Korean J Physiol Pharmacol
Vol 2: 9–19, February, 1998

Sensory Inputs to Upper Cervical Spinal Neurons Projecting to Midbrain in Cats

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The present study was primarily carried out to characterize the properties of the spinomesencephalic tract (SMT) neurons that project from the upper cervical spinal segments to the midbrain. It was also investigated whether these neurons received convergent afferent inputs from other sources in addition to cervical inputs. Extracellular single unit recordings were made from neurons antidromically activated by stimulation of midbrain. Recording sites were located in lamina I~VIII of C1~C3 segments of spinal cord. Receptive field (RF) and response properties to mechanical stimulation were studied in 71 SMT neurons. Response profiles were classified into six groups: complex (Comp, n=9), wide dynamic range (WDR, n=16), low threshold (LT, n=5), high threshold (HT, n=6), deep/tap (Deep, n=10), and non-responsive (NR, n=25). Distributions of stimulation and recording sites were not significantly different between SMT groups classified upon their locations and/or response profiles. Mean conduction velocity of SMT neurons was 16.7±1.28 m/sec. Conduction velocities of SMTs recorded in superficial dorsal horn (SDH, n=15) were significantly slower than those of SMTs recorded in deep dorsal horn (DDH, n=18), lateral reticulated area (LRA, n=21), and intermediate zone and ventral horn (IZ/VH, n=15). Somatic RFs for SMTs in LRA and IZ/VH were significantly larger than those in SDH and DDH. Five SMT units (4 Comps and 1 HT) had inhibitory somatic RFs. About half (25/46) of SMT units have their RFs over trigeminal dermatome. Excitabilities of 5/12 cells and 9/13 cells were modulated by stimulation of ipsilateral phrenic nerve and vagus nerve, respectively. These results suggest that upper cervical SMT neurons are heterogenous in their function by showing a wide range of variety in location within the spinal gray matter, in response profile, and in convergent afferent input.

Key Words: Spinomesencephalic tract, Vagus nerve, Phrenic nerve

INTRODUCTION

The involvement of spinomesencephalic tract (SMT) in transmission of somatosensory information has become well recognized. SMT cells respond to inputs, both noxious and non-noxious, from cutaneous and deep structures including joints and muscles (Bowscher, 1976; Menetréy et al, 1980; Yezierski & Schwartz, 1986; Hylden et al, 1986; Willis & Coggeshall, 1991; Park & Kim, 1994). The SMT originates from cells in the dorsal and ventral horns of the spinal cord. SMT axons cross segmentally and ascend in the ventro- and dorsolateral quadrants of the spinal cord to terminate in a variety of midbrain structures. Mesencephalic terminal area of this projection in the cat includes the following structures: periaqueductal gray (PAG), lateral part of central gray, deep layers of superior colliculus, intercollicular nucleus, anterior and posterior pretectal nuclei, red nucleus, nucleus of Darkschewitsch, and nucleus of cuneiformis (Bjorkeland & Boivie, 1984; Wiberg & Blomqvist, 1984; Yezierski, 1988).

The PAG and the central gray, principal targets of spinomesencephalic projections, are complex regions involved in diverse functions and states. PAG stimu-

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lation suppresses nociceptive reflexes and inhibits the responses of nociceptive cells in the spinal and medullary dorsal horns. The antinociceptive effects of PAG activation are mediated, at least in part, by a synaptic relay in the rostral ventromedial medulla which contains many neurons projecting directly to the spinal dorsal horn and spinal trigeminal nucleus (Basbaum & Fields, 1984; Besson & Chaouch, 1987). Furthermore, recent studies have shown that the PAG plays important roles in co-ordinating both cardiovascular and respiratory adjustment and in controling defensive and/or female reproductive behavior (Depaulis & Bandler, 1991). Therefore the midbrain PAG is known to be involved in initiating and integrating many aspects of behavioral, somatomotor and autonomic activities in addition to analgesia. Considering the integral function of the PAG in the generation of animal responses to threatening or stressful stimuli, the SMT that affects PAG may play an important role in rapid coordinated somatic and autonomic adjustments associated with significant alteration in pain threshold, with which other spinal ascending pathways such as dorsal column and spinothalamic tract (STT) are not much concerned.

The upper cervical segment (UCS) of spinal cord is markedly different somatosensory relay region from other spinal regions in several aspects. First, there is a high concentration of cells of origin of spinal sensory tract in the upper cervical cord. Approximately one-third of all STT neurons in monkey (Apkarian & Hodge, 1989), rat (Granum, 1986; Kemplay & Webster, 1986) and cat (Jones et al, 1987) originate in the UCS ($C_1 \sim C_3$) of the spinal cord. The distribution of large number of cells in UCS is also common to the SMT (Menetréy et al, 1982; Yezierski & Mendez, 1991), spinoreticular (Menetréy et al, 1983), and spinohypothalamic pathways (Burstein et al, 1990) in rats. Second, UCS contains the lateral cervical nucleus (LCN), which is the relay nucleus of the spinocervicothalamic pathway (Craig & Tapper 1978; Giesler et al, 1988). Third, UCS is a region where information transmitted through trigeminal and cervical nerves may converge. Anatomical (Humphrey, 1955; Kerr, 1972) and electrophysiological studies (Kerr & Olafson, 1961; Abrahams et al, 1979) have demonstrated that trigeminal primary afferent fibers project as far caudal as C_2 and C_3 cervical segments of the spinal cord. However, the supraspinal projection site of these UCS neurons that receive convergent afferent inputs has not been evaluated precisely.

Putting all the above information together, it is likely that functional characteristics of dorsal horn cells in UCS are different from those in other spinal region. However, most of previous electrophysiological studies of SMT neurons have examined cells in the lumbar enlargement (Menetréy et al, 1984; Yezierski & Schwartz, 1986; Park & Kim, 1994). The present study was designed to charicterize the electrical and mechanical response properties of SMT neurons in UCS and to determine whether activity of SMT neurons in UCS is altered by stimulation of afferent fibers in other sensory nerves than cervical nerve such as trigeminal and phrenic nerves.

METHODS

Animal preparation

Experiments were carried out in 17 adult male cats weighing between 2.5 and 4 kg. Cats were pretreated with atropine sulfate (0.4 mg, i.m.) and initially anesthetized with ketamine hydrochloride (40 mg/kg, i.m.). The femoral vein and artery of the left leg were cannulated for infusing drugs and fluid and for recording blood pressure, respectively. A tracheostomy was performed for artificial respiration. Anesthesia was subsequently maintained with alpha-chloralose (60 mg/kg, i.v.). During recording sessions, cats were paralyzed with periodic injections of gallamine triethiodide (3~4 mg/kg) and artificial ventilation was employed to keep the end-tidal CO_2 concentration between 3.5 and 4.5%. Rectal temperature was monitored and maintained between 36.5 and 37.5°C. Anesthetic level was maintained throughout the experiment with an infusion of sodium pentobarbital (2~4 mg/kg/h).

Cats were placed in a stereotaxic apparatus and a vertebral clamp was attached to spinous process at the mid-thoracic level. A craniotomy was performed to permit recording and subsequent stimulation of the midbrain. A laminectomy from the foramen magnum to the third cervical vertebrae was performed to expose the spinal C1~C3 segments and to search for spinal neurons.

The dura mater over the exposed spinal cord was opened and a mineral oil pool was made around the spinal cord by retracting the skin flap and fixing it to the stereotaxic frame. Copper coils connected to a circulating water bath were used to keep the tem-

perature of mineral oil at 37°C throughout the experiment.

Stimulation and recording

Spinal neurons projecting to the midbrain structure were characterized by antidromic activation (0.1 msec, 2 Hz, 500 μA). Antidromic stimulating electrode (stainless steel; monopolar; tip diameter 0.1 mm; epoxy-coated; tip exposure 0.2 mm) was stereotaxically placed in the midbrain. One array (mediolateral orientation) of 3 monopolar stainless steel electrodes was positioned in the rostral midbrain and/or medial thalamus (A4.5~6.0), and the second array (anteroposterior orientation) was positioned in the caudal (P0.5~1.5) midbrain. The lateral electrode in the rostral array was positioned for activation of axons ascending to more rostral brain stem nuclei, such as the thalamus. The following criteria were used to identify an antidromic activation: 1) constant spike latency, 2) ability to follow high frequency (333 Hz) stimulus without change in latency, 3) collision with spontaneous or evoked orthodromic spikes, and 4) discrete threshold (Fig. 1).

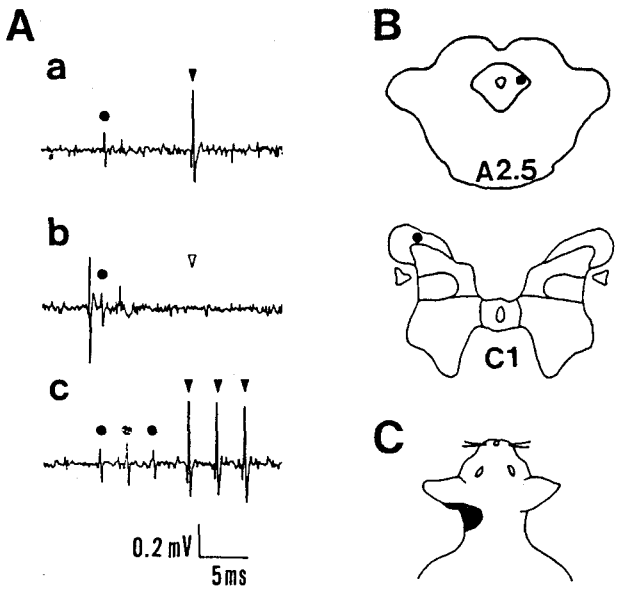

Fig. 1. Criteria for the identification of antidromically activated SMT neuron. A: antidromic responses of C_1 SMT neuron. Discrete threshold and constant latency of antidromic spike to midbrain stimulation (a), collision with spontaneous or evoked orthodromic impulse (b), and ability to follow a high frequency (333 Hz) stimuli without any modification in latency (c) were considered as criteria. The latency of the response was constant at 9.8 ms. Solid circle, the midbrain stimulus; solid triangle, location of antidromic spike; open triangle, expected location of anitdromic spike. B: locations of stimulation and recording sites of this cell. C: cutaneous receptive field of neuron.

Extracellular recordings from spinal neurons were made with carbon-filament microelectrodes (tip resistance: 1~4 MΩ). Neuronal activity was amplified (bandpass 0.3~10 KHz; gain 10,000) with AC differential amplifier (DAM 80, WPI), and displayed on oscilloscope (5113, Tektronix). The single cell activity was extracted using a window discriminator (WPI), sampled at a rate of 67 KHz (1401 plus, CED), and stored on a personal computer for further analysis.

Classification of response types

The responses of neurons to mechanical stimulation of their cutaneous receptive field (RF) were characterized by applying graded intensity of mechanical stimuli during extracellular recording. Neurons were classified as wide dynamic range (WDR) cells if they responded in a graded manner to innocuous tactile stimuli and noxious pinch, as low-threshold (LT) cells if they responded maximally to innocuous tactile stimuli, as high-threshold (HT) cells if they responded only to noxious mechanical stimuli, and as deep/tap (Deep) cells if they responded not to cutaneous stimuli but to tap, joint movement, or probing of subcutaneous structures such as muscles. Neurons with either mixed types of response or RFs over various part of the body were classified as complex (Comp) cells.

Stimulation of phrenic and vagus nerves

Phrenic nerves were isolated at the level of innominate artery. Vagus nerves were separated from the external carotid artery in the neck. Hooks of a bipolar electrode were placed on the nerve and held in place with Reprosil, a dental impression material. Stimulations of phrenic and vagus nerves were induced with single or trains of spikes of 0.5 Hz, 0.2 msec, 0.5~3 mA. The response to nerve stimulation was obtained with poststimulus time histogram in 0.5 msec bin width after 15~30 repetitions of stimulus.

Identification of stimulation and recording sites

At the end of the recording of each unit, electrolytic lesions were made to mark the recording site in the spinal gray matter by passing a DC current of 50 ~100 μA through the recording electrode for 20~30 seconds. For marking the midbrain stimulation sites similar procedure was used. Following transcardiac perfusion with a 1% solution of potassium ferrocyanide in 10% formalin, the midbrain and medulla were removed and post-fixed in 10% formalin solution for 3~5 days. Coronal sections of 50 μm thickness were obtained and stained with cresyl-violet. Antidromic stimulation and recording sites were reconstructed on the basis of electrolytic lesion site.

Statistical analysis

Statistical comparisons were made with ANOVA (Newman-Keuls test), and $p<0.05$ was used for significance. Mean values were represented with their standard errors.

RESULTS

A total of 71 single unit were recorded in upper cervical segments of spinal cord. Of these, 46 units satisfied all criteria for antidromic activation. The remaining 25 cells were unresponsive to any type of peripheral stimuli and termed "non-responsive (NR)". Data analysis in the present study was made mainly on SMT cells having peripheral receptive field.

Stimulation sites

The location of antidromic stimulation sites at five different midbrain levels is shown in Fig. 2. Antidromic thresholds for all units ranged from 40 to 750 μA (mean 174±15.2 μA). The antidromic stimulation sites in midbrain included PAG (29 cells), mesencephalic reticular formation in adjacent to PAG (39 cells), deep layers of superior colliculus (3 cells). There was no difference in the distribution of midbrain stimulation sites between responsive and NR SMT neurons in the upper cervical cord.

Recording sites

Recording sites for most of SMT cells (58/69) in this study were in C_1~C_2 segments. The distribution of recording sites in spinal gray matter is shown in Fig. 3. Based on the location of recording sites in different regions of the spinal gray matter (block diagram in Fig. 3 based on Rexed, 1954), 69 SMT cells were classified into four groups: superficial dorsal horn (SDH, n=15), deep dorsal horn (DDH, n=18), lateral reticulated area (LRA, n=21), and intermediate zone and ventral horn (IZ/VH, n=15). The electrolytic lesions of two cells were found immediately adjacent to dorsal horn near lateral cervical nucleus. The distribution of recording sites of 23 NR neurons was

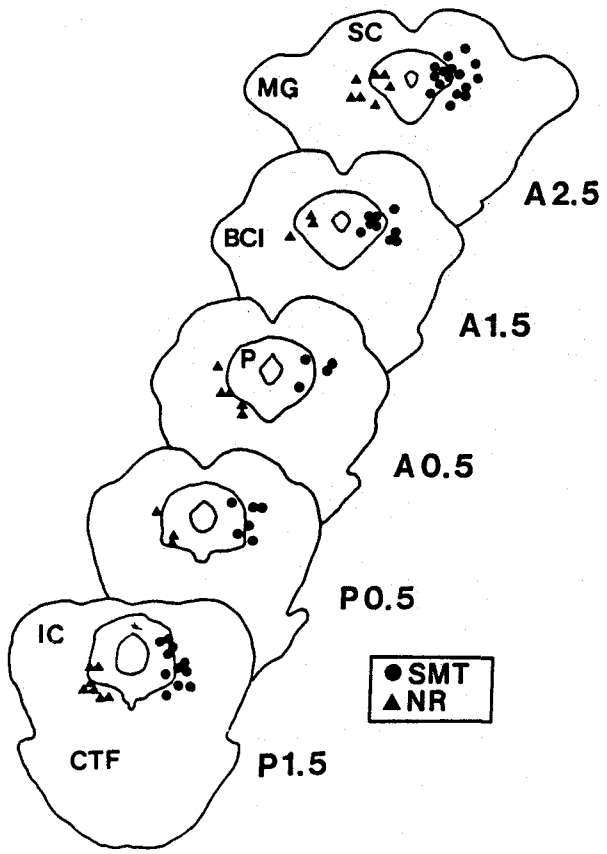

Fig. 2. Histological reconstruction of antidromic stimulation sites marked with electrolytic lesions. Solid circles and triangles represent effective midbrain stimulation sites to activate responsive and non-responsive (NR) SMT neurons in the upper cervical cord, respectively. In all cases, midbrain stimulation was performed in the right side. Stimulation sites for NR neurons are plotted on the left side to compare with those of cells having cutaneous receptive field. SC, superior colliculus; MG, medial geniculate; BCI, brachium colliculi inferioris; P, periaqueductal gray; IC, inferior colliculus; CTF, central tegmental field.

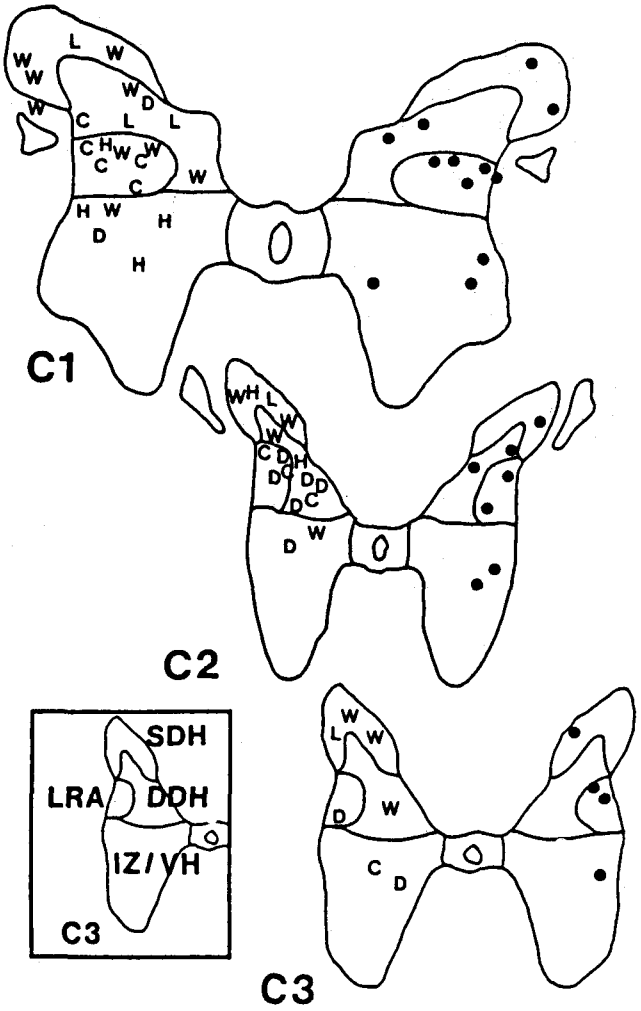

Fig. 3. Distribution of recording sites for 69 SMT cells in C_1~C_3 segments of spinal cord. Although all recordings were made in the left wide, recording sites for 23 non-responsive SMT units (solid circle) were seperately marked in the right side to contrast with those of responsive SMT units. W, wide dynamic range; L, low threshold; H, high threshold; D, Deep; C, complex: SDH, superficial dorsal horn; DDH, deep dorsal horn; LRA, lateral reticulated area; IZ/VH, intermediate zone and ventral horn.

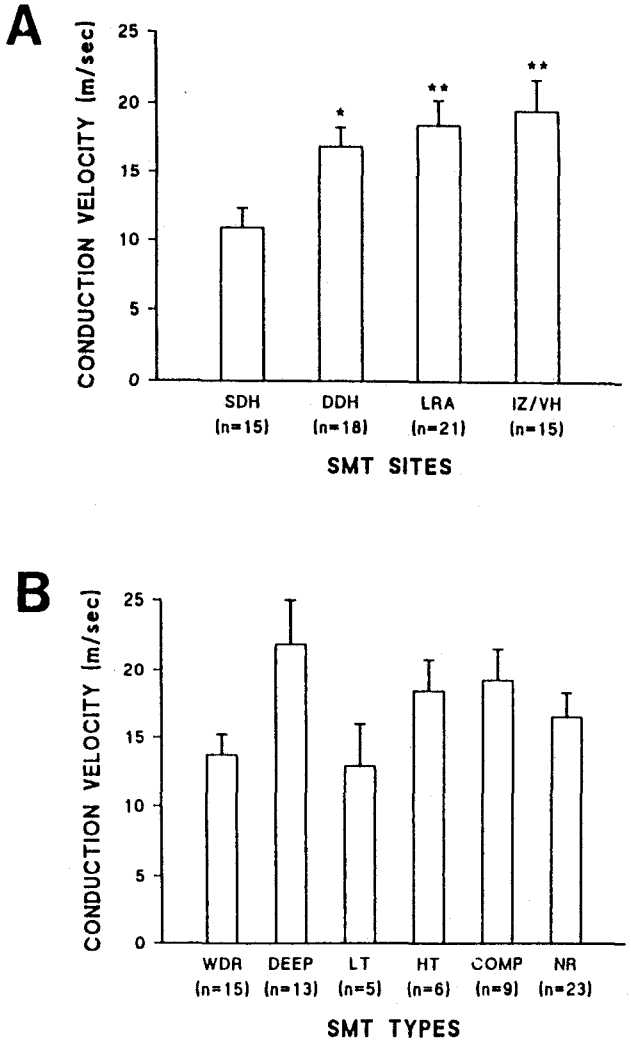

Fig. 4. Comparison of the conduction velocity of the SMT units among different groups on the basis of recording sites (A) and response types (B). Asterisks, * and **, indicate the significant difference from SDH at $p<0.05$ and $p<0.01$, respectively.

similar with that of 46 SMT neurons. The 6 of 9 complex type SMT neurons were found in LRA. All 5 LT cells located in lamina I~IV (3 in SDH and 2 DDH), where as most of Deep cells (8/10) located in lamina V~VIII (3 in DDH, 3 in IZ/VH, and 2 in LRA).

Conduction velocity

The conduction velocities (CV) of the SMT ranged from 3.7 to 45.6 m/sec with a mean of 16.71 ± 1.28 m/sec. Although there was no significant variation in the CV of the SMT units on the basis of response type (Fig. 4B), the conduction velocity of neurons recorded in SDH (10.9 ± 1.42 m/sec, n=15) is significantly slower than those recorded in DDH (16.9 ± 1.41, n=18, $p<0.05$), LRA (18.6 ± 1.78, n=21, $p<0.01$), and IZ/VH (19.6 ± 2.21, n=15, $p<0.01$) as shown in Fig. 4A.

Receptive field size

Receptive field (RF) sizes of 46 SMT cells were compared between groups classified by the location of recording sites (Fig. 5). The RFs of LRA group cells were significantly larger than those of DDH cells ($p<0.05$), and the RFs of IZ/VH group units were larger than those of SDH ($p<0.05$) and DDH cells ($p<0.05$).

Inhibitory responses of SMT cells

The 5 SMT units had inhibitory RFs (Fig. 6). Four cells were Comp type and the remaining one is HT type. As shown in Fig. 6, inhibitory responses were always evoked by noxious stimuli, such as pinch and squeeze, and were found in cells having large RF. One inhibitory SMT cell, HT type (Fig. 6A), had only inhibitory RFs spanning all four limbs and neck. The other 4 Comp type neurons also had large or wide-spread excitatory RF and additional, separated or not-separated (mixed), inhibitory RF (Fig. 6D). Even in the same cutaneous field, brush stimulus produced excitatory response whereas stronger stimuli

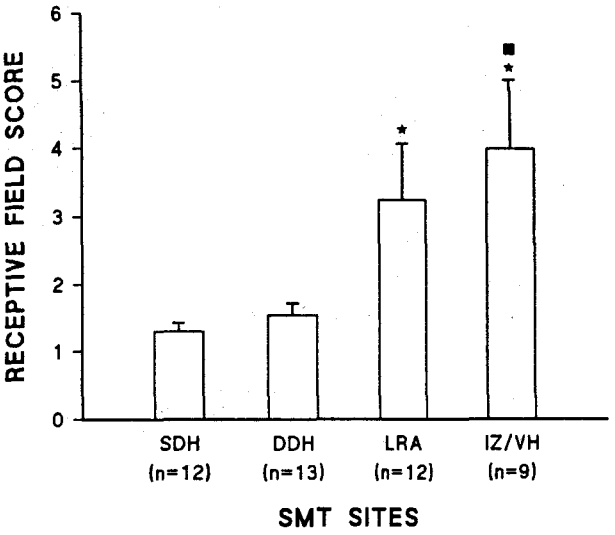

Fig. 5. Comparison of the receptive field (RF) size of the SMT units according to their location of recording sites. The basis of calculating RF score of SMT unit is to give one point to each area of the following; unilateral face, unilateral occiput and/or neck, a limb, and trunk. For example, SMT neuron with whole body RF gets 9 as RF score. Solid square and asterisk indicate the significant difference from SDH and DDH at $p<0.05$, respectively.

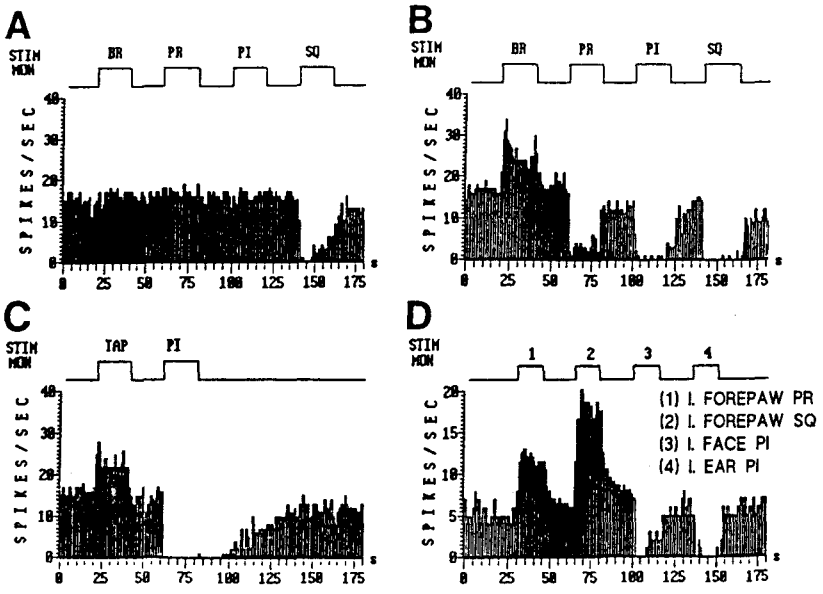

Fig. 6. Inhibitory responses observed 1 HT (A) and 4 Comp type units (B in 2 units, C, and D). A, inhibitory response evoked only by squeeze stimulus (SQ); B, excitatory response to brush (BR) and inhibitory responses to pressure (PR), pinch (PI) and SQ; C, excitatory response to tapping (TAP) and inhibitory response to PI stimulus in the ipsilateral forelimb; D, different responses to inputs from RFs spread over ipsilateral (I.) side.

(pinch or squeeze) evoked inhibitory responses (Fig. 6B, 2 units). Another cell (Fig. 6C) showed excitatory response to tapping or probing the ipsilateral biceps brachii and inhibitory response to pinching the skin overlying that muscle.

Convergent afferent inputs onto SMT neuorns

Trigeminal input: RF properties of 46 SMT unit were evaluated to figure out the incidence of SMT neurons receiving cutaneous input from trigeminal dermatome (orofacial area). About half of SMT units in UCS (25/46) investigated in the present study had their RFs, additionally or solely, over trigeminal dermatome (Table 1). Of these 25 units, 13 units had their RFs within trigeminal and cervical dermatomes (6 Comp, 5 WDR, 1 LT, and 1 HT units), and were mainly located in C_1 segments (13/25).

Effect of phrenic nerve stimulation: Twelve cells were tested for their responses to electrical stimulation of the ipsilateral phrenic nerve (IPN) at the level of innominate artery. Five of the 12 cells were excited by stimulation of IPN (Fig. 7). The remaining 7 cells did not change activity in response to stimulation of IPN. All of 5 cells that responded to IPN stimulation had large RFs which included the ipsilateral face, neck, upper forelimb, or shoulder. Responses of a typical cell are shown in Fig. 7. The single spike stimulation (0.5~3 mA, 0.5 Hz, 0.2 msec) evokes 1~4 impulses (Fig. 7A).

Effect of vagus nerve stimulation: Effect of electrical stimulation of the cervical vagus nerve was determined in 13 SMT neurons. In segments C_1~C_2, the activities of 9/13 neurons were modulated by vagus nerve stimulation: 4 excitatory (Fig. 8), 3 inhibitory (Fig. 9A) and 2 mixed responses (excitation by ipsilateral cervical vagus stimulation (ICVS) and inhibition by contralateral cervical vagus stimulation (CCVS), Fig. 9B and C). Response profiles of these 9 neurons were 4 Comps, 3 WDRs and 2 HTs. In 4 cells with excitatory responses to both ICVS and CCVS, responses to ICVS were greater in magnitude and faster than those to CCVS. This pattern was also found in 3 cells with inhibitory responses. Inhibitory responses to ICVS and/or CCVS were investigated on spontaneous activity (3 cells) and pinch-evoked firing (2 cells).

Table 1. Representation of SMT neurons receiving afferent inputs from trigeminal dermatome

Type / Segment	C_1	C_2	C_3	Total
Complex	4(5)	2(3)	1(1)	7(9)
WDR	6(9)	2(4)	1(3)	9(16)
LT	2(3)	1(1)	0(1)	3(5)
HT	3(4)	1(2)	–	4(6)
Deep	1(2)	1(6)	0(2)	2(10)
	16(23)	7(16)	2(7)	25(46)

Parenthesized numbers indicate numbers of total cells in corresponding type/segments

DISCUSSION

The present study demonstrates that there are clear

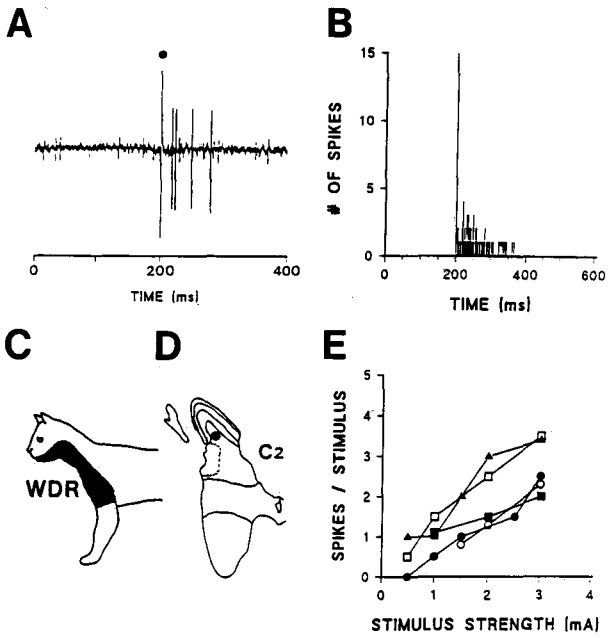

Fig. 7. Excitatory responses of SMT unit to electrical stimulation of ipsilateral phrenic nerve (IPN). A: single trace of the response to electrical stimulation (3 mA, 0.2 msec, 0.5 Hz) of IPN at the level of innominate artery. The first deflection (marked with a solid circle) is the stimulus artifact, followed by action potentials at 16 msec initial latency. B: peristimulus histogram (PSTH) of the response to IPN stimulation. PSTH was generated from 15 sweeps of stimulus; stimulus delay 200 msec; bin width, 2.5 msec. C and D: cutaneous receptive field and recording site of this cell, respectively. E: stimulus-dependent responses of 5 SMT units responding to stimulation of IPN.

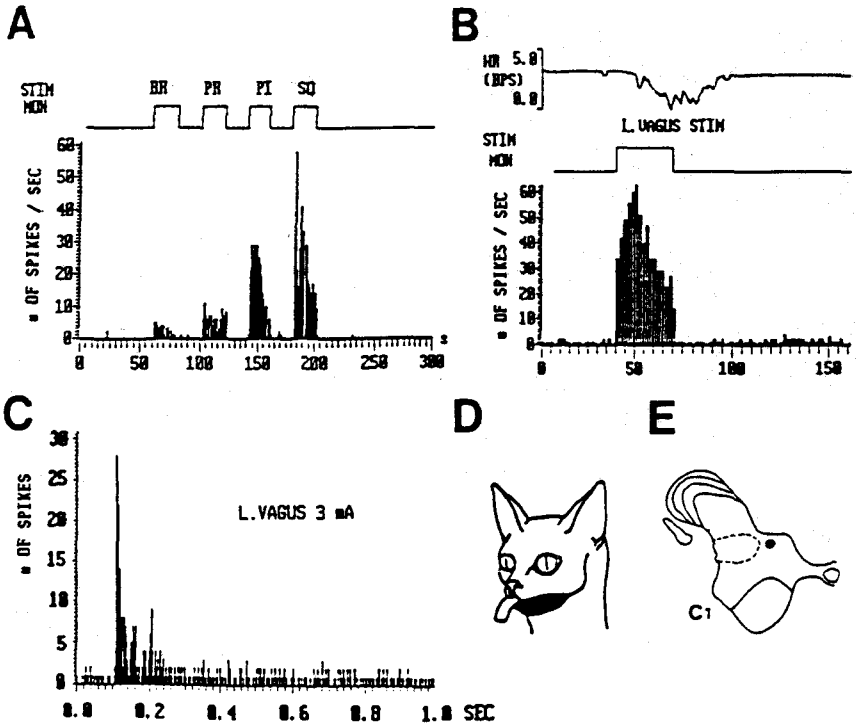

Fig. 8. Excitatory response of a C_1 SMT cell to electrical stimulation of ipsilateral cervical vagus (ICV). A: WDR response to cutaneous inputs. B: effect of stimulation of ICV (3 mA, 10 Hz, 0.1 msec) on heart rate (HR) and SMT activity. C: peristimulus time histogram (1 msec bin width) of the response to stimulation of ICV. The stimulus was 30 repetitions of single spike (3 mA, 0.1 msec, 1 Hz). D and E: locations of somatic receptive field and recording site, respectively.

differences between cervical SMT reurons in the SDH and those in LRA or IZ/VH in the conduction velocity in the size of their RFs, and in the range of stimuli to which they respond. These findings are well consistent with the previous reports that ventral horn cells have different functional characteristics from dorsal horn cells in primate STT (Giesler et al, 1981) cat lumbar unit (Molinari, 1982), cat C_2 STT (Carstens & Trevino, 1978; Smith et al, 1991), rat lumbar SRT (Menetréy et al, 1980), and rat lumbar SMT (Park & Kim, 1994) neurons. However, previous studies paid little attention to the difference between LRA and DDH. In this study, SMTs in LRA have larger RFs than DDH groups and showed a higher incidence of complex response profiles. Histologic investigation on sources of SMT cells (Wiberg & Blomqvist, 1984) revealed that there was clear separation for the distribution of origin of SMT cells between medial and lateral portions in the distribution of SMT in lamina IV~VI of C_1~C_2 segment in cats. Additionally, the distribution of central treminalis of trigeminal afferent fibers in C_1 dorsal horn of cats was mediolaterally distinguished from each other among individual branches of trigeminal division: some branches terminated at the medial border of dorsal horns, the others terminated at the lateral border (Shigenaga et al, 1986). These findings suggest that the composition of cells may differ mediolaterally in the laminae IV~VI in C_1~C_3, and support the present data that SMTs in LRA have different functional characteristics from those in DDH.

The overall distribution of SMT recording sites in the present study is well consistent with previous histologic observation (Wiberg & Blomqvist, 1984). However, it was notable that large portion of SMT in UCS were located in SDH and LRA, which contrasted with observations that numerous SMTs in lumbar spinal segments were located in the middle of spinal gray matter in the cat as well as in the rat. The high incidence of NR (non-responsive) type units is quite impressive. These NR type neurons have been routinely reported from neurophysiological re-

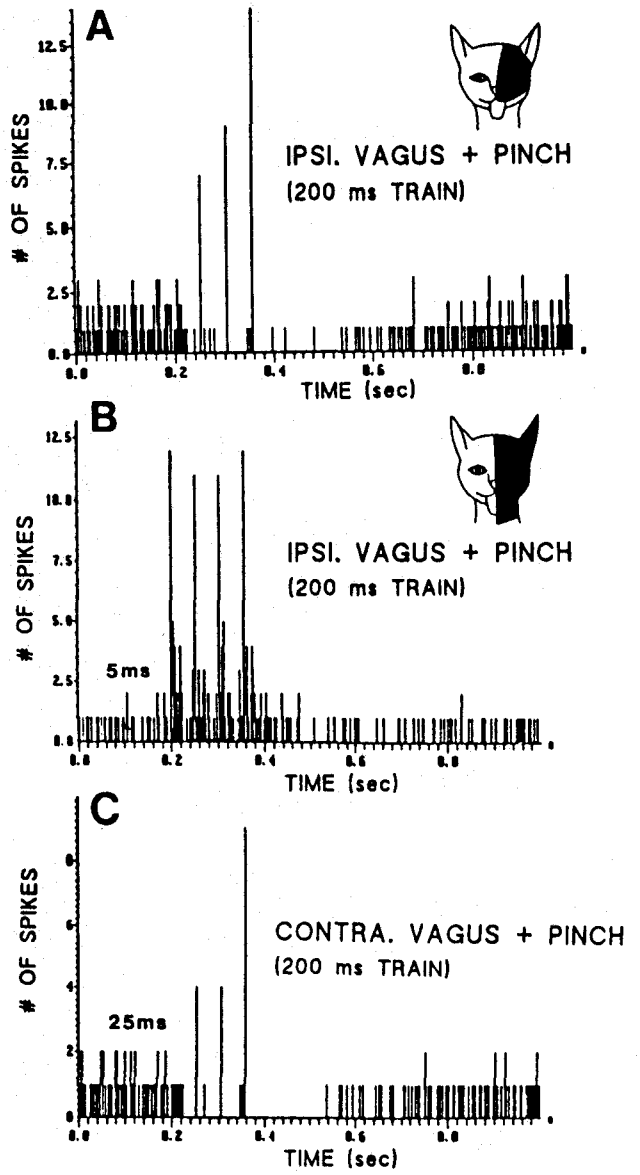

Fig. 9. Inhibitory responses of two C2 SMT cells to ipsilateral cervical vagus stimulation (ICVS) and contralateral cervical vagus stimulation (CCVS). A: inhibition by ICVS. B and C were recorded from the same SMT unit. Excitation by ICVS (5 msec latency in B) and inhibition by CCVS (25 msec latency in C). All histograms were generated from 30 repetitions of single electrical stimuli (2 MA, 200 msec, 4 train pulses 50 msec apart) and drawn in 0.5 msec bin width.

cording studies regardless of types of spinal sensory tracts. However, their functional roles still remain unlcear. NR type neurons generally produced large spikes in response to antidromic stimulation, and showed much similar patterns to responsive SMTs in the distribution of their recording sites, midbrain activations sites and conduction velocities. It was not clear whether or not some NR units of SMTs in UCS were involved in transmitting cardiopulmonary inputs solely because the present study focused on the converging afferent inputs and dealt with SMT units having somatic RFs. Nevertheless, it is unlikely that these NR units are involved only in transmitting visceral afferent information, based on the experimental results of Razook et al. (1995) in which 35 of 40 dorsal horn cells in UCS receiving phrenic afferent inputs had distinct somatic RFs. This ratio of NR (5/40) is obviously too small to accept the possibility that NRs might transmit the visceral information.

Inhibitory responses were evoked by noxious stimuli in 5 SMT cells, all of which had wide-spread RFs and spontaneous firings. Similar inhibitory responses have been described for STT (Carstens & Trevino, 1978; Gerhart et al, 1981) and SRT (Fields et al, 1977; Menetréy et al, 1980) neurons. Although the present study did not address the neuronal circuitary mediating these inhibitory responses, an involvement of inhibitory interneurons would be reasonable assumption.

When compared with C_2 STT and non-STT neurons (Carstens & Trevino, 1978; Smith et al, 1991), SMTs in the present study were similar to C_2 STT neurons in conduction velocity, response profile, and RF size. Smith et al (1991) emphasized larger RF size of STT than that of non-STT unit. But it should be pointed out that much of their STTs were recorded in the lateral cervical nucleus whose projecting neurons have large RFs. Generally RFs of SMTs are usually larger than those of STTs in the segment of spinal cord at the same level (Yezierski & Schwartz, 1986; Park & Kim, 1994). In the present study, 4 SMTs were activated also by antidromic stimulation of medial thalamic area (data not shown). Three of these 4 cells had shorter latency in antidromic activation from thalamic sites than from midbrain sites, which indicated that projecting fibers of these 3 cells to midbrain were collaterals of STT neurons.

The present report is the first one to demonstrate the convergence of various afferent inputs onto single SMT neuron in UCS. Convergence of trigeminal inputs onto dorsal horn cells in UCS has been well accepted since the first description of Kerr (1961). Anatomical studies using various techniques have demonstrated that trigeminal primary afferent fibers from a number of nerves project as far caudal as the C_2 and C_3 segments of the spinal cord (Arvidsson &

Gobel, 1981; Marfurt, 1981; Shigenaga et al, 1986). Electrophysiological reports (Abrahams et al, 1979; Chudler et al, 1991) confirmed that trigeminal and cervical inputs converge onto single neurons in dorsal and ventral horns of the UCS. The result of the present study provides the extended data concerning cutaneous convergence between different response classes (i.e. WDR or LT) of SMT. Vagal afferent modulation of nociception is recently appreciated (for reviews see Gebhart & Randich, 1992; Randich & Gebhart, 1992). Overviewing accumulated previous reports, the effect of vagal afferent stimulation (VAS) on spinal nociceptive transmission varied depending on spinal segments and species. VAS produced excitation of neurons in UCS and inhibition of lumbar spinal neurons in the rat (Fu et al, 1992). For cervical STT in primates, VAS produced the inhibitory effect (Chandler et al, 1992). Perhaps it would be rather reasonable to regard the VAS effect on the nociceptive transmission in the spinal cord as biphasic, as previously shown in the rat. The VAS effects observed in the present data were both excitatory (n=4) and inhibitory (n=3). Furthermore, ICVS and CCVS exerted opposite (excitatory vs inhibitory) effects on a given individual SMT unit (n=2). These results suggest that VAS effect would be determined in the supraspinal structure. In contrast to VAS effect, the stimulation of IPN produced only excitatory responses, which was consistent with the result obtained from $C_1 \sim C_2$ dorsal horn cells in rats (Razook et al, 1995) and data from cervical STT in primates (Bolser et al, 1991).

ACKNOWLEDGEMENT

This work was supported by a grant from Chonnam University Research Institute of Medical Science.

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