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Electroencephalography and clinical Neurophysiology 97 (1995) 332-340

Comparison of various coils used for magnetic stimulation of peripheral motor nerves: physiological considerations and consequences for diagnostic use [1]

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Accepted for publication: 26 June 1995

Abstract

We compared the ability of 4 magnetic coils to activate peripheral nerves in healthy subjects. No differences in motor threshold intensities were found between the coils, but the intensities needed to elicit maximum compound muscle action potential (CMAP) amplitudes were different. For superficial nerves maximum CMAPs in comparison with electrical stimulation were usually but not always found. CMAPs were at their maximum only when the direction of induced current flowed from proximal to distal and when a certain part of the coil was over the nerve. Distal nerve stimulation was time consuming. Due to artifacts many stimuli were necessary and sometimes no maximum CMAP could be elicited. CMAPs were much less sensitive to position changes of the coil than to changes in an electrical stimulator. Small circular coils were superior to larger coils in terms of the lower intensities necessary to elicit maximum CMAPs, better focusing of the stimulus, and less artifacts. For deep nerves amplitudes were always submaximal. Coactivation of nearby nerves and underlying muscles was another main drawback especially at proximal sites and for coils of large diameter. Despite better focusing, double coils are less useful due to their great diameter. Magnetic stimulation cannot replace electrical neurography at the moment, even if different coils are used at different sites of stimulation.

Keywords: Magnetic stimulation; Peripheral nerve; Conduction studies

1. Introduction

In the last few years magnetic stimulation has been used increasingly for research and clinical investigation of peripheral nerves. The magnetic technique is less painful for the patient compared to electrical stimulation, and allows for the depolarization of deep-lying nerves (Evans, 1991; Jalinous, 1991). The judgment of the practical applicability and reliability of the results of the investigation of peripheral nerves varies between researchers (Evans et al., 1988, 1990; Olney et al., 1990). The reasons for the variability in the results are: (1) poor knowledge of the actual site of stimulation, despite good mathematical models of magnetic stimulation of axons (Roth et al., 1990a,b) and simulation experiments (Maccabee et al., 1990, 1991); (2) the various magnetic stimulation coils and devices used, differ in their stimulation characteristics; and (3) stimulation sites as well as different positioning and handling of the coil.

The goal of the present study was to compare various commercially available magnetic coils, commonly used in magnetic stimulation of peripheral nerves. The comparison between various coils as well as between magnetic and electrical stimulation was done with regard to: (1) threshold stimulus intensity necessary to elicit a motor response, (2) change of onset latencies, areas, and amplitudes of the compound motor action potentials (CMAP) using increasing stimulus strength, (3) maximum amplitude and area of the CMAP in comparison to electrical stimulation, (4) the actual site of magnetic stimulation, the virtual cathode, in comparison to the electrical cathode, (5) effects of longitudinal and lateral spread of the stimulus on the CMAP, and (6) handling of various coils at different stimulation sites.

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[1] Presented in part at the IXth International Congress of Electromyography and Clinical Neurophysiology in Jerusalem, 8-12 June 1992.

SSDI 0013-4694(95)00146-8

EEM 94640

2. Methods

Sixteen healthy subjects, aged 21–57 years (mean 37 years; weight 52–92 kg) who gave informed consent were investigated. In all subjects the median and ulnar nerves were studied with stimulation at the wrist, elbow, and at Erb's point. In 10 subjects the median and ulnar nerves at the proximal part of the upper arm, the sciatic nerves at the gluteal fold and the peroneal nerves at the fibular head were studied.

2.1. Recordings

The CMAPs of various muscles (abductor pollicis brevis, abductor digiti quinti, extensor digitorum, biceps brachii, deltoid, extensor digitorum brevis, abductor hallucis) were recorded using surface electrodes mounted in a belly-tendon style. The small muscles of the hand innervated by the median and ulnar nerves were recorded at the same time to detect simultaneous activation of both nerves.

The signals were amplified using a Tönnies 4-channel EMG machine with a bandpass of 2 Hz–10 kHz. The recordings were checked on an oscilloscope, A/D converted using CED 1401 hardware, and stored on the hard disk of a PC. The data were analyzed using the Spike 2 program (Cambridge Electronic Design Ltd., Cambridge, UK). The onset of the CMAP was determined automatically as the moment when the negative value exceeded the baseline by 30 μV. CMAP amplitudes were measured from peak to peak, total CMAP area from the onset until the end of the CMAP, and the CMAP negative area from the start of the potential to the baseline crossing of the downward phase following the maximum positive peak.

The amplitudes and areas were plotted against the intensity of the stimulator devices. For the comparison of various coils and subjects areas and amplitudes were normalized with the individual maximum amplitude or area set at 1 (= 100%). The plot of the amplitude versus stimulus strength is called the recruitment curve (Fig. 1). Since the maximum amplitude of CMAP was slightly unstable the value at 98% of the mean maximum amplitude was taken for statistical analysis.

2.2. Electrical stimulation

Percutaneous electrical stimulation was performed using a constant current stimulator (Tönnies, Freiburg, Germany). The duration of the square-wave pulse was 0.1 msec. A bipolar surface electrode with an inter-electrode distance of 2.3 cm was used (Medelec). To bring the cathode as close to the nerve as possible, a position was sought where a CMAP could be elicited with the lowest stimulus intensity. This site was marked on the skin and used as reference point for further investigations.

2.3. Magnetic stimulation

To compare 2 different types of magnetic stimulator devices, all studies were performed using a Magstim 200 (Magstim Company, Whitland, Dyfed, UK) and a Cadwell MES-10 (Cadwell Laboratories, Inc., Kennewick, WA, USA). The main difference between the 2 stimulators is the wave form of the magnetic pulse. The Magstim 200 produces a roughly monophasic pulse with a rise time of about 100 μsec and a maximum stimulus duration of 1 msec using circular coils. In contrast, the wave form of the MES-10 stimulator is a damped, oscillating cosine wave with a rise time of 75–100 μsec. The stimulation is assumed to have occurred by the end of the first phase (Barker, 1991).

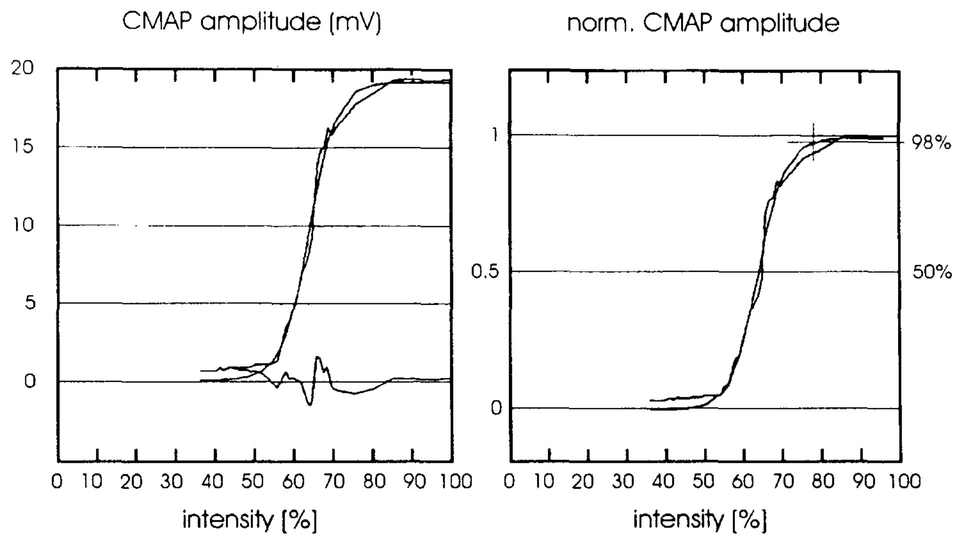

Fig. 1. Recruitment curve: stimulus intensity versus CMAP amplitude of the abductor pollicis brevis muscle using the 40 mm circular coil at the cubital fossa. Left: CMAP amplitudes of a recording and fitting curve; the curve around the zero line represents the variation of the actual values from the fit curve. Right: normalization of the amplitude curve shown on the left; the maximum amplitude is set at 1.0.

With the Magstim stimulator we used a 90 mm circular coil, a 40 mm circular coil, and a 70 mm double coil. The coils differ in their physical properties, i.e., magnetic flux density, maximum induced electrical field strength, and induced charge density per phase as well as in the geometry of the induced fields (Barker, 1991). The technical data of the coils used in this study were recently summarized by Jalinous (1991). With the Cadwell stimulator a focal point coil was used, a circular coil whose windings nearly form a right angle at the tip of the coil. This configuration is thought to produce a more focused stimulation. The maximum electrical field is similar to the 90 mm Magstim coil (Claus et al., 1990). The coils were fixed in a special holder during the investigations to avoid displacement and thus to guarantee a stable position. Unless otherwise stated, all studies were performed with the direction of the induced current along the course of the nerve, i.e., from proximal to distal. The common expression, "A" (or B) side of the coil, is indistinct when reporting results of peripheral nerve stimulation and should, therefore, be avoided. With either A or B side directed towards the nerve the direction of the induced current can be from proximal to distal or vice versa depending on the position of the coil in relation to the handle.

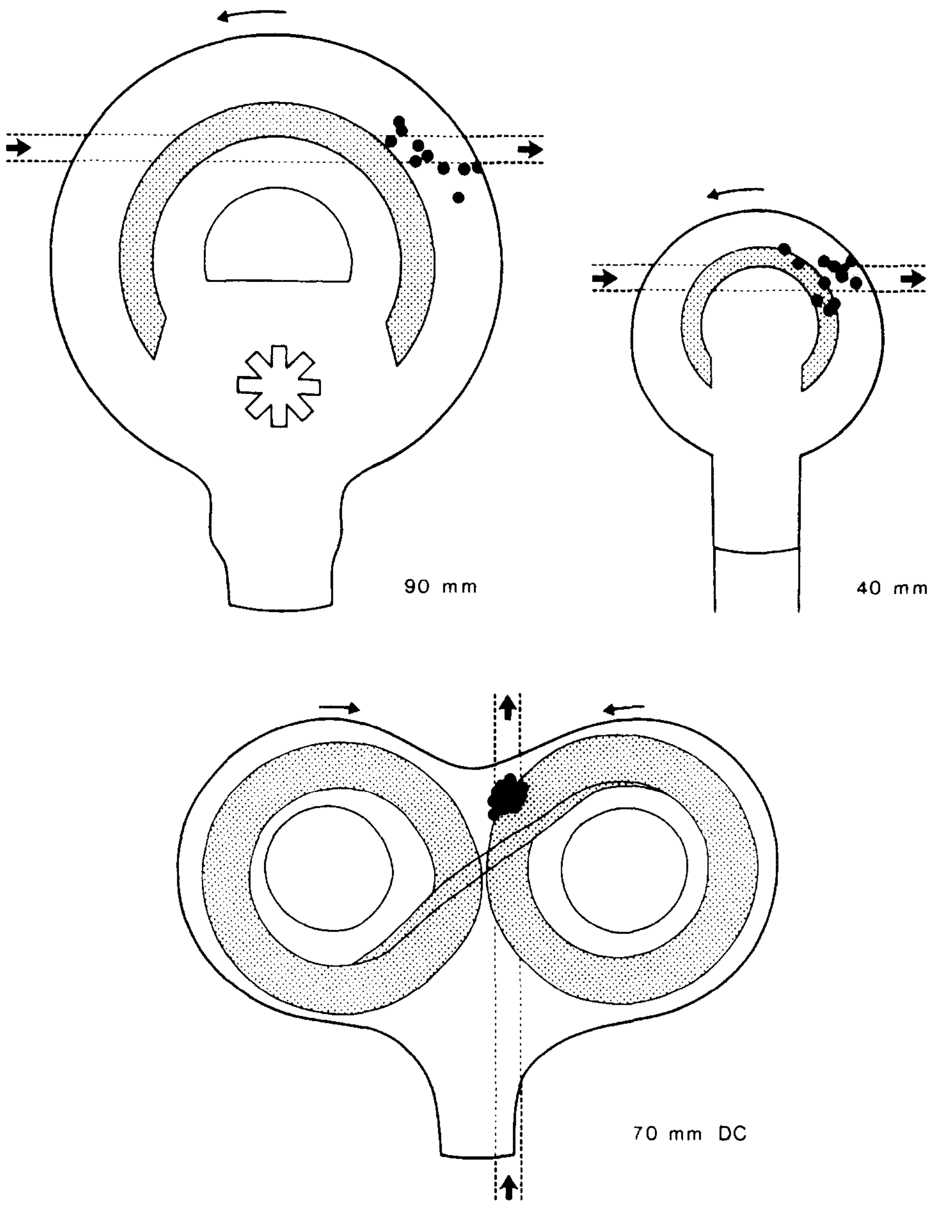

Fig. 2. Area of stimulation of the Magstim coils with the coil at a tangent to the nerve under investigation. The position of the electrical cathode was marked on the surface of the coil with a black dot at each position of the coil when a CMAP of the same amplitude, shape, and onset latency was elicited compared to the electrical stimulation.

2.4. Investigations

2.4.1. Site of stimulation

The electrical cathode was placed as close as possible to the nerve using the lowest stimulus intensities strong enough to elicit a CMAP. At that position a supramaximal stimulus was given with an intensity of 10–15% above the intensity at which a maximum CMAP was first elicited. The position of the magnetic coil was optimized until a CMAP showing the same onset latency, shape, and amplitude in comparison with the electrical stimulation was elicited. The position of the electrical cathode was marked on the surface of the coil. Presuming that the stimulation point is equal, it is called the "virtual" magnetic cathode. This investigation was done at the wrist, in the cubital region, and at Erb's point.

2.4.2. Recruitment curves

During the investigation of the median and ulnar nerves at the elbow, stimulus intensity was increased in increments of 1% of the maximum output of the Magstim stimulator and in steps of 2% with the Cadwell device. The following parameters were measured and calculated: threshold intensity of the motor responses, intensity necessary to elicit the maximum CMAP amplitude, slope of the curve of intensity dependent amplitude increase, and changes of onset latencies from threshold to maximum stimulation intensities. The study was done for both directions of the induced current. To do that, the coil was flipped over. The values were compared with those elicited with electrical stimulation in the same position.

2.4.3. Effects of lateral spread of the stimulus

In 5 subjects the CMAP amplitudes of the abductor pollicis brevis and abductor digiti quinti muscles were investigated during stimulation of the median nerve at the elbow when the coil was shifted in a latero-median direction over the cubital fossa in steps of 1 cm. For the circular coils, the handle was positioned laterally, for the double coil it was positioned distally. At each position, the stimulus intensity was increased in increments of 10%. In another 5 patients the same investigation of the median nerve was done at the wrist.

2.4.4. Handling of the coil

All coils were tested at all stimulation sites with regard to maximum CMAP amplitude, artifacts, coactivation of other nerves situated nearby, and practicability of the application.

3. Results

(1) Reproducible CMAPs similar to those elicited by electrical stimulation could be recorded independent of the site of stimulation on superficial nerves. For each coil, the site of the virtual cathode could be determined where a CMAP of the same shape, amplitude, and onset latency was elicited when compared with electrical stimulation. The black dots marked on the coils in Fig. 2 correspond to the position of the electrical cathode in comparison with magnetic stimulation found at an investigation of the median nerve in the cubital fossa. For the circular coils, all

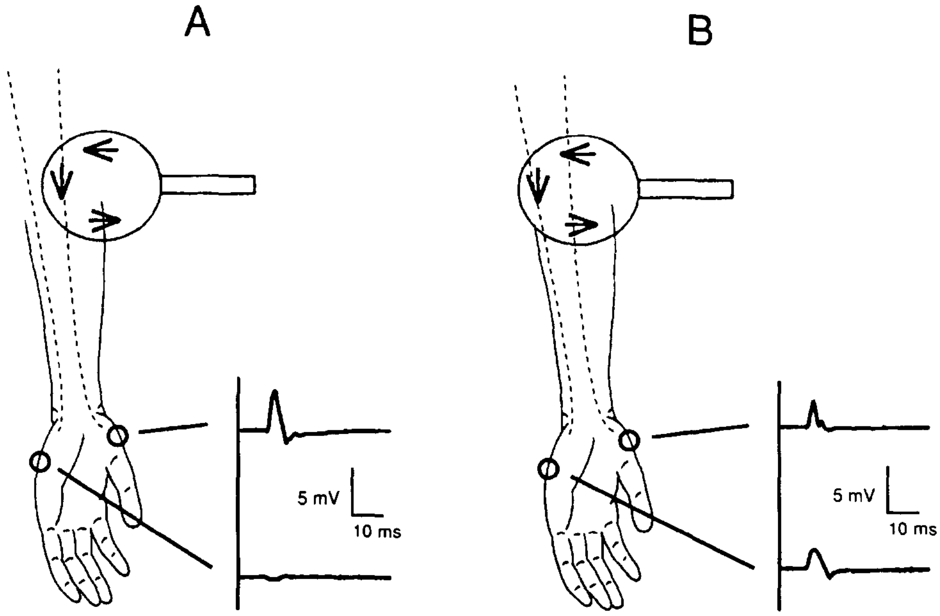

Fig. 3. Stimulation of the median nerve in the cubital fossa. Effects of the coil position on the amplitudes of the abductor pollicis brevis and abuctor digiti quinti muscles with the circular coil in an optimal position (A: current in the direction of the median nerve) and a suboptimal position (B: flow of the current perpendicular to the median nerve). In position B, simultaneous stimulation of the ulnar nerve occurred.

dots were within an area of about 3 cm, independent of the site of stimulation (distal at the wrist, proximal at the elbow, and at Erb's point). This area was between the outer and inner rims of the windings at the opposite side of the handle and distal with regard to the course of the nerve. In 20% of the investigations, a similar CMAP was elicited when the windings near the handle crossed the nerve. With this coil position, the intensities necessary to elicit a maximum CMAP were higher than with the position mentioned above. The maximum CMAPs were recorded when the coil was placed tangentially on the nerve. When the nerve bisected the coil, CMAPs of similar latencies but lower amplitudes were recorded (Fig. 3).

With the 70 mm double coil, the handle had to be parallel to the nerve to elicit maximum responses. In other positions unpredictable responses occurred with regard to amplitude, shape, and onset latency. The "virtual cathode" was distal and 1 cm lateral to the center of the coil (Fig. 2).

(2) For superficial nerves the threshold intensities to elicit a CMAP did not significantly differ from each other with regard to the type of the coil (Student t test), the direction of the induced current, and the site of investigation. Fig. 4 shows the result of mean increase of CMAP amplitude with increasing stimulus strength. In contrast to motor thresholds, the intensities to elicit a maximum CMAP were significantly different for the various coils. The intensity necessary to evoke a maximum CMAP was lowest using the 40 mm coil, higher for the 90 mm coil and highest for the focal and double coil. When the current flowed from proximal to distal the intensity was much less than when the current flowed in the opposite direction. The slope of the curves showing the intensity dependent increase of CMAP amplitudes was significantly ($P < 0.01$) less steep when the direction of the current was inverted (Fig. 4). In some cases no maximum CMAP was reached. The threshold intensities necessary to elicit CMAPs of deep nerves were higher than those used for superficial nerves. The bigger the distance between nerve and coil, the higher the intensity necessary. A comparison of maximum CMAPs with electrical evoked CMAPs was not possible because a maximum CMAP could never be elicited here.

The onset latencies became shorter with increasing stimulus intensities, the same as for electrical stimulation. A further increase of the stimulus intensity after reaching a maximum amplitude of the CMAP sometimes caused a further shortening of latencies on the order of 0.1 and 0.4 msec. However, there was no striking difference between various coils nor between magnetic and electrical stimulation.

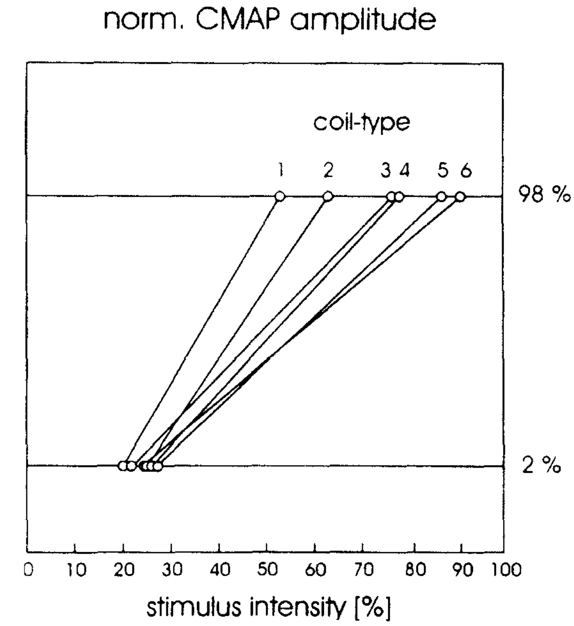

Fig. 4. Comparison of mean values of the 2% and 98% amplitude of the CMAP of the abductor pollicis brevis muscle using different magnetic coils. 1 = 40 mm circular coil; 2 = 90 mm circular coil; 3 = 70 mm double coil; 4 = focal coil; 5 = 40 mm circular coil with an inverse stimulus current; 6 = 90 mm circular coil with an inverse stimulus current.

Table 1 shows the ratio between the maximum electrically and magnetically elicited CMAP amplitudes (E/M ratio) for stimulation of the median nerve at the elbow. In 16 investigations, no maximum amplitude could be elicited with inversed current direction. No significant difference among the various coils was observed. The findings were the same for ulnar nerve stimulation and stimulation of both nerves at Erb's point and the wrist.

Changing the direction of the induced current resulted in a change of onset latencies of the CMAPs. For the 90 mm coil, a prolongation of 0.36 ± 0.11 msec was found and for the 40 mm coil the latency was 0.24 ± 0.11 msec longer when the current flowed from distal to proximal.

Table 1
Ratio of maximum electrically to maximum magnetically elicited CMAP amplitudes (n = 32)

	90 mm coil		40 mm coil		70 mm double coil	Focal coil
Direction of the induced current	Distal-proximal	Proximal-distal	Distal-proximal	Proximal-distal	Proximal-distal	
Mean	0.942 [a]	1.014	0.997 [b]	1.021	1.004	1.05
S.D.	0.06	0.023	0.041	0.00412	0.0023	0.0041

[a] No maximum CMAP could be elicited in 7 cases.
[b] No maximum CMAP could be elicited in 9 cases.

The mean nerve conduction velocity was 57.4 ± 3.3 m/sec. Thus, following the inversion of the current, a displacement of the virtual cathode of 21 mm for the 90 mm coil and 12 mm for the small circular coil was calculated.

(3) An example of the effect of the lateral spread of the magnetic stimulus is shown in Fig. 5 for the 90 mm coil. A CMAP could be recorded when the coil was distant from the nerve. By definition, the maximum CMAP amplitude was elicited when the virtual cathode was over the nerve (Pos. 3 in Fig. 5). The lower part of the figure shows the amplitude recorded simultaneously in the abductor digiti quinti muscle. No CMAP of the hypothenar was elicited when the coil was positioned quite distant from the optimal stimulation point for the median nerve. Electrical stimulation at this site also elicited an ulnar coactivation, but the CMAP was smaller than of the magnetic stimulation. A similar result was found in the investigation of the other circular coils. With the double coil, the maximum amplitude was elicited with the center of the coil parallel to the nerve and 2 smaller peaks occurred at the outer parts of both circles. This investigation was also performed at the wrist. The findings here were similar to the stimulation at the elbow except that a hypothenar CMAP was recorded earlier. It was impossible in 3 out of 7 subjects to get a maximum CMAP of the abductor pollicis muscle without a simultaneous hypothenar response.

(4) It was not possible to use each coil successfully at every site of investigation due to 3 major problems: artifacts, coactivation of other nerves and muscles, and a very low stimulus intensity. At distal stimulation sites an overload of the preamplifier often distorted the CMAP due to the small distance between the coil and the recording electrode. This artifact could often be diminished by turning the coil. However, in 8 of 55 investigations no reproducible responses could be elicited at the wrist. In addition, optimization of the coil position was time consuming and many stimuli were necessary to get a maximum response. With the double coil, since the handle was over the hand, a stimulus artifact as well as a coactivation of nearby nerves usually occurred. Artifacts produced by the

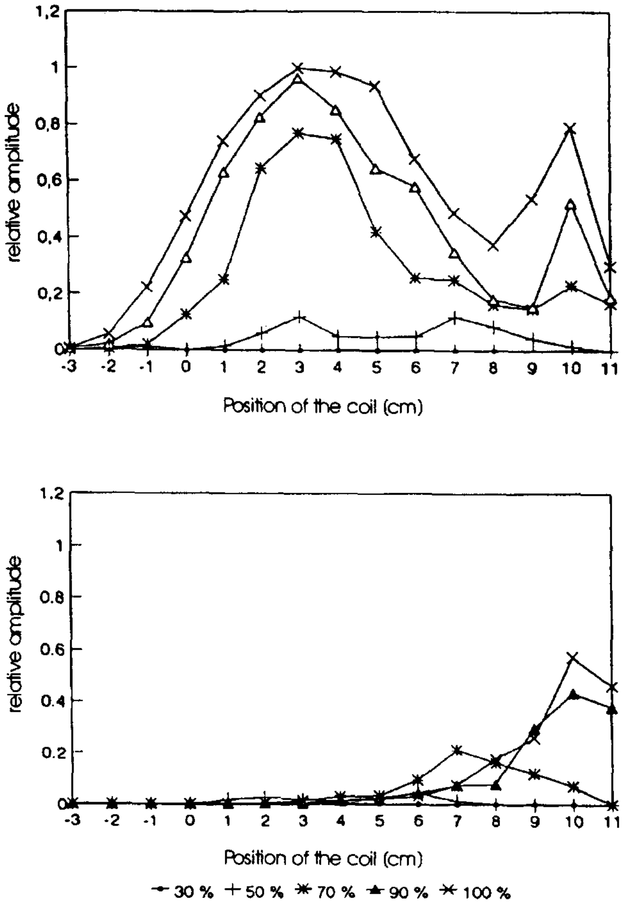

Fig. 5. Change of CMAP amplitudes of the abductor pollicis brevis muscle (upper part) and abductor digiti quinti muscle (lower part) following the stimulation of the median nerve at the elbow using the 90 mm circular coil at different positions in relation to the nerve. At position 0 the outer edge of the coil was over the electrical cathode; negative values indicate that the outer edge was more lateral to the position of the cathode of the electrical stimulation, positive values indicate a more medial position, i.e., over the cathode point.

double coil could be diminished by extending the hand, but in this case, the nerves were stretched and the standardization of the investigation was lost. A more distal excitation

Table 2
Recommendations for the usage of different stimulation coils in the investigations of various peripheral nerves

Nerve and site of stimulation	90 mm coil focal coil	40 mm coil	70 mm double coil
Median and ulnar nerves at the wrist	+ / −	+ +	+ / −
Median and ulnar nerves at the elbow	+	+ +	+
Median, ulnar and radial nerves at the upper arm	+	+ +	+
Erb's point	+	+ +	−
Paravertebral nerve roots	+ +	− −	+
Femoral nerve at the inguinal region	+	+ +	+ / −
Sciatic nerve at the gluteal fold	+ +	− −	+
Peroneal and sciatic nerves in the fossa poplitea	+	+ +	+
Peroneal nerve at the fibular head	+ +	+ +	+ +
Peroneal nerve, distally	+	+ +	+
Sciatic nerve at the medial malleolus	+	+	− −

+ +, recommended; +, possible; + / −, possible, sometimes difficult; −, less suitable; − −, not suitable.

of the nerve occurred using the double coil at high stimulus intensities. This was probably due to the magnetic field induced around the handle of the coil which was parallel with the distal part of the nerve. Coactivation of nerves nearby occurred when the circular coil laid over the wrist, but the contact area could be reduced by turning the coil.

At Erb's point, no stimulus artifact occurred, only an unpleasant coactivation of the muscles near the coil, especially when coils with greater diameters were used. The most stable responses could be achieved using the 40 mm coil with the top of the coil at the insertion area of the sternocleidomastoid muscle at the clavicle and with the head of the subject turned to the opposite side and rotated slightly backwards.

The peroneal nerve at the fibular head as well as the fibular nerve at the groin were easily stimulated. Areas, amplitudes, and latencies were equal to those elicited using electrical stimuli. The tibial nerve could not be investigated distally because it was impossible to adjust the coil close enough to the nerve at the ankle. In the popliteal fossa the results were the same using electrical and magnetic stimuli.

Regardless of the coil used, stimulation of superficial nerves was always supramaximal except when artifacts made the calculation of amplitudes impossible. Deep nerves, e.g., the sciatic nerve, could only be stimulated using the 90 mm and 70 mm double coil; amplitudes were always submaximal. Table 2 summarizes the applicability of various coils at different investigation sites with regard to handling, artifacts, and stimulus intensity necessary to elicit a reliable CMAP.

4. Discussion

Magnetic stimuli can be used to investigate peripheral nerves since they induce a depolarizing electrical current near the nerve like primary electrical stimuli. The present study shows the difficulties and restrictions of magnetic stimulation for the investigation of peripheral nerves.

The problems using magnetic stimulation are based on physiological, anatomical, and technical factors which are closely related to one another. As has recently been shown by others (Nilsson et al., 1992), accurate prediction of the stimulation point is impossible. With slight changes in the position of the magnetic coil, it was possible, however, to elicit a CMAP of equal amplitude and onset latency compared to electrical stimulation. For that, a particular part of the coil must lie over the position of the electrical cathode. However, the final stimulation positions of a given coil varied slightly for different subjects, nerves, and stimulation sites. The lower focality in comparison to electrical stimulation is due to the physical properties of magnetic stimulation. Using magnetic stimuli the nerve is stimulated preferentially at low threshold points along its course as recently shown by in vitro experiments (Maccabee et al., 1993). Since the human body is not a homogeneous conducting volume, excitation takes place where the nerve bends or where it is near regions with decreased field homogeneity. An example of that in routine nerve investigation is the paravertebral magnetic stimulation of spinal roots (Epstein et al., 1991; Maccabee et al., 1991), but it must also be taken into account at the ulnar sulcus and at regions where the nerve is close to the surface of the body, for instance the ulnar nerve at the wrist. Change of the depth of the nerve may also change onset latencies and/or CMAP amplitudes. This is often found with stimulation of the median nerve at the elbow where a sudden change of the muscle response appears when the coil is shifted longitudinally.

To evoke a maximum CMAP, the induced electrical current must be directed from proximal to distal, i.e., along the course of the nerve. This is true for each nerve and coil investigated. But even if this requirement is taken into account, a maximum CMAP equal to the electrically evoked maximum CMAP cannot be elicited at each stimulation site. Maximum CMAPs could usually be elicited at proximal stimulation sites of the upper extremities including the radial nerve at the upper arm, at the groin (femoral nerve), and at the knee. At more distal stimulation sites in the upper and lower extremities magnetic stimulation was (i) more time consuming because many stimuli were necessary to optimize the coil position and (ii) less effective due mostly to persistent artifacts or to the geometry of the coil (see below). For the stimulation of deep nerves (e.g., the sciatic nerve at the gluteal fold) no maximum CMAP could be evoked regardless of the coil used.

The increase in CMAP amplitudes with increasing stimulation intensity was qualitatively the same using electrical and magnetic stimuli. Thus, there is no difference between the two techniques with regard to the order of activation of various motor fibers. The absolute value of the increase in amplitude depends, however, on the coil configuration and therefore the strength of the electrical field induced locally. For the investigation of superficial nerves, the 40 mm circular coil is highly recommended because a maximum CMAP was elicited using the lowest stimulus intensity due to the strong electrical field induced in superficial tissue (Jalinous, 1991). However, the peak field of the small coils decreases more rapidly with increasing distances from the nerve (Roth et al., 1990b) and therefore the 40 mm coil is not suitable for the investigation of deep nerves.

To guarantee supramaximal stimulation, intensity has to be increased by 10–15% above the level necessary to elicit a maximum CMAP for the first time (Brown, 1984). For magnetic stimulation this is difficult and sometimes impossible because the range between the lowest intensity necessary to elicit a maximum CMAP and the maximum output intensity of the devices is much smaller than that for electrical stimulation. Moreover, a prolongation of stimulus duration that increases the excitatory effect of the electrical stimulation is for technical reasons still impossible with magnetic stimulator devices. In most investigations of superficial nerves of healthy subjects, the intensity of the magnetic stimulus was sufficient to evoke a maximum CMAP, but it is well known that higher intensities are necessary for the investigation of pathologically altered nerves (Brown, 1984). Thus, the stimulus intensity of present devices is not sufficient to guarantee a supramaximal stimulation in every situation and, therefore, limits the use of magnetic stimulation of peripheral nerves at the moment.

A further increase of stimulus intensity after eliciting the maximum CMAP amplitude sometimes causes a shortening of onset latencies using electrical as well as magnetic stimuli. This may be due to the propagation of the magnetic field along the course of the nerve and change of the stimulation point (Nilsson et al., 1992) or to the fact that the depolarization itself occurs faster without a change of the site of depolarization (Hodgkin and Huxley, 1952). This implies that stimulus intensity has to be carefully adjusted to avoid measurement errors.

Because magnetic fields are less attenuated by poorly conductive tissues than electrical fields, the nerve is also excited when the coil is distant from it. This finding has 2 implications. (i) During stimulation of a peripheral nerve other nearby nerves may also be depolarized. Therefore, it is essential to maximize the distance between the coil and nerves not under investigation. Because the electrical field around the handle of the coil can also depolarize a nerve, the handle must be kept away from nerves. (ii) CMAP amplitudes increase with decreasing distance between the coil and the nerve. Therefore, the position of the coil must be optimized with regard to CMAP amplitude to obtain reliable CMAP values. This also reduces the practicability of the magnetic investigation because an increase in CMAP may also be due to the coactivation of nearby nerves, especially if high stimulus intensities are used. To avoid this error a simultaneous recording of CMAPs of muscles innervated by neighboring nerves is necessary. Since onset latencies change less when the coil is not exactly over the nerve, this parameter is less useful to optimize the stimulation position of the coil.

Another drawback of magnetic stimulation is the geometry of commercially available coils. From a practical point of view, the coils should be as small as possible. (1) If the diameter of the coil is too large – as is the case with the 70 mm double coil – it is impossible to keep the distance between coil and nerve small due to the local anatomy. This becomes a problem when bones hinder the proper, flat placement on the surface of the body, e.g., in the investigation at Erb's point, at the ulnar sulcus, or at the ankle. Here, the focality of the double coil (Olney et al., 1990) is outweighted by the greater distance between nerve and coil resulting in smaller and more unreliable CMAPs. (2) Due to the extension of the magnetic fields, the nerve under investigation as well as neighboring tissues, muscles and nerves are excited. The strength of the magnetic fields which exist under the outer wings of the double coil is weaker than the peak field in the middle of the coil (Jalinous, 1991), but it is still sufficient to depolarize the small nerve branches within the muscles (Machetanz et al., 1994). Since it is unpleasant for the patient local muscle contraction is undesired. This contraction often causes a movement of the extremity or the neck when the sternocleidoid muscle is simultaneously excited with the brachial plexus at Erb's point. In addition, this causes an artifact due to volume conducted activity. Displacement of the coil can alter the site and the intensity of the stimulation which is a major problem in repetitive nerve stimulation (Bischoff et al., 1994). To avoid a contraction of underlying muscles the area of contact between the coil and the body must be kept as small as possible. Using circular coils, only the outer part of the coil opposite to the handle should be pressed firmly to the surface and the rest of the coil has to be turned away. This requirement cannot be met when using double coils and it is expected that the application of butterfly coils (Roth et al., 1990c) will cause similar problems, even though their induced field is much more localized than that of circular coils. Due to a greater fall-off of the induced electrical field with increasing distance between the coil and the nerve (Maccabee et al., 1990), the double coil is not able to depolarize deep nerves better than the 90 mm circular coil. Thus, there is no advantage to this type of coil for the investigation of peripheral nerves.

We conclude that at the moment magnetic stimulation is not a technology applicable to investigate the peripheral nervous system in place of electrical neurography. The major limitations are: (i) Maximum amplitudes cannot generally be guaranteed even if stimulation of superficial nerves takes place at locations where maximum CMAPs are typically elicited. In addition, for various stimulation sites and for all deep nerves a supramaximum stimulation is impossible. (ii) The point of stimulation is not exactly predictable and reproducible with regard to different coils, stimulation sites, and subjects. (iii) Coactivation of nearby nerves occurs and small changes of coil position may vary CMAP parameters. The stimulation of underlying muscles makes the stimulation unpleasant especially at proximal stimulation sites. (iv) Even if all the conditions necessary to reduce the stimulus artifact are taken into account, it is sometimes impossible to get a reproducible result, especially at distal stimulation sites. (v) In comparison to the small electrical stimulator electrodes, the coil geometry is unfavorable in anatomic regions where the surface to place the electrode on is reduced by bony structures.

Acknowledgements

This work was supported by a grant from the Sander Foundation, Neuburg, Germany. The authors thank Renate

Gobitz-Pfeiffer and Reinhold Soyer for their technical assistance.

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