bottom right). The amplitude of the H-reflex was significantly reduced ($P < .01$) when vibration at 60 Hz was applied to the Achilles tendon during magnetic stimulation of the posterior tibial nerve (Fig 1, top middle).

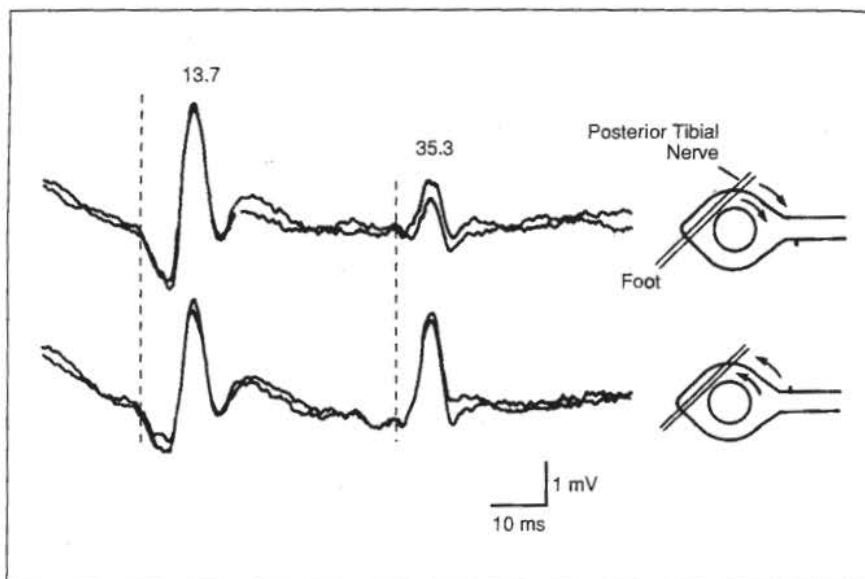


Fig 2.—Effect of reversal of current flow in a 9-cm round magnetic coil during magnetic stimulation of the posterior tibial nerve at the popliteal fossa. Each tracing represents the mean of three responses.

Table 1.—Soleus H-reflex From Stimulation to the Posterior Tibial Nerve at the Popliteal Fossa*

	Latency, m/s	Difference Between Two Sides, m/s	Amplitude, mV	Difference Between Two Sides, mV
Magnetic stimulation	30.7 ± 2.5	0.7 ± 0.5	2.5 ± 1.9	2.1 ± 1.9
Electrical stimulation	30.6 ± 2.3	0.6 ± 0.5	4.9 ± 1.6	2.5 ± 1.0

* Values are mean \pm 1 SD in 10 healthy subjects.

A soleus muscle M_{max} was never obtained with magnetic stimulation of the posterior tibial nerve at the popliteal fossa. The maximal amplitude of the soleus muscle M wave obtained with magnetic stimulation was approximately 70% of the M_{max} defined by electrical stimulation. The soleus muscle H_{max} obtained with magnetic stimulation was approximately 40% to 60% of the H_{max} elicited from electrical stimulation.

Normal Values for Latency and Amplitude of the Soleus Muscle H-reflex

Normal values for the latency and amplitude of the soleus muscle H-reflex elicited by magnetic stimulation to the posterior tibial nerve at the popliteal fossa and the interside difference are shown in Table 1. The onset latencies for both the H-reflex and the M wave did not change with stimulus strength or direction of the current flow in the coil (Figs 1 and 2). No significant difference was found between absolute latencies (Fig 3, left) and interlimb latency differences (Table 1) of the soleus muscle

H-reflex to magnetic and electrical stimulation. The amplitude of H_{max} elicited by magnetic stimulation was significantly lower ($P < .01$) and showed a wider range of differences, both between subjects and between the two limbs, than the H_{max} elicited by electrical stimulation.

Stimulation Along the Sciatic Nerve

Magnetic stimulation with the 9-cm coil excited both Ia sensory fibers and motor nerve fibers at different sites along the length of the sciatic/tibial nerve (Fig 4). In all seven subjects tested, H-reflexes from soleus muscle were easily recorded from stimulation of the sciatic/tibial nerve at the first sacral vertebra, the posterior aspect of the thigh between the gluteus and the popliteal fossa, the popliteal fossa, and the belly of the gastrocnemius. In three of the subjects who were relatively thin, H-reflexes were also reliably recorded when magnetic stimulation was applied at the midpoint of the gluteal fold. H-reflexes were never obtained when the coil was placed over the gluteus

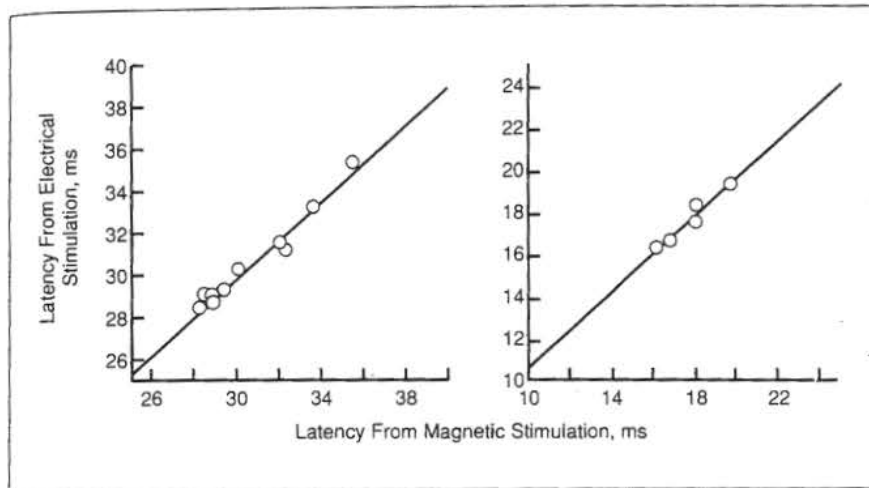
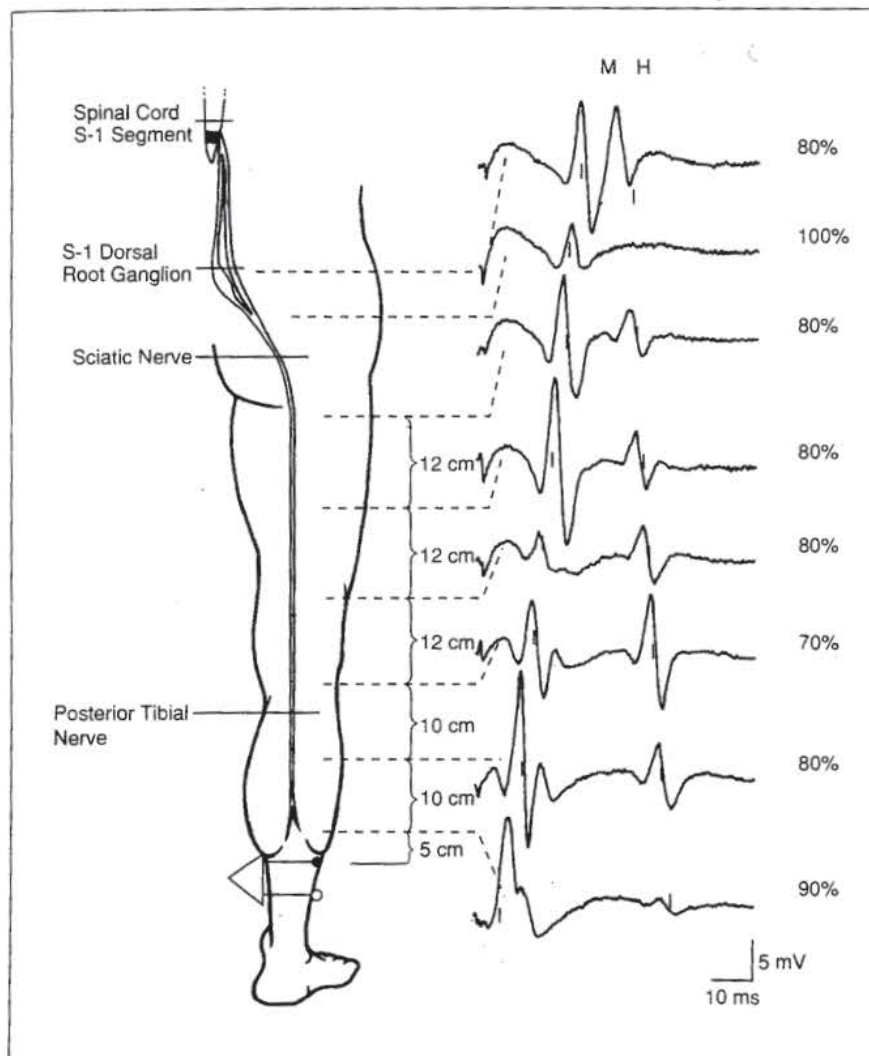


Fig 3.—The latencies of the soleus muscle H-reflex from magnetic stimulation of the posterior tibial nerve at the popliteal fossa (left) and the quadriceps muscle H-reflex from stimulation of the femoral nerve at the inguinal region (right). Each point represents results from a single subject.

Fig 4.—Soleus muscle H-reflexes elicited by magnetic stimulation at different points along the length of the sciatic/tibial nerve. Note the progressive increase in M wave latency and decrease in the H-reflex latency as the stimulation was moved in the rostral direction. No H-reflex was recorded when stimulation was applied to the nerve segment under the gluteus maximus muscle.



maximus (second tracing from the top in Fig 4). It was not possible to elicit an H-reflex with the 5-cm coil following stimulation at sites other than the popliteal fossa.

Magnetic Stimulation of Sacral Nerve Roots

In all seven healthy subjects tested, magnetic stimulation with the 9-cm coil to the S-1 nerve roots at the sacrum usually produced a complex of responses that consisted of two distinct components: the M wave and the H-reflex. The difference between the peak latency of these two major components was approximately 6 milliseconds. Figure 5 shows the responses from soleus muscle with the use of magnetic stimulation applied to the S-1 vertebra at different stimulus intensities. An H-reflex occurring in isolation from the M wave response was elicited with a stimulus intensity at 80% (the bottom tracing in Fig 5). The thresholds of the H-reflex at this stimulus site were lower than that of the M wave response in the three subjects tested.

IaCV and MCV

Table 2 shows that the IaCV was 18.9% faster than MCV in the segment between the popliteal fossa and the first sacral vertebra in seven healthy subjects. During sacral nerve root stimulation, it was difficult to define the onset latency of the H-reflex in four cases because the H-reflex was partially contiguous with the preceding M wave. The peak latency of the major negative phase of the H-reflex was measured to calculate the IaCV. In three subjects with a clear onset of the H-reflex, the IaCV measured to the peak of the major negative phase showed no significant difference from that measured to the onset of the H-reflex.

Quadriceps Muscle H-reflex in Healthy Subjects

A quadriceps muscle H-reflex was obtained bilaterally in four of the five subjects tested with both magnetic and electrical stimulations (Fig 6). In two subjects, H-reflexes could be recorded when the subjects were relaxed. In the other two subjects, facilitation from voluntary contraction of the muscle tested was needed to obtain an H-reflex with both magnetic and electrical stimulation. In the fifth subject, a quadriceps muscle H-reflex was obtained on one side with facilitation but could not be obtained on the other side. No significant difference was noted in the latency of the quadriceps muscle H-reflex between magnetic stimulation (18.5 ± 0.9 milliseconds) and electrical stimulation

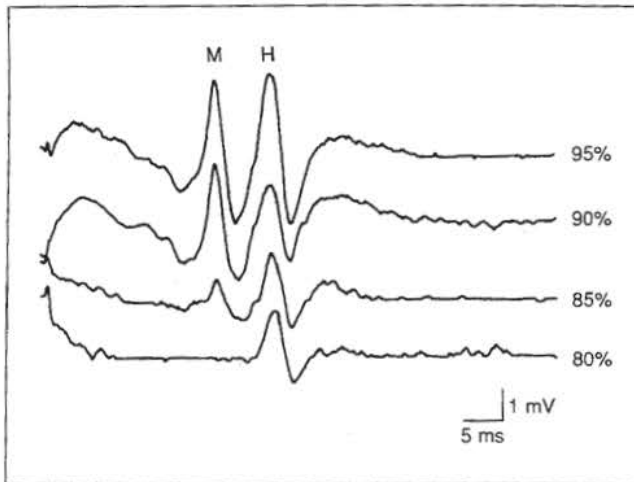


Fig 5.—The response complex of the H-reflex and M wave from the soleus muscle in a healthy subject elicited by magnetic stimulation of the S-1 root. Note the stability of the peak latency of the H-reflex and the onset latency of the M wave compared with the significant variation in their amplitudes. The peak latency interval between the H-reflex and M wave responses was 6.6 milliseconds. At 80% of maximal stimulation, an H-reflex was recorded without a preceding M wave (bottom tracing).

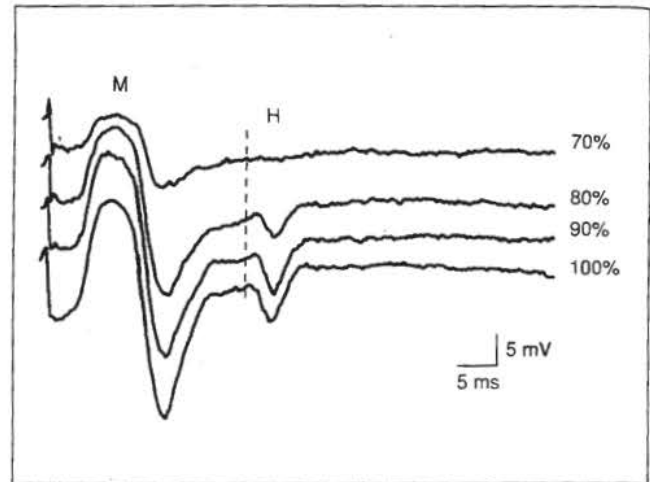


Fig 6.—The H-reflex from the vastus medialis muscle elicited by magnetic stimulation to the femoral nerve at the inguinal region in a healthy subject.

Table 2.—Ia Sensory Fiber and Motor Nerve Fiber Conduction Velocity in the Sciatic/Tibial Nerve Segment Between the Popliteal Fossa and the S-1 Vertebra (m/sec)

Subject No.	Ia Sensory Fiber (IaCV)*	Motor Nerve Fiber (MCV)†	MCV/IaCV, %
1	73.6	60.5	82.2
2	75.4	59.6	79.0
3	76.0 (75.4)‡	63.3	83.3
4	74.4	60.7	83.9
5	70.5 (70.0)‡	57.8	82.0
6	66.6 (67.3)‡	59.0	88.6
7	70.2	63.1	89.9
Range	66.6 - 76.0	57.8 - 63.3	79.0-89.9
Mean‡	72.4 ± 3.3	60.6 ± 2.0	84.1 ± 3.8

*Values represent latency measured to the peak of the major negative phase. IaCV indicates Ia sensory fiber conduction velocity.

†Values represent latency measured to the onset of the response. MCV indicates motor nerve conduction velocity.

‡Values are mean ± 1 SD in seven subjects.

(18.4 ± 0.6 milliseconds) (Fig 3, right). The mean threshold of the quadriceps muscle H-reflex by magnetic stimulation was $75.0\% \pm 3.0\%$. In each case, the threshold of the quadriceps muscle H-reflex was higher than that of the M wave.

Soleus Muscle H-reflex in S-1 Radiculopathy

In one patient, the H-reflex was absent on the affected side with both magnetic and electrical stimulation. In another patient, the latency of the H-reflex on the affected side was 3 milliseconds longer than on the other side, which was beyond the upper limit value (1.7 milliseconds).

COMMENT Latency of the H-reflex

We examined the suitability of magnetic stimulation to elicit the H-reflex. This study was prompted by our previous finding that Ia afferent fibers can be activated by magnetic stimulation of the muscle or nerve trunk.¹⁹ Our results show that there is no difference between the latencies of the H-reflex produced by magnetic and electrical stimulation of selected nerves in the lower extremities. The latencies of the H-reflex evoked by magnetic stimulation are stable over a range of intensities, suggesting that the Ia nerve fibers that are

activated initially are large with fast conduction velocities. This result is similar to that obtained by Cros et al,¹⁶ who observed that the large-diameter, fast-conducting motor fibers are activated by magnetic stimulation before slow conducting ones. Our finding that the latencies of both H-reflex and M wave responses showed little shift when the current flow in the coil is reversed is believed to be secondary to the biphasic configuration of the major complex of the induced voltage flow produced by the Cadwell MES-10 magnetic stimulator.^{9,20}

IaCV

One advantage of magnetic stimulation is the ease with which an H-reflex can be elicited from a deep nerve, such as the sciatic nerve in the thigh or the sacral nerve roots, which are difficult to test with percutaneous electrical stimulation. The use of magnetic stimulation to evoke H-reflexes may help to reveal lesions in proximal segments of peripheral nerve, plexus, and root. The ability to stimulate multiple sites along the nerve by the magnetic coil allows a separate calculation of proximal segmental conduction velocities along Ia sensory and motor nerve fibers. The IaCV at the segment between the popliteal fossa and the S-1 sacral foramen (72.4 ± 3.3 m/s) averages approximately 19% higher than the MCV (60.6 ± 2.0 m/s) in the same segment of sciatic nerve (calculated as $72.4 - 60.6/60.6 = 19\%$). Different values for the IaCV in humans have

been reported. Using needle electrodes to stimulate the sciatic nerve in the posterior aspect of the thigh and surface electrode at the popliteal fossa, Magladeri and McDougal² reported a value of 60.4 m/s at the segment between the popliteal fossa and the site 9 cm proximal, whereas Mayer and Mawdsley²¹ reported a value of 82.6 m/s between the popliteal fossa and the site 20 cm proximal. The value at the segment between the popliteal fossa and the S-1 sacral foramen reported here is compatible with the measurement of 72.2 ± 4.2 m/s at the same segment attained with an indirect method derived from a recording of both the H-reflex and the F wave of the gastrocnemius.²² The different values of the IaCV reported in these studies may be due to the different techniques used or the different segments of the sciatic nerve tested.

Quadriceps Muscle H-reflex to Magnetic Stimulation

Several features support the concept that the late potential recorded from the vastus medialis muscle with magnetic stimulation is an H-reflex opposed to a F response. The H-reflex is recorded at submaximal stimulation intensity for the M wave and is greatly facilitated by voluntary contraction of the muscle tested. The waveform is constant in latency, with an amplitude of several millivolts. The clinical usefulness of the quadriceps muscle H-reflex has been limited because of the inconsistency in obtaining this reflex by electrical stimulation. This was believed to be due to the relatively deep location of the femoral nerve at the inguinal region compared with the posterior tibial nerve at the popliteal fossa.^{23,24} Our study shows that magnetic stimulation has no particular advantage over electrical stimulation in eliciting an H-reflex from the quadriceps muscle.

H_{max} and M_{max}

M_{max} could not be achieved by magnetic stimulation to the posterior tibial nerve at the popliteal fossa. H_{max} obtained by magnetic stimulation was 40% to 60% of the H_{max} to electrical stimulation. Thus, the magnetic stimulator we used was unable to provide a reliable measurement of H_{max}/M_{max} as an index of the excitability of α motor neurons or the degree of damage to the axons of the sciatic nerve.²⁵

H-reflex Threshold to Magnetic Stimulation

The fact that the soleus muscle H-reflex threshold is usually higher than the M wave threshold with magnetic

stimulation of the posterior tibial or femoral nerves suggests that magnetic stimulation applied to a mixed nerve activates Ia afferents at a higher threshold than motor nerve fibers. This observation is in agreement with that of other studies showing that magnetic stimulation can preferentially activate motor but not sensory axons.^{19,26} This is in contrast to electrical stimulation (usually of 0.2 to 1.0 milliseconds in impulse duration) of the nerve, which activates sensory axons at lower stimulus levels than needed to activate motor axons. The differences in thresholds between sensory and motor nerve fiber activation to magnetic and electrical forms of stimulation are likely due to differences in their stimulus duration: with magnetic activation, the stimulus is extremely brief (0.05 milliseconds), whereas for electrical activation, the stimulus is usually of longer duration.^{17,27} Thus, when electrical stimulus duration was reduced to 0.04 milliseconds in our study, the thresholds for H-reflex and M wave became the same. One exception to this is that when magnetic stimulation was applied to the sacral nerve roots at the sacral region, the threshold of the H-reflex was lower than that of the M wave in three subjects tested. This may reflect the separation of sensory and motor fibers into distinct roots in this region.

The clinical usefulness of magnetic stimulation to elicit H-reflexes is suggested by the abnormal findings we observed in the two patients tested in our study who clearly had S-1 radiculopathy.

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