Exp Brain Res (1990) 80:333–344

Experimental Brain Research



# Modulation of somatosensory evoked responses in the primary somatosensory cortex produced by intracortical microstimulation of the motor cortex in the monkey

**W. Jiang, C.E. Chapman[1,2], and Y. Lamarre[1]**

[1]Département de Physiologie, [2]Ecole de Réadaptation, and Centre de Recherche en Sciences Neurologiques, Université de Montreal, PO Box 6128, Station A, Montréal, Québec H3C 3J7, Canada

**Summary.** Previous studies have shown that the amplitude of somatosensory evoked potentials is diminished prior to, and during, voluntary limb movement. The present study investigated the role of the motor cortex in mediating this movement-related modulation in three chronically prepared, awake monkeys by applying low intensity intracortical microstimulation (ICMS) to different sites within the area 4 representation of the arm. Air puff stimuli were applied to the contralateral arm or adjacent trunk at various delays following the ICMS. Somatosensory evoked potentials were recorded from the primary somatosensory cortex, areas 1 and 3b, with an intracortical microelectrode. The principal finding of this study was that very weak ICMS, itself producing at most a slight, localized, muscle twitch, produced a profound decrease in the magnitude of the short latency component of the somatosensory evoked potentials in the awake money. Higher intensities of ICMS (suprathreshold for eliciting electromyographic (EMG) activity in the "target" muscle, i.e. that muscle activated by area 4 stimulation) were more likely to decrease the evoked response and produced an even greater decrease. The modulation appeared to be, in part, central in origin since (i) it preceded the onset of EMG activity in 23% of experiments, (ii) direct stimulation of the muscle activated by ICMS, which mimicked the feedback associated with the small ICMS-induced twitch, was often ineffective and (iii) the modulation was observed in the absence of EMG activity. Peripheral feedback, however, may also make a contribution. The results also indicate that the efferent signals from the motor cortex can diminish responses in the somatosensory cortex evoked by cutaneous stimuli, in a manner related to the somatotopic order. The effects are organized so that the modulation is directed towards those neurones serving skin areas overlying, or distal to, the motor output.

**Key words:** ICMS – Motor cortex – Cutaneous – Somatosensory evoked potentials – Somatosensory cortex – Sensory gating – Monkey

*Offprint requests to:* C.E. Chapman (address see above)

## Introduction

Previous studies have shown that there is a diminution of somatosensory transmission in the medial lemniscal system during voluntary movement in the monkey (Dyhre-Poulson 1978; Chapman et al. 1988). Movement-related sensory modulation has also been observed in the medial lemniscus of cats (Ghez and Lenzi 1971; Ghez and Pisa 1972; Coulter 1974) and in the somatosensory cortex of humans (for example, Rushton et al. 1981; Cohen and Starr 1987).

Several observations indicate that this movement-related decrease in somatosensory transmission *at the level of the medial lemniscus* is *central* in origin. First, the modulation precedes the onset of muscle activity (Ghez and Lenzi 1971; Coulter 1974; Chapman et al. 1988) and second, passive movements (which evoke peripheral feedback) do not produce any significant change in the lemniscal response (Ghez and Pisa 1972; Coulter 1974; Chapman et al. 1988). At higher levels of the somatosensory system, *peripheral* influences may also act to modulate somatosensory transmission since passive movements can result in a decrease in the amplitude of cutaneous evoked responses recorded in the sensory thalamus (ventral posterior lateral nucleus, caudal division, VPLc) and in the primary somatosensory cortex (Chapman et al. 1988). Although the central structure(s) responsible for this modulation has not yet been determined, a comparison of the modulation seen at three levels of the lemniscal system (medial lemniscus, VPLc and primary somatosensory cortex) in response to either peripheral or central stimulation led Chapman and coworkers (1988) to suggest that the central effects are exerted, in large part, at the level of the first relay, the dorsal column nuclei.

Our previous results further indicated that the structure(s) which might modulate these central effects should (i) project to the dorsal column nuclei and (ii) be active well in advance of the onset of movement. Anatomical studies in monkeys indicate that both the primary somatosensory and motor cortices send fibres to the dorsal column nuclei (Kuypers 1960; Jones and Wise 1977; Cheema et al. 1985; Bentivoglio and Rustioni 1986) with the bulk of the descending projection originating

from the primary somatosensory cortex. Evidence that these descending projections do indeed modulate the activity of the dorsal column nuclei has been provided by electrophysiological studies carried out in anaesthetized animals; it appears, however, that the effects are complex as both excitation and inhibition have been reported (Towe and Jabbur 1961; Jabbur and Towe 1961; Levitt et al. 1964; Harris et al. 1965; Cole and Gordon 1983; Giuffrida et al. 1985). Although some somatosensory cortical neurones modify their discharge prior to the onset of electromyographic (EMG) activity (Soso and Fetz 1980; Fromm and Evarts 1982), the vast majority of sensory cortical neurones are not activated until after the onset of EMG activity (Evarts 1972), their discharge representing sensory feedback from the moving limb (Bioulac and Lamarre 1979). On the other hand, numerous studies have shown that motor cortical neurones are active well in advance of movement (reviewed by Evarts 1981), making this an ideal candidate for mediating the movement-related diminution of sensory transmission.

The present study was designed to determine the role of the primary motor cortex in modulating the responsiveness of the primary somatosensory cortex to natural, cutaneous stimulation in the awake monkey. Motor cortical activity was elicited by low intensity, intracortical microstimulation (ICMS) applied to loci in the arm area of motor cortex. At various delays after the conditioning produced by motor cortical stimulation, evoked responses to air puff stimuli, applied to the contralateral arm or trunk, were recorded from the arm area of the somatosensory cortex. As the predominant effect of motor cortical conditioning stimulation was found to be a decrease in the amplitude of the somatosensory evoked responses, further experiments investigated the topographical relationship between the efferent output and the area of skin stimulated. Preliminary accounts of the results have been published (Jiang et al. 1986, 1988).

## Methods

Three macaca mulatta monkeys (MIC, NO and SM; weights 3.6, 5 and 6 kg, respectively) were conditioned to sit in a primate chair with the forearm pronated and strapped, along with the hand and individual digits, onto an immobile metal support rigidly mounted on the chair (Chapman et al. 1988), and to accept the application of air puff stimuli to the arm. The monkeys were kept alert but quiet by randomly delivering drops of juice (controlled by the experimenters). One of the monkeys (NO) was also used in a previous study (Chapman et al. 1988). After the monkey was accustomed to the experimental situation, it was anaesthetized with pentobarbital and, under aseptic conditions, a recording chamber which permitted access to the motor and sensory cortices was implanted over the cerebral hemisphere contralateral to the arm to be tested (Lamarre et al. 1970). Teflon-coated, multi-stranded stainless steel wires were chronically implanted into selected arm and shoulder muscles for EMG recordings. When needed, additional recordings were taken with insulated copper wires inserted percutaneously into the muscle of interest. The same type of percutaneous wire electrode was also used for direct muscle stimulation (see below).

### *Data collection and analysis*

In each experiment, following the fixation of the animal's head, a glass-coated tungsten microelectrode (impedance 50 to 500 kΩ, measured at 1 kHz) was lowered transdurally into the arm region of the motor cortex. This electrode was used to search for loci from which limb muscles could be activated by a cathodal train of constant current pulses (11 pulses at 330 Hz, 0.2 ms pulse duration, generated by a Grass S8 stimulator) with a threshold intensity of less than 15 μA. The "threshold" current (T) was determined at the beginning of the experiment before restraining the arm and was defined as the least intensity which produced a small, localized muscle twitch in 50% of the trials. The muscle activated at threshold is referred to in this paper as the "target" muscle for the motor cortical stimulation site (Note: While visual inspection suggested that only a single muscle was activated at threshold intensities, and there was also good agreement between the threshold intensity as determined visually and electromyographically, we acknowledge the obvious limitations inherent in this approach. Thus, other muscles may have been coactivated at this low intensity and so may have contributed to the observed effects. Nevertheless, the timing of the EMG activity should be similar for all such coactive muscles (Cheney and Fetz 1985; Lemon et al. 1987)). It is a common observation that the threshold for evoking motor effects with ICMS can vary widely with the animal's behavioural state and posture. Our values estimated for the unrestrained arm were, as a result, sometimes at variance with the threshold measured in the experimental situation, i.e. with the forearm and hand immobilized. In most cases, the error was on the conservative side; threshold was sometimes higher in the immobilized, than in the freely moving, situation.

Following localization of a low threshold site in the motor cortex, the recording microelectrode (glass-coated tungsten, impedance 0.2 to 1.0 MΩ) was lowered transdurally into the arm or trunk region of the primary somatosensory cortex. For each recording site, multi-unit recordings were first taken in order to define the limits of the receptive field using a hand-held probe. The effects of ICMS were tested only at sites from which an evoked potential could be elicited in response to an air puff (usually at sites receiving input from hair receptors). Evoked potentials were elicited by a brief air puff (20 ms) directed to the centre of the receptive field. The air puff tube was mounted so that the nozzle was about 1–3 cm away from the skin; this position was kept constant throughout the data collection period. In some experiments, evoked potentials were also elicited by a weak electrical stimulus (single pulse of 0.3 ms) delivered through a pair of insulated, copper wire electrodes inserted percutaneously into the centre of the receptive field. Such stimulation did not produced any contraction of the underlying muscle. The electrically-evoked potentials showed the same modulation following ICMS as the corresponding air puff-evoked potential.

The individual evoked potentials were amplified, band-pass filtered (1 Hz to 0.3 kHz) and digitized on-line (2 kHz). The timing of the air puff stimulus (opening of the solenoid) with respect to the onset of the conditioning ICMS was stored along with a separate channel of EMG activity. The latter was full-wave rectified and integrated prior to digitization. Trials in which the animal was either moving or drowsy were rejected.

Conditioning stimulation was applied to the motor cortex and this was followed by an air puff which elicited an evoked potential in the primary somatosensory cortex. In this report, the delays tested ranged from 12 to 111 ms between the onset of the ICMS train and the onset of the pressure change measured 1 mm from the tip of the nozzle (measures taken with a strain gauge in separate control experiments). The time at which the air puff displaced the hair was 0.1 to 0.8 ms later than the stated delay for experiments in which the air puff was positioned, respectively, 1 to 3 cm away from the hair. For each pair of stimulating (motor cortex) and recording (sensory cortex) loci, the intensity of ICMS employed was usually varied (range, 1.5 to 24 μA, corresponding to 0.5 to 2.5 X T in different experiments). For each intensity of ICMS, at least two different delays were tested. A laboratory mini-computer (PDP 11-23) was used to control the delivery of both the conditioning stimulation and the air puff (through a solenoid valve). Conditioned and unconditioned trials were alternated. Trials were initiated by one of the experimenters, the inter-trial interval being about 2 s. A block of 40 trials (20 conditioned, 20 unconditioned) was recorded for each

delay. In some experiments, peripheral conditioning stimulation was applied through percutaneous wire electrodes inserted into the belly of the target muscle. The threshold current was defined as above. The conditioning stimulation consisted of either single cathodal, constant current pulses (0.2 ms duration) or, more often, a brief train (3–11 pulses at 330 Hz, 0.2 ms pulse duration). The aim of the muscle stimulation was to produce a twitch at least as large as that elicited by ICMS, and with a similar duration; the effects produced by such stimulation were not dependent upon the number of pulses in the train, a single pulse could be as effective as a lower intensity train of stimuli.

As shown in Fig. 1, separate averages were calculated for the conditioned and unconditioned trials off-line. In order to quantify the changes produced by ICMS, the amplitude of the conditioned response (onset-to-peak) was expressed as a percentage of the corresponding unconditioned response. As a result of the proximity of the recording electrode to the stimulating electrode, however, the evoked potential recordings often contained stimulus artifacts, and also slow waves produced by the ICMS. In the examples shown in Fig. 1, these were most evident at higher intensities of stimulation (12 $\mu$A, right). The artifacts and the slow baseline shift were eliminated by subtracting the averaged response to ICMS stimulation alone from the corresponding conditioned average. The results of the subtraction are shown below (thicker traces), superimposed upon their corresponding controls. This subtraction process did not essentially modify the conditioned evoked response. Furthermore, efforts to correlate the amplitude of the slow wave generated by ICMS alone with the magnitude of the change in the conditioned response across different experiments were unsuccessful, indicating that the latter was not responsible for the modulation observed in the present experiments.

Effective experiments were defined as those in which the magnitude of the conditioned response remained below, or above, the variation range fo the unconditioned response ($\pm 2.58$ standard deviations, S.D.) for at least two different, but consecutive, delays, tested with one intensity of ICMS. The variability of the unconditioned response was estimated by calculating the overall mean amplitude and standard deviation (S.D.) from the averaged data. In practice, a minimum of 4 averages (each an average of 20 trials) were pooled for this calculation. In several experiments, the reliability of this method was evaluated by also measuring the amplitude of each individual potential (conditioned and unconditioned), onset-to-peak. Paired t-tests were used to test for changes in the amplitude of the conditioned response (level of significance, $P < 0.01$). The results were identical – for those delays at which the evoked response was considered to be outside the variation range of the unconditioned response as determined by pooling together the averages, the evoked response was also significantly different from control according to the results of the t-tests.

### *Histological methods*

Towards the end of the recording period, electrolytic lesions were made in selected electrode tracks in monkeys SM and MIC. After the final recording session, the animals were deeply anaesthetized and

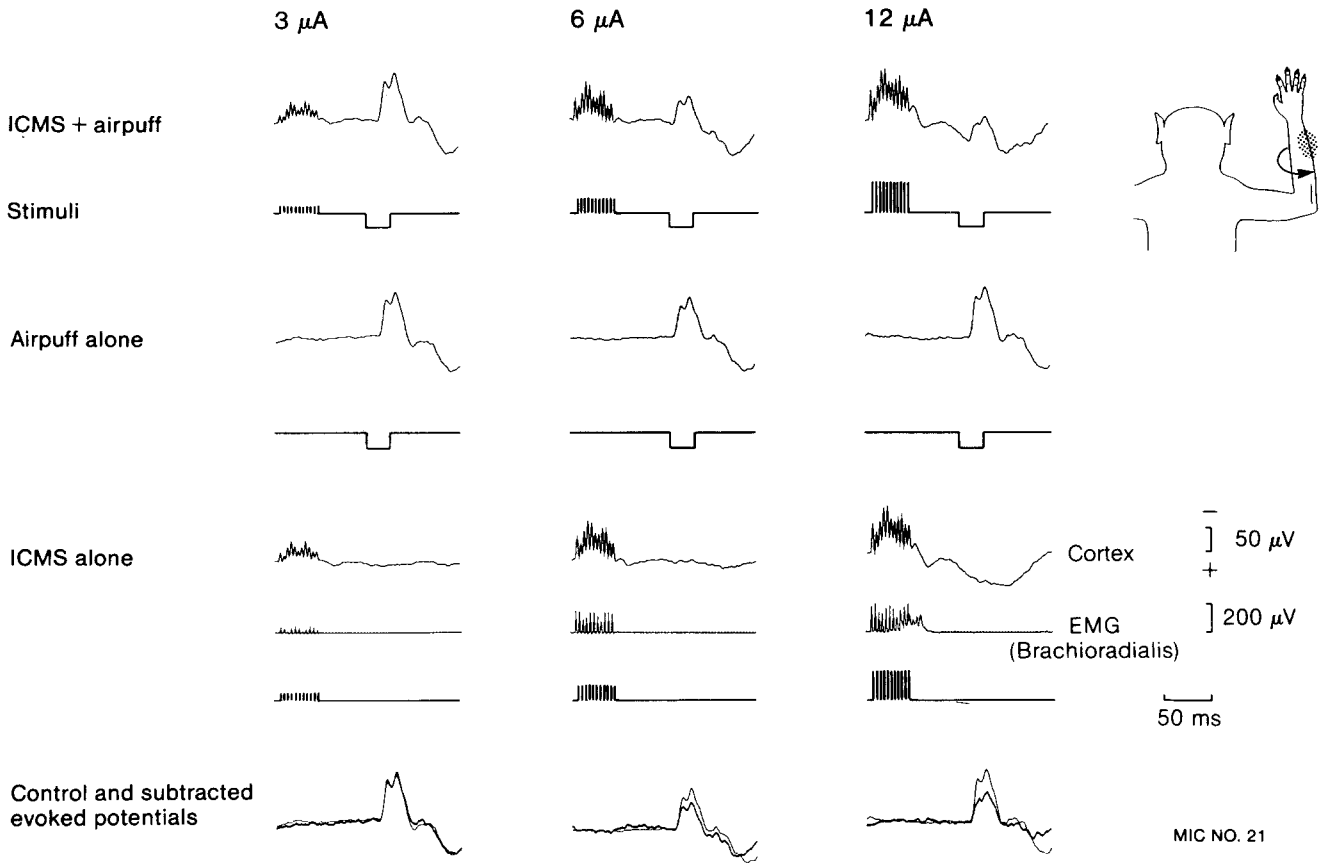


**Fig. 1.** Effects of three different intensities of motor cortical ICMS on air puff-evoked responses in sensory cortex (delay 71 ms). Each trace is an average of at least 16 trials in this and all subsequent figures. Along with each evoked potential there is a schematic representation of the stimuli which were applied: the ICMS train is indicated by a series of 11 upwards ticks while the air puff is indicated by a downwards deflection. The timing of the air puff is shown relative to the first pressure change measured 1 mm from the tip of the nozzle. On the right is shown the location of the receptive field identified in somatosensory cortex (dotted region; multi-unit activity was evoked by hair displacement). The action of the target muscle for the ICMS is indicated by the arrow (forearm supination, but also elbow flexion)

perfused through the heart with buffered formol-saline solution. The dura mater was removed from the cortex, known stereotaxic points on the surface were marked with India ink and the brain was subsequently photographed. Electrode tracks were reconstructed from 10 to 30 $\mu$m saggital sections stained with cresyl violet. Reconstructions were based upon histological evidence of the penetrations and lesions, the recording coordinates, the depths noted during the recording sessions and the physiological identification of the location of the central sulcus. The criteria described by Powell and Mountcastle (1959) and Jones et al. (1978) were used to distinguish between areas 3b and 1.

Figure 2A and B show the locations of the stimulating and recording areas in two of the monkeys used in these experiments (MIC and SM). The stimulation sites were located in the posterior portion of the precentral gyrus (area 4) in both monkeys. All of the stimulation sites were located within 0.5 to 3.0 mm of the cortical surface. The cortical recording sites were located in a narrow strip just posterior to the central sulcus within areas 3b and 1. All of the recording sites were located within 0.5 to 3.5 mm of the cortical surface. For one monkey (SM), the borders of the areas which were stimulated and recorded from are shown below in Fig. 2C.

In the third monkey (NO), in which only a small number of experiments were performed, the histology was not available. The location of the central sulcus was determined electrophysiologically during the recordings. The cortical stimulation and recording sites in this animal were located within 2.5 mm rostral and 2.0 mm caudal, respectively, to the central sulcus.

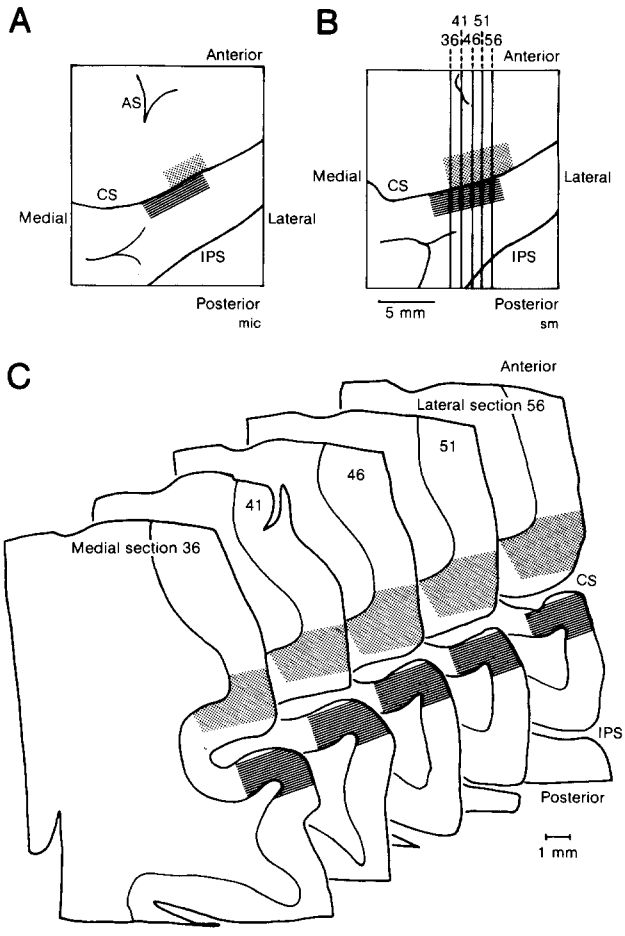


**Fig. 2A–C.** Locations of stimulating (dotted) and recording (hatched) sites in monkeys MIC (**A**) and SM (**B**). **C** Five parasagittal sections from monkey SM cut at levels shown by the vertical lines above (**B**). Abbreviations: AS, arcuate sulcus; CS, central sulcus; IPS, intraparietal sulcus

**Table 1.** Mean latencies of cortical air puff-evoked potential components, measured relative to the onset of the change of pressure measured 1 mm from the tip of the nozzle, as a function of the location of the receptive fields in one monkey (SM)

| | Onset (ms) | First negative peak (ms) |
|---|---|---|
| Shoulder (n = 14) | 9.1 ± 1.5[a] | 15.0 ± 5.9 |
| Upper arm (n = 16) | 10.0 ± 2.5 | 15.3 ± 2.0 |
| Forearm (n = 52) | 11.3 ± 5.0 | 17.0 ± 4.5 |
| Hand (n = 8) | 14.8 ± 1.7 | 20.0 ± 4.8 |

[a] ± 1S.D.

## Results

The typical averaged evoked response to air puff stimulation in the somatosensory cortex was composed of a short latency negative peak, or sometimes two peaks as shown in Fig. 1, followed by a long-lasting positive potential. In the present report, only the effects of ICMS on the amplitude of the initial wave (onset-to-peak) are examined. The latency of the evoked response varied with the location of the receptive field, as shown in Table 1 for one monkey (SM). When the receptive field was located more distally on the arm, the onset latencies were longer. The latencies for monkey NO were similar. In the third and smallest monkey (MIC), slightly shorter mean latencies were obtained.

A total of 116 pairs of stimulating and recording sites were tested in three monkeys (monkey SM, n = 90; monkey MIC, n = 19; monkey NO, n = 7). All of the target muscles activated by low intensity ICMS applied to the motor cortical loci were located in the contralateral upper limb. The receptive fields of the sensory cortical recording sites were located on the hairy skin of either the contralateral arm or the adjacent trunk area. Most recording sites received input from hair receptors, although a few recordings were made from sites responding to light touch on the hairy skin. For 67 of the 116 pairs tested, a decrease in the amplitude of the cortical evoked response was observed following suprathreshold, area 4 stimulation. A slight facilitation was seen in only 3 pairs, with subthreshold or threshold stimulation (monkey MIC). For the remaining 46 pairs, ICMS had no effect. In 55 of the 67 pairs (or experiments) in which suprathreshold ICMS was effective, threshold stimulation was also tested: 73% were modulated (39 decreased, 1 increased) and 27% were unmodulated (n = 15). Finally, subthreshold stimulation (usually 0.5 X T) was tested in 20 effective experiments but only 25% were modulated (3 decreases and 2 increases).

For monkey SM, a total of 60 recording sites in the sensory cortex were reconstructed from the histology. Of 45 sites which were assigned to area 1, 53% (24/45)

showed a decrease in the amplitude of the cortical evoked response following motor cortical conditioning stimulation. A similar proportion of recording sites in area 3b, 47% (7/15), showed a decreased evoked response following ICMS in area 4. In the other monkey (MIC), 11 out of 19 recording sites were reconstructed. The majority were in area 1 (n=8) and most of these (75%) showed a modulated evoked response following ICMS. The remaining 3 recording sites were in area 3b; none of these showed any modulation of their evoked response.

*Attenuation of the evoked response produced by ICMS*

Figure 1 shows an example of the effects produced by different intensities of ICMS at one of the most effective delays, 71 ms after the beginning of the 33 ms long ICMS train, in one experiment. The target muscle activated by the motor cortical stimulation was brachioradialis; the receptive field of the recording site in somatosensory cortex was located on the ulnar side of the distal forearm. While ICMS of low intensity had no effect (3 $\mu$A), a reduction in the amplitude of the evoked potential of 30% was produced by ICMS of 6 $\mu$A, and this in the *absence* of any EMG activity (shown below). A more pronounced decrease (44%) was produced with a higher intensity of stimulation (12 $\mu$A) which was associated with EMG activity in brachioradialis.

The results of eleven separate experiments, at two intensities of stimulation (threshold and suprathreshold for EMG activity), are pooled together in Fig. 3 (n=3, monkey SM; n=8, monkey MIC). For these 11 experiments, the sensory cortical receptive field was either located on the same limb segment as the target muscle (n=7) or on the segment immediately distal to the target muscle (n=4). The target muscles activated by the ICMS applied to motor cortex included brachioradialis (n=5), biceps (n=3), brachialis (n=1), a wrist extensor (n=1) and wrist flexor (n=1). As shown in Fig. 3A, threshold ICMS (mean current, 9±3 $\mu$A) produced a gradual decrease in the amplitude of the evoked potential, with the effects peaking at 71 ms (mean decreases of 34 to 38%). Recovery was incomplete at 91 ms. The two curves shown in Fig. 3A were obtained by sorting the trials according to the presence or absence of EMG (each trial was visually inspected). It is readily apparent that the two curves are virtually identical, i.e. that the modulation was just as pronounced in the absence of EMG activity as in its presence. Paired t-tests (conditioned versus unconditioned), at each delay, indicated that the response was significantly decreased at most delays tested. A similar, but more pronounced, modulation (Fig. 3B) was produced with suprathreshold ICMS (mean decrease of 53% at 71 ms; mean current, 15±5 $\mu$A or 1.5 to 2.0 X T). In the latter case, EMG activity was elicited in each trial in all experiments and a significant decrease was observed at all delays tested (26 to 111 ms). Finally, the effects of weaker stimulation were also tested in 9 of the above experiments (mean intensity 4.9 $\mu$A or 0.54 X T, results not shown). A decrease in the air puff-evoked response was, however,

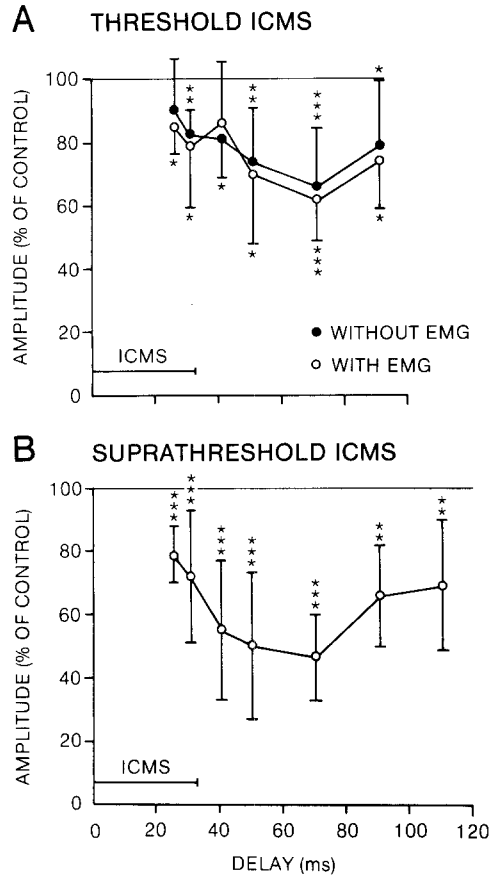


**Fig. 3A, B.** Summary of the effects of threshold (**A**) and suprathreshold (**B**) conditioning stimulation applied to motor cortex on the mean amplitude of air puff-evoked responses (onset-to-peak) in primary somatosensory cortex at various delays following the onset of the ICMS. The results of 11 experiments are pooled together (4 in area 1, 1 in area 3b, 6 in the transition zone between areas 3b and 1). Each point in an average of at least 6 experiments (all delays were not tested in each experiment) and is shown with its standard deviation. A significant decrease in the amplitude of the evoked response occurred at most delays tested (*, $P<0.02$; **, $P<0.01$; ***, $P<0.001$)

only observed in 2 of the experiments (onset 26 and 51 ms).

In 19 experiments, the first effective delay at which a substained and significant modulation occurred was determined using threshold and/or suprathreshold stimulation (all of these experiments showed an effect with one, or sometimes both, of these intensities of stimulation). At low intensities of stimulation (1 X T), the mean latency for an effect was 50±15 ms after the onset of the train (range, 31–71 ms (n=13); in one further experiment, the response was decreased at the shortest delay tested, 26 ms; 5 experiments were unmodulated); at suprathreshold intensities of stimulation, the effects began earlier (mean, 44 ±17 ms; range, 21–71 ms (n=13); in 3 further experiments, the response was decreased at the shortest delay tested, respectively 21, 26 and 31 ms; 3 experiments were

unmodulated). Overall, the shortest latency observed was 21 ms; for 81% of the experiments, however, the shortest effective latency was 31 ms or more.

Latencies were also calculated relative to the onset of EMG activity elicited by the motor cortical ICMS in 19 experiments for which at least one intensity of stimulation modulated the air puff-evoked response (mean EMG onset, 38 and 28 ms for, respectively, threshold and suprathreshold intensities of ICMS). No differences in timing were observed as a function of the intensity of the conditioning stimulation, so the data were pooled together. Overall, the latencies for the first effective delay were distributed in a normal fashion about the onset of EMG activity, with 5 experiments showing a modulation that preceded the onset of EMG activity (mean, −13 ms), 7 showing a modulation which began during the first 4 ms of EMG activity and 9 showing a late modulation, well after the onset of EMG (mean, +25 ms; n=9). Thus, the modulation could be attributed to central effects only in the experiments (23%) in which it occurred before the EMG activity started; in the other 77%, the timing data provided no information about whether the effect was either central or peripheral in origin, or a combination of these. Further to this, however, the ICMS-induced effects did not appear to be tightly linked to the presence of EMG activity: with threshold stimulation, in some of the latter experiments (n=3), EMG was elicited and yet the air puff-evoked response was not modulated, while in others the evoked response was modulated in the absence of any EMG activity (n=6).

The observation that the modulation frequently followed the onset of EMG, along with the fact that the decrease was more profound and more frequently observed when suprathreshold intensities of ICMS were employed, suggested that peripheral feedback associated with the muscle response to ICMS made a substantial contribution to the effects observed. This issue was systematically studied in 20 pairs of cortical stimulating and recording sites for which a single recording site in the sensory cortex was conditioned both by suprathreshold motor cortical ICMS (effective in all cases) and by direct stimulation of the corresponding target muscle (range: 1.2 to 2.0 X T, corresponding to 55–400 $\mu$A in different experiments). The parameters of stimulation were adjusted to produce a twitch of the muscle which was similar to that produced by suprathreshold ICMS. Stimulation of the muscle had no effect in 9 experiments and produced a decrease in the amplitude of the evoked potential in 11 experiments. Although the muscle stimulation itself elicited an evoked cortical response (subtracted as for the ICMS) in some experiments, there was no clear relationship between the modulation produced by direct muscle stimulation and the presence or absence of this evoked response. In addition, although the depth of modulation cannot be directly compared in the two situations, it was noted that the modulation produced by muscle stimulation was always less than that produced by suprathreshold ICMS in the same experiments. Thus, while it is likely that peripheral feedback contributed to the modulation produced by ICMS, central influences also appear to play an important role in producing this modulation.

*Topographical organization of the ICMS conditioning effects*

Since motor cortical ICMS frequently did not modulate the amplitude of the air puff-evoked potentials (49 out of 116 tested pairs), we tested the hypothesis that some specific relationship existed between the central motor output and the location of the peripheral receptive field. This question was addressed by comparing different combinations of stimulation and recording sites to determine if changing the spatial relationship between the target muscle of the stimulation site in motor cortex and the receptive field of the recording site in somatosensory cortex would change the magnitude of the effect. The delays tested in these experiments were mostly between 51 and 91 ms as the strongest effects were usually observed at these delays (Fig. 3). Also, the intensity of stimulation used was suprathreshold (but not greater than 2 X T), as this intensity produced a more profound modulation.

Figure 4 illustrates the data obtained in one experiment in which the topographical organization of the modulation was investigated. Stimulation of one motor cortical site activated brachioradialis (A and B). Two penetrations were made into sensory cortex: the receptive field was located on the forearm at one site (A) and on the upper arm at the other site (B). Motor cortical conditioning stimulation markedly reduced the amplitude of the evoked response from the forearm site ($P<0.001$) but failed to significantly modify the potential evoked from the upper arm site. After moving the motor cortical electrode to another location from which a more proximal muscle was activated (middle deltoid, C), the evoked response recorded at that same sensory cortical recording site (receptive field on the upper arm) was now significantly decreased ($P<0.001$). Thus, the evoked response from the *same* segment as the target muscle was diminished by ICMS while the evoked response from a segment *proximal* to the target muscle was not.

Results similar to those shown in Fig. 4 were obtained in six experiments in which the effects of stimulating a single motor cortical site were tested on at least two different recording sites in sensory cortex, including one with a receptive field located either on the same segment of the limb as the target muscle, or just distal, and another with a field on the segment immediately proximal to the target muscle. The motor cortical stimulation sites activated target muscles acting on the shoulder (n = 3), elbow (n=2) and wrist (n=1). In all experiments, ICMS decreased the amplitude of evoked responses from the same segment as the target muscle, but failed to modify evoked responses from the segment proximal to the target muscle (respectively, the trunk, the upper arm and the proximal forearm).

Table 2 shows the distribution of all the experiments in which the amplitude of the evoked potential was decreased following suprathreshold ICMS (67–116), as a function of the target muscle activated by the ICMS and the location of the sensory cortical receptive field. For convenience, the target muscles were classified according to the joint(s) at which they exert their major action (e.g. deltoid/shoulder joint, biceps/elbow joint, etc.). For the

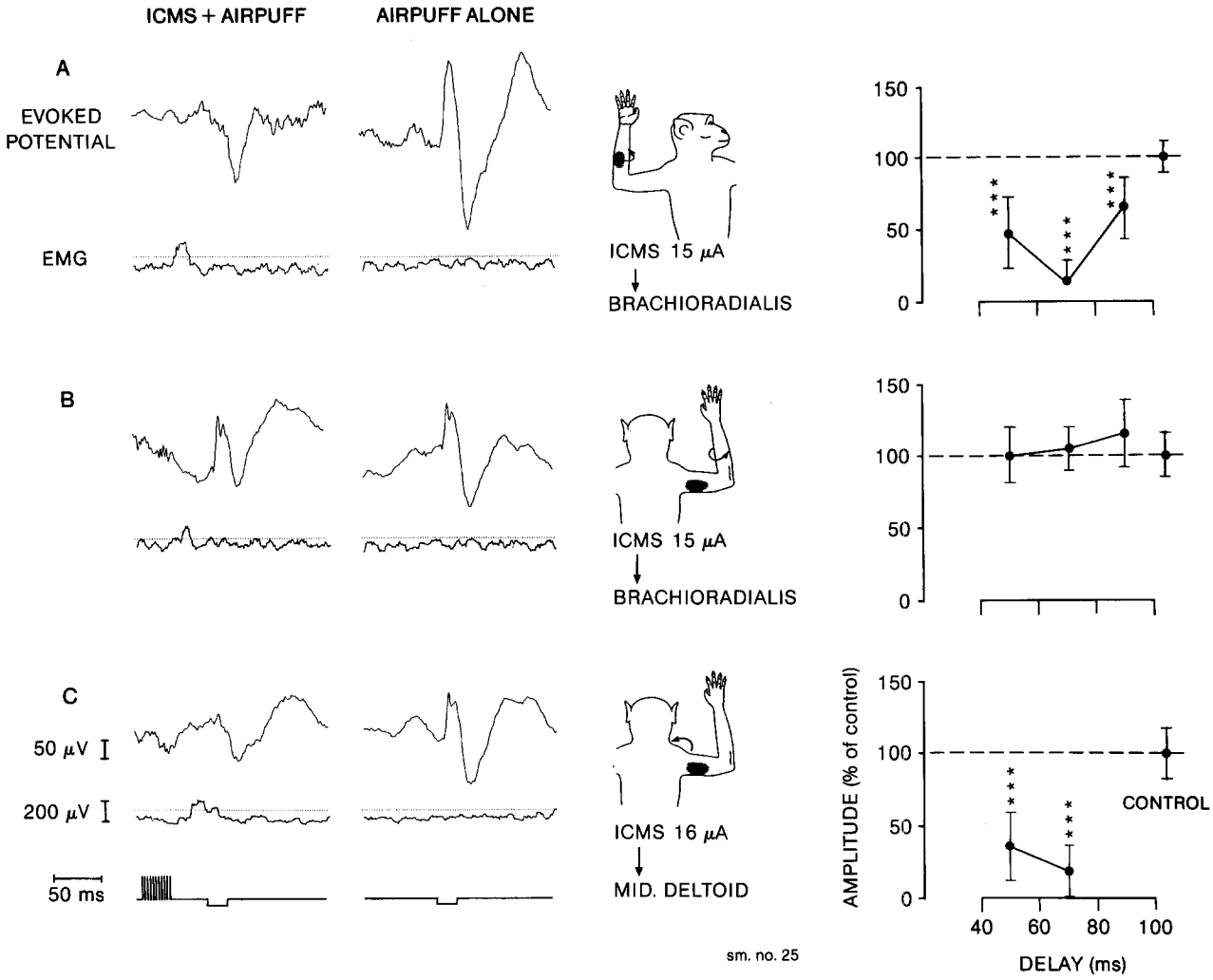


**Fig. 4A–C.** Topographical specificity of the modulation in the amplitude of the sensory cortical air puff-evoked response produced by suprathreshold ICMS. Data, collected from a single recording session, are plotted in the order of testing (**A–C**). Shown from left to right are examples of the raw data (n = 20 trials each, delay 71 ms), the locations of the sensory cortical receptive fields and the actions of the muscles activated by the ICMS (as in Fig. 1), and plots of the amplitude of the conditioned response at each delay tested (each point is an average of 20 trials, shown with the corresponding S.D.; For these series, the amplitude of each individual potential was measured; ***, $P < 0.001$). Two different target muscles were activated (**A**, **B**, brachioradialis; **C**, middle deltoid) in 2 penetrations into motor cortex; two sensory cortical receptive fields were tested, again recorded in 2 separate tracks (**A**, forearm (area 1); **B**, **C**, upper arm (transition zone between areas 3b and 1)). Both sensory cortical recording sites responded to hair displacement

**Table 2.** Distribution of the experiments in which the amplitude of the evoked potential was decreased by suprathreshold ICMS, as a function of the location of the sensory cortical receptive field (RF) and the target muscle which was activated by ICMS applied to motor cortex (n = 116 experiments, in 3 monkeys)*

| Target Muscles \ RF location | Trunk | Shoulder | Upper arm | Elbow | Forearm | Wrist | Hand | Digits (hairy dorsum) |
|---|---|---|---|---|---|---|---|---|
| Shoulder | 0/3** | 10/11 | 8/11 | 1/2 | 6/6 | — | — | 0/2 |
| Elbow | — | 0/2 | 2/6 | 1/2 | 20/24 | 3/4 | 3/6 | — |
| Wrist | — | — | 0/2 | — | 4/15 | 4/5 | — | — |
| Digits + wrist | — | — | — | — | 2/8 | 2/3 | 1/3 | 0/1 |

* Facilitatory effects were observed in 3 experiments, classified as ineffective here since suprathreshold stimulation had no effect. Stimulation/recording site: elbow/forearm, n = 1; shoulder/digits, n = 2

** Number of experiments showing a decrease/number of combinations tested (motor cortical stimulation site: sensory cortical recording site)

sensory cortical recording sites, the receptive fields were assigned to the portion of the limb upon which the centre of the receptive field was located, i.e. where the stimulus was generally applied. As described above, it is evident that conditioning stimulation of the motor cortex diminished the somatosensory responses from limb segments distal, but not proximal, to the articulation at which the target muscle acted. The effects were not, however, restricted to that part of the body immediately adjacent to the target muscle for the ICMS: activation of motor cortical loci controlling shoulder muscles modulated the amplitude of evoked responses not only from the shoulder and upper arm, but also from the forearm. For the more distally located muscles activated by ICMS, the modulatory effects were less widespread, still being confined to sites on the limb distal to the muscle affected by ICMS. Thus, for example, activation of wrist muscles modulated somatosensory evoked responses from the wrist and the dorsum of the hand but never from the upper arm and more infrequently from the forearm. Finally, the hand and digits appear to be relatively spared from the modulation. Only a small proportion of sites (33%) on the hairy dorsum of the hand or digits were affected by suprathreshold ICMS (glabrous inputs not investigated here). This was also true even when considering the more distal muscles controlling the digit and/or wrist muscles. In addition, the depressant effects appeared to exclude the digits, since a facilitation was seen in 2 out of 3 recording sites (threshold or subthreshold stimulation).

In some experiments, evidence was obtained which ruled out the possibility that the physical proximity between the stimulating and recording electrodes might underlie the apparent topographical organization of the effects. In the experiment shown in Fig. 5, the effects of stimulating a single motor cortical locus (target muscle, extensor digitorum communis) were studied on the air puff-evoked responses from three different receptive fields recorded *within the same electrode penetration.* A reconstruction of the penetration is shown in Fig. 5C. All recording sites were located within the same cytoarchitectonic field, 3b. For the first series of recordings (open triangles) the receptive field, as judged with multi-unit recordings, was located over the dorsum of the wrist. As shown in Fig. 5A, suprathreshold ICMS (17.5 $\mu$A, 1.5 X T) significantly decreased the evoked response to a minimum of 40% (delay to air puff: 71 ms). The recording electrode was subsequently lowered 300 $\mu$m. The receptive field for neurones at this depth (filled circles) was located on the ulnar side of the distal forearm. Conditioning stimulation of the motor cortex, using the same parameters of stimulation, again decreased the air puff-evoked response significantly (minimum response 25% at a delay of 91 ms). Finally, the recording electrode was lowered a further 200 $\mu$m and the receptive field shifted to the proximal forearm (open circles). The conditioning stimulus was now ineffective. Thus, ICMS was ineffective when the recording site received input from a more proximally located receptive field, but the physical distance between

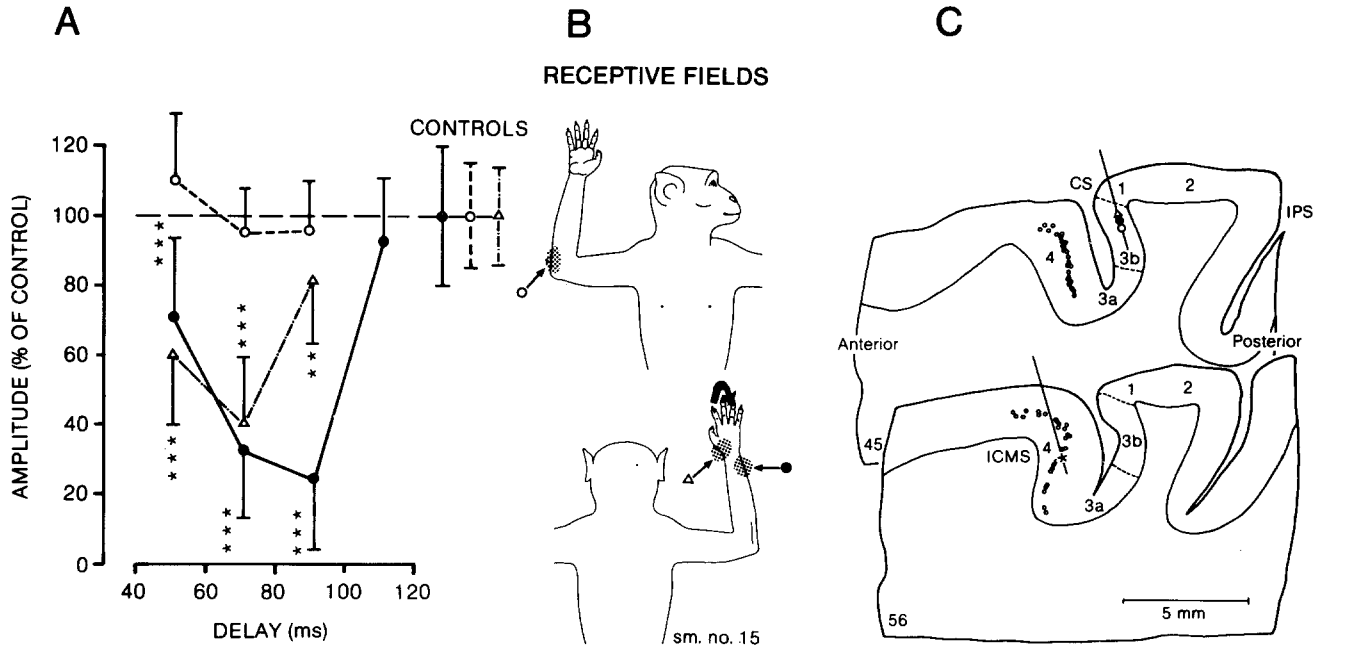


**Fig. 5A–C.** Differential effects of ICMS on air puff-evoked potentials recorded at three different heights within a single electrode penetration into sensory cortex. The reconstructions of the tracks are shown in **C**. The lower section shows the site at which the conditioning stimulation was applied in motor cortex. The upper section shows the reconstruction of the sensory cortical recording track through area 3b. The same symbols are used in **A** (plots of the amplitude of the conditioned responses recorded at the three sites as a function of the delay tested; **, $P<0.01$; ***, $P<0.001$), **B** (location of the receptive fields mapped at the three recording sites; all sites responded to hair displacement) and **C**. Suprathreshold ICMS (for all series: 17.5 $\mu$A, 1.5 X T) activated extensor digitorum communis, an extensor of the wrist and digits. The data in **A** are plotted as in Fig. 4. For these recordings, the amplitude of each individual potential was measured

the recording and stimulating electrodes had changed only an insignificant amount.

## Discussion

The principal finding of this study was that very weak ICMS of motor cortex in the awake monkey, itself producing no more than a slight and localized, isometric muscle twitch, can produce a profound reduction in the amplitude of air puff-evoked potentials recorded from the primary somatosensory cortex, areas 3b and 1. The modulation is long-lasting, topographically organized, and also very widespread in some instances.

The present analyses were restricted to the initial negative wave of the intracortically recorded, somatosensory evoked potential which represents the first postsynaptic event in somatosensory cortex (Gardner et al. 1984). We chose to use the evoked potential in the present study because of the large body of literature, mostly experiments done in human subjects, indicating that postcentral somatosensory evoked potentials are "gated" prior to and during movement (for example, Rushton et al. 1981; Cohen and Starr 1987). By using this method, we also hoped to make direct comparisons between the present findings and those of our previous study which had used the same method to study the modulation of somatosensory transmission during voluntary movements in monkeys (Chapman et al. 1988). The present experiments were designed as an initial step to investigate the origin of the central component of this movement-related modulation. Further experiments are required to determine the underlying mechanisms. For example, one might argue that the changes in the evoked potential seen in the present study simply reflect the addition of new current sources and sinks with no change in the responsiveness of the population of cortical neurones to the air puff. On the other hand, preliminary results from single unit recordings show that the decrease does represent a reduced responsiveness of cortical neurones to peripheral inputs (unpublished observations, Jiang, Chapman and Lamarre). Therefore, the results indicate that, in a presently unknown manner, somatosensory information is processed differently following the application of ICMS to the motor cortex, that this process produces, in virtually all cases (excluding the recording sites serving the dorsum of the digits), a decrease in the amplitude of the evoked potential, and that the latter decrease is similar to that seen during voluntary movement. Thus, while the evidence is indirect, the observation that ICMS produces a modulation similar to that associated with voluntary movement suggests that motor cortex plays an important role in producing this movement-related modulation.

### *Intracortical microstimulation of the motor cortex*

In this study we used intracortical microstimulation of the motor cortex (1.5 to 24 $\mu$A) to elicit very localized motor activity with minimal peripheral feedback (slight isometric contractions). Using previously published analyses of current spread (Stoney et al. 1968; Ranck 1975; Asanuma et al. 1976), our maximal current would have activated the largest myelinated fibres up to 500 $\mu$m from the electrode tip and small axons and cell bodies up to 200 $\mu$m from the tip. Taking into account spread through axon collaterals (Asanuma and Rosén 1972), the cortical effects should have been confined to within 1.5 mm of the tip of the electrode, i.e. much less than the minimal physical difference between the stimulating and recording electrodes in the present experiments (4 mm). In fact, in most experiments much lower currents were used. Thus, the modulation observed was not likely to have been mediated through direct spread of current to the recording site. Further to this, it is assumed that the elements directly activated by the ICMS were located within motor cortex. An exception to this may have been the most posterior sites in motor cortex; in those cases, the current may have spread to sensory cortex, activating neural elements which may have then directly influenced the excitability of pre- and/or postsynaptic elements at the recording site, via cortico-cortical projections (DeFelipe et al. 1986). This is unlikely, however, because more posterior stimulation sites did not have more frequent and/or more powerful effects. Furthermore, shifting the position of the recording electrode as little as 200 $\mu$m within the same track was shown to abolish the effects of ICMS in some experiments (Fig. 5). Thus it appears likely that the elements directly activated by the ICMS were indeed located within the motor cortex.

### *Topographical organization*

We observed a topographical relationship between the motor cortical conditioning stimulus and the decreased amplitude of cutaneous evoked responses. Irrespective of the articulation at which the muscles activated by the ICMS acted (shoulder to digits), the responses evoked from skin surfaces on the limb segment proximal to the target muscle were not modulated by motor cortical stimulation whereas those evoked from sites distal to the activated muscle were influenced by ICMS. As a consequence of this organization, ICMS which activated proximal limb muscles had a more widespread influence than did ICMS applied to sites controlling distal limb muscles. Interestingly, responses evoked from the hairy skin of the dorsum of the hand and digits were infrequently "gated" by ICMS, sometimes even showing a facilitation instead of a depression. Even when considering those distal muscles most closely associated with the hand, ICMS was frequently ineffective. Although the intrinsic muscles of the hand were not activated in any of the present experiments, our unpublished observations indicate that stimulation of such sites likewise does not decrease the amplitude of air puff-evoked potentials from the dorsum of the hand (Chapman, Jiang and Lamarre). The apparent sparing of hand inputs from the generalized suppression directed towards other cutaneous inputs from the arm is consistent with an important role of the hand in tactile exploration.

The topographically organized modulation of somatosensory evoked potentials reported here is reminiscent of observations made of a selective modulation, or "gating", of post-central cortical somatosensory evoked potentials during voluntary movement of the fingers in man (Rushton et al. 1981; Cohen and Starr 1987). Our results suggest, however, that the modulation associated with active movements of the digits may originate from sources other than the motor cortex, one possible source being peripheral feedback from the moving digits since this has been shown to modulate digital evoked potentials during movement (Rushton et al. 1981; Jones et al. 1989). Finally, our findings are also consistent with the demonstration by Giuffrida et al. (1985) that unitary activity in the dorsal column nuclei of the rat is modified in a somatotopic manner by motor cortical stimulation.

*Origin and level of the modulation*

At least part of the modulation produced by ICMS appears to be central in origin since it preceded the onset of EMG activity. In addition, direct muscle stimulation, which was used to mimic the effects of peripheral feedback from the ICMS-activated muscle, was ineffective in almost half of the experiments. Finally, effects were also observed in the absence of any EMG activity. It would be imprudent, however, to place too much emphasis on the latter as our EMG monitoring was not extensive. Peripheral feedback undoubtedly also contributed to the modulation, particularly at longer delays, a suggestion which is consistent with our previous results (Chapman et al. 1988), showing that passive movement decreases the amplitude of thalamic and cortical air puff-evoked potentials. The most conservative conclusion from our data is that the threshold for producing an effect with ICMS was about the same as the threshold for eliciting EMG activity. This observation may simply reflect the fact that the two roles for motor cortex are functionally coupled together so that the motor cortical output only modulates the responsiveness of sensory cortical neurones in the presence of actual movements.

In the present experiments the earliest mean delays at which the ICMS-induced modulation occurred were relatively long, 44 ms (suprathreshold) and 50 ms (threshold) after the onset of the train, although earlier effects were also occasionally seen (21 ms). In addition, the effects were very long-lasting (up to 111 ms), possibly due to long-acting processes such as presynaptic inhibition, the action of neuromodulatory substances, or the action of neurotransmitters such as GABA which can act over similarly long periods of time (Connors et al. 1988). The long onset latency appears to be compatible with a long pathway mediating the effects, but it should be pointed out that these latency values are not very precise since the adjacent delays tested were separated by a minimum of 5 to 20 ms (mean 12 ms for the delays relevant to the experiments in which timing was measured). Further to this, the onset latencies need to be expressed relative to the first effective pulse in the train, measures which we did not make systematically.

The topographically organized effects most probably reflect the specific pattern of connectivity between the motor cortex and the structure(s) mediating these effects. Although the level at which the motor cortex exerts its effects on the responsiveness of the sensory cortex to peripheral stimulation was not determined here, a number of structures may potentially be involved.

One possibility is that the modulation is a direct *cortico-cortical* effect, either through activation of motor cortical projections to area 1, and indirectly to area 3b, or through antidromic activation of sensory cortical neurones projecting to area 4 (Jones and Wise 1977; Jones et al. 1978; DeFelipe et al. 1986)). Yet, we found no difference between the results in areas 3b and 1 in one monkey (SM), despite the fact that there are no direct connections between areas 4 and 3b. In the other monkey (MIC), the few recordings in area 3b ($n=3$) did not show any modulation following ICMS, in contrast to the high proportion of effective experiments in area 1 of the same animal. Those recordings in area 3b, however, included 2 recording sites which had receptive fields on the digits and 1 experiment in which the receptive field was located on a segment proximal to the target muscle activated by the ICMS. combinations which were almost invariable ineffective in area 1 as well. In addition, for the majority of experiments, the latency data indicated that a rather long pathway (31 ms or more) was involved; this does not, of course, rule out the possibility that a shorter latency pathway requiring considerable temporal summation was involved.

With regards to the subcortical structures which might be involved, transmission of afferent signals may be diminished at either of the two major relays within the dorsal column-medial lemniscal pathway, the *thalamus* (probably indirectly through the reticular nucleus (Jones 1975)) and the *dorsal column nuclei* (see below). Finally, an action at the *spinal* cord level is also possible, but unlikely as the motor cortical projection terminates mainly in the intermediate zone and the ventral horn, areas involved primarily in controlling motoneurones and transmission through reflex motor pathways.

Anatomical and electrophysiological evidence (reviewed in the Introduction) indicate that one of the most likely subcortical sites of action is the dorsal column nuclei. This suggestion is also consistent with our previous results which showed that there is a centrally mediated suppression of somatosensory transmission during movement, an effect which is most probably exerted at the level of the dorsal column nuclei in the monkey (Chapman et al. 1988). In addition, there is direct evidence, from Ghez and Pisa (1972), that voluntary movement produces pre- and postsynaptic inhibition in the cuneate nucleus of the cat and that this contributes to the depression of the medial lemniscal evoked response during voluntary movement in the cat.

*Functional significance*

The modulation produced by ICMS is qualitatively similar to that modulation associated with voluntary

movement in the monkey (Chapman et al. 1988), a surprising observation in view of the enormous difference in the degree and quanitity of EMG activity in the two situations, as well as in the degree and type of peripheral feedback. The present results thus strongly support our previous suggestion that the motor cortex plays an important role in mediating the early modulation of cutaneous transmission that precedes the onset of movement (Chapman et al. 1988). This strengthens the notion that the efference copy arising from the motor cortex plays a role in controlling sensory feedback, perhaps suppressing redundant inputs which might be predicted from the motor command so that the detection of other, novel inputs is enhanced (Coulter 1974; Chapman et al. 1988). In addition, for cutaneous areas distal to a particular limb muscle, the results indicate that the modulation is very *nonspecific*, a finding consistent with our own previous work (Chapman et al. 1988).

The topographical organization described in the present study in highly reminiscent of the input-output relationships which have been described for motor cortical neurones in both the cat (Asanuma et al. 1968; Armstrong and Drew 1984) and the monkey (Rosén and Asanuma 1972; Murphy et al. 1978). Such studies have shown that motor cortical neurones receive peripheral inputs from limb segments either overlying or distal to the motor output. Inputs are infrequently received from parts of the limb proximal to the target muscle (Armstrong and Drew 1984). In the present study, the receptive field properties of the stimulation sites in the motor cortex were not systematically characterized. Future experiments could determine the relationship between the peripheral inputs to the motor cortex and the pattern of modulation of sensory inputs. Such information might assist in explaining why, for example, some motor cortical sites did not modulate input from distal or adjacent limb segments. Perhaps these sites controlled deep, and not cutaneous, inputs from the arm. Certainly there is evidence of selective controls over the transmission of cutaneous and deep inputs (Tsumoto et al. 1975). Finally, the present experiments did not attempt to study, in an exhaustive manner, all motor cortical sites activating any single muscle. It would be interesting to determine if all sites are equally effective in suppressing cutaneous inputs. Any differences might help to shed some light upon the functional significance of the multiple representation of single muscles in the motor cortex.

*Acknowledgements.* We gratefully acknowledge the excellent technical assistance provided by S. Bergeron, R. Bouchoux, D. Cyr, G. Filosi, C. Gauthier, M.-T. Parent and C. Valiquette. We thank Dr. T. Drew for his helpful comments on an earlier version of the manuscript and also during the experiments. We also thank Drs. R.W. Dykes and J.F. Kalaska for comments on the manuscript. Supported by the Medical Research Council of Canada (MRC). C.E. Chapman is a Chercheur-Boursier of the Fonds de la Recherche en Santé du Québec. Y. Lamarre is a member of the MRC Group in Neurological Sciences.

## References

Armstrong DM, Drew T (1984) Topographical localization in the motor cortex of the cat for somatic afferent responses and evoked movements. J Physiol (Lond) 350: 33–54

Asanuma H. Rosén I (1972) Topographical organization of cortical efferent zones projecting to distal forelimb muscles in the monkey. Exp Brain Res 14: 243–256

Asanuma H, Arnold A, Zarzecki P (1976) Further study on the excitation of pyramidal tract cells by intracortical microstimulation. Exp Brain Res 26: 443–461

Asanuma H, Stoney SD, Abzug C (1968) Relationship between afferent input and motor outflow in cat motorsensory cortex. J Neurophysiol 31: 670–681

Bentivoglio M, Rustioni A (1986) Corticospinal neurons with branching axons to the dorsal column nuclei in the monkey. J Comp Neurol 253: 260–276

Bioulac B, Lamarre Y (1979) Activity of post-central cortical neurons of the monkey during conditioned movements of a deafferented limb. Brain Res 172: 427–437

Chapman CE, Jiang W, Lamarre Y (1988) Modulation of lemniscal input during conditioned arm movements in the monkey. Exp Brain Res 72: 316–334

Cheema S, Rustioni A, Whitsel BL (1985) Sensorimotor cortical projections to the primate cuneate nucleus. J Comp Neurol 240: 196–211

Cheney PD, Fetz EE (1985) Comparable patterns of muscle facilitation evoked by individual corticomotoneuronal (CM) cells and by single intracortical microstimuli in primates: evidence for functional groups of CM cells. J Neurophysiol 53: 786–804

Cohen LG, Starr A (1987) Localization, timing and specificity of gating of somatosensory evoked potentials during active movement in man. Brain 110: 451–467

Cole JD, Gordon G (1983) Timing of corticofugal actions on the gracile and cuneate nuclei of the cat. J Physiol (Lond) 340: 139–152

Connors BW, Malenka RC, Silva LR (1988) Two inhibitory postsynaptic potentials, and $GABA_A$ and $GABA_B$ receptor-mediated responses in neocortex of rat and cat. J Physiol (Lond) 406: 443–468

Coulter JD (1974) Sensory transmission through lemniscal pathway during voluntary movement in the cat. J Neurophysiol 37: 831–845

DeFelipe J, Conley M, Jones EG (1986) Long-range focal collateralization of axons arising from corticocortical cells in monkey sensory-motor cortex. J Neurosci 6: 3749–3766

Dyhre-Poulson P (1978) Perception of tactile stimuli before ballistic and during tracking movements. In: Gordon G (ed) Active touch. Pergamon Press, Oxford, pp 171–176

Evarts EV (1972) Contrasts between activity of precentral and postcentral neurons of cerebral cortex during movement in the monkey. Brain Res 40: 25–31

Evarts EV (1981) Role of motor cortex in voluntary movements in primates. In: Brooks VB (ed) Handbook of physiology, Sect 1. The nervous system, Vol II, Part 2. American Physiological Society, Bethesda MD, pp 1083–1120

Fromm C, Evarts EV (1982) Pyramidal tract neurons in somatosensory cortex: central and peripheral inputs during voluntary movement. Brain Res 238: 186–191

Gardner EP, Hamalaïnen HA, Warren S, Davis J, Yong W (1984) Somatosensory evoked potentials (SEPs) and cortical single unit responses elicited by mechanical tactile stimuli in awake monkeys. Electroenceph Clin Neurophysiol 58: 537–552

Ghez C, Lenzi GL (1971) Modulation of sensory transmission in cat lemniscal system during voluntary movement. Pflügers Arch 323: 273–278

Ghez C, Pisa M (1972) Inhibition of afferent transmission in cuneate nucleus during voluntary movement in the cat. Brain Res 40: 145–151

Giuffrida R, Sanderson P, Sapienza S (1985) Effects of microstimulation of movement-evoked cortical foci on the activity of neurons in the dorsal column nuclei. Somatosens Res 2: 237–247

Harris H, Jabbur SJ, Morse RW, Towe AL (1965) Influence of the cerebral cortex on the cuneate nucleus of the monkey. Nature 208: 1215–1216

Humphrey D, Corrie WS (1978) Properties of pyramidal tract

neuron system within a functionally defined subregion of primate motor cortex. J Neurophysiol 41: 216–243
Jabbur SJ, Towe AL (1961) Cortical excitation of neurons in dorsal column nuclei of cat, including an analysis of pathways. J Neurophysiol 24: 499–509
Jiang W, Chapman CE, Lamarre Y (1988) The topographical modulation of somatosensory transmission to SI cortex produced by microstimulation of MI cortex in the monkey. Abstr Soc Neurosci 14: 509
Jiang W, Lamarre Y, Chapman CE (1986) Modulation of somatosensory input to sensory cortex produced by intracortical microstimulation of motor cortex in the monkey. Abstr Soc Neurosci 12: 259
Jones EG (1975) Some aspects of the organization of the thalamic reticular complex. J Comp Neurol 162: 285–308
Jones EG, Coulter JD, Hendry SHC (1978) Intracortical connectivity of architectonic fields in the somatic sensory, motor and parietal cortex of monkeys. J Comp Neurol 181: 291–348
Jones EG, Wise SP (1977) Size, laminar and columnar distribution of efferent cells in the sensory-motor cortex of monkeys. J Comp Neurol 175: 391–438
Jones SF, Halonen J-P, Shawkat F (1989) Centrifugal and centripetal mechanisms involved in the 'gating' of cortical SEPs during movement. Electroenceph Clin Neurophysiol 74: 36–45
Kuypers HGJM (1960) Central cortical projections to motor and somato-sensory cell groups: an experimental study in the rhesus monkey. Brain 83: 161–184
Lamarre Y, Joffroy AF, Filion M. Bouchoux R (1970) A stereotaxic method for repeated sessions of central unit recording in the paralyzed or moving animal. Rev Can Biol 29: 371–376
Lemon RN, Muir RB, Mantel GWH (1987) The effects upon the activity of hand and forearm muscles of intracortical stimulation in the vicinity of corticomotor neurones in the conscious monkey. Exp Brain Res 66: 621–637
Murphy JT, Kwan HC, MacKay WA, Wong YC (1978) Spatial organization of precentral cortex in awake primates. III. Input-output coupling. J Neurophysiol 41: 1132–1139
Powell TPS, Mountcastle VB (1959) Some aspects of the functional organization of the cortex of the postcentral gyrus of the monkey: a correlation of findings obtained in a single unit analysis with cytoarchitecture. Bull Johns Hopkins Hosp 105: 133–162
Ranck Jr JB (1975) which elements are excited in electrical stimulation of mammalian central nervous system: a review. Brain Res 98: 417–440
Rosén I, Asanuma H (1972) Peripheral afferent inputs to the forelimb area of the monkey motor cortex: input-output relations. Exp Brain Res 14: 257–273
Rushton DN, Rothwell JC, Craggs MD (1981) Gating of somatosensory evoked potentials during different kinds of movement in man. Brain 104: 465–491
Soso MF, Fetz EE (1980) Responses of identified cells in postcentral cortex of awake monkeys during comparable active and passive joint movements. J Neurophysiol 43: 1090–1110
Stoney SD, Thompson WD, Asanuma H (1968) Excitation of pyramidal tract cells by intracortical microstimulation: effective extent of stimulating current. J Neurophysiol 31: 659–669
Towe AL, Jabbur SJ (1961) Cortical inhibition of neurons in dorsal column nuclei of cat. J Neurophysiol 24: 488–498
Tsumoto T, Nakamura S, Iwama K (1975) Pyramidal tract control over cutaneous and kinesthetic sensory transmission in the cat thalamus. Exp Brain Res 22: 281–294

Received July 7, 1989 / Accepted October 24, 1989