Effect of trigeminal tractotomy on behavioral response to dental pulp stimulation in the monkey

RONALD F. YOUNG, M.D., TERRENCE D. OLESON, PH.D., AND KENT M. PERRYMAN, PH.D.

Division of Neurosurgery and Department of Anesthesiology, University of California at Los Angeles (UCLA) School of Medicine, Harbor/UCLA Medical Center, Torrance, California

Trigeminal tractotomy near the level of the obex was carried out in 10 macaque monkeys. Behavioral responses were evaluated by a quantitative paradigm measuring lever-press responses to electrical stimulation of the dental pulp or facial skin, and by assessing facial response to cutaneous pin-scratch before and after the tractotomy. Two pharmacological agents, strychnine and L-dopa, were administered and their effect on behavioral responses to these stimuli was studied.

Tractotomy did not produce dental analgesia. Thresholds for escape from cutaneous electrical stimulation of facial skin, however, were elevated, consistent with marked hypalgesia to pin-scratch. The adversive responses to pin-scratch were absent in peripheral portions of the face, but near the midline and inside the oral cavity they were usually decreased or normal. Pharmacological agents caused a reduction in escape thresholds to cutaneous electrical stimulation and a shrinkage or abolition of the zone of analgesia to pin-scratch.

The results imply that trigeminal nucleus caudalis, which undergoes deafferentation by tractotomy, may not be essential for processing of nociceptive information from the teeth, oral cavity, and midline facial zones. This finding is contrary to long-held hypotheses concerning facial pain mechanisms. The ability of strychnine and L-dopa to alter nociceptive escape thresholds is consistent with the idea, suggested by Denny-Brown, that facial nociception depends on central summation in the entire spinal trigeminal nucleus from overlapping afferent inputs contained in the trigeminal nerve, other cranial nerves, and the upper cervical nerve roots.

KEY WORDS • trigeminal nerve • trigeminal tractotomy • dental pain • facial pain • monkey • strychnine • L-dopa

TRIGEMINAL tractotomy was introduced by Sjoqvist in 1938 for the treatment of intractable facial pain. Many authors have subsequently reported their clinical results with this procedure. From these reports, it has been generally accepted that trigeminal tractotomy, performed at approximately the level of the obex, results in facial analgesia and thermanalgesia, with preservation of tactile sensation. Early reports described the procedure as being least effective or ineffective in producing analgesia in perioral and intraoral areas. More recent reports ascribe such results to failure to place the lesion sufficiently rostral, or to incomplete tract section. Based on these clinical observations, it has been assumed, even in the most current reports, that the portion of the spinal trigeminal nucleus caudal to the level of the obex (the nucleus caudalis of Olszewski) was the exclusive locus for processing facial nociceptive information. Two basic theories have been put forward to explain the observed results of tractotomy.

The first proposal, which has received recent neurophysiological support, stated that the trigeminal nucleus caudalis was the exclusive termination point of primary afferent fibers related to facial nociception. Such afferents were assumed to synapse with second-order neurons, which relayed nociceptive-related information centrally to the thalamus and other higher centers for cognitive processing. Anatomical and physiological evidence
of internuclear interaction within the various divisions of the spinal trigeminal brain-stem complex gave rise to an alternate hypothesis. This latter view argued that the trigeminal nucleus caudalis acted to modulate output from more rostral portions of the spinal trigeminal complex in order to code a stimulus as noxious or innocuous.20,58

Recent primate5,6 and human16 studies have suggested that the analgesia resulting from trigeminal tractotomy was incomplete, and could be reduced or totally abolished by certain pharmacological manipulations. These studies have questioned an exclusive role for the nucleus caudalis in facial nociception, and have suggested a more general role of the entire spinal trigeminal nucleus.5,6 This hypothesis is based upon only a few human cases that lack pathological documentation of the location and completeness of the lesions,16 and upon determination of avoidance responses to facial pin-scratch in monkeys.5,6

The present experiments were designed to utilize a more quantitative noxious stimulus, electrical stimulation of the dental pulp, to evaluate the role of the trigeminal nucleus caudalis in orofacial nociception. In addition, responses to facial pin-scratch and to intradermal electrical stimulation of the facial skin were examined. Behavioral responses to these stimuli were evaluated before and after tractotomy and after the administration of strychnine and L-dopa. The results are consistent with the idea that the entire spinal trigeminal complex is involved in orofacial nociception. In addition, it appears that the perception of dental pain is affected little, if at all, by tractotomy. The results are pertinent to the design of surgical procedures for the relief of intractable facial pain, and offer a deeper perspective of our understanding of the neurophysiological mechanisms involved in facial pain perception. A portion of this work has been presented in abstract form.56

Materials and Methods

Animal Preparation

Ten young female macaque monkeys weighing 5 to 6 Kg were used in this study. They were maintained in primate chairs in the neurosurgical laboratory throughout the test period of 3 to 4 months, except for brief intervals when they were returned to their cages to recover from surgical procedures.

Under general anesthesia, two chronic stimulating electrodes, made of insulated No. 30 multistrand stainless steel or silver wire bared for about 1 to 2 mm at the tips, were implanted into the dentine of each maxillary canine tooth. Access to the dentine was obtained via openings made with a small dental burr.21,53 The electrodes were secured with dental amalgam and insulated with a layer of dental acrylic. The electrode leads from the teeth were passed subcutaneously to the skull vertex where they were connected to a multiple-pin plug, which was affixed to the skull with dental acrylic. Behavioral training was begun after a recovery period of several days.

Behavioral Testing

All behavioral assessments were carried out in a sound-attenuating acoustic chamber with a one-way observation panel. The output of a custom-made constant current stimulator was connected to the previously placed head plug via a cable which passed through the test-chamber wall. A lever, which terminated electrical stimulation when depressed, was placed within easy reach of the animal. Monophasic, square-wave pulses were delivered in a bipolar manner to the previously implanted dental electrodes at a rate of 5 Hz, and a pulse duration of 0.5 msec. Stimulus intensities varying from 0.25 to 4 mA in 0.25-mA steps were randomly delivered. Stimulation could be terminated by the animal with a single press of the lever or was automatically terminated after a maximum period of 7 seconds. Originally, both this random method to determine escape thresholds and a titration method34 were utilized; however, we have previously shown that thresholds determined by the two methods are identical,34 and thus only results utilizing the random method are reported here. The ability of the animal to immediately terminate painful tooth stimulation, and the automatically limited maximum period of stimulation, assured that animals were subjected to a minimum of discomfort. Animals were trained in the test paradigm for several weeks. Repeated trials were then carried out over several weeks before and after surgical procedures to obtain accurate assessments of escape thresholds. Likewise, repeated trials were carried out after administration of pharmacological agents. An identical testing and escape paradigm was employed for cutaneous electrical stimulation, except that stimuli were applied via bipolar stainless-steel electrodes inserted a few millimeters into the skin.

Escape latencies (time from stimulus onset to lever depression) typically varied from 0.5 to 1.2 seconds and the escape threshold was defined as that stimulus intensity above which all response latencies were less than 3.0 seconds. Escape latencies did not tend to decrease with increasing shock intensity. Latencies for suprathreshold stimuli were usually less than 1.2 seconds, and at subthreshold levels only occasional random escape responses occurred during the maximum
stimulation period of 7.0 seconds. Determination of the threshold level for escape was reasonably easy in well trained animals, since at or above the threshold level the animal reliably exhibited a forceful depression of the lever usually within 1.2 seconds. In three recently studied animals, computerization of the paradigms has allowed collection of larger volumes of data as well as statistical evaluation utilizing analysis of variance. In these animals, we have observed the number of escape responses exhibited at each stimulus strength for both dental and cutaneous stimulation.

**Tractotomy**

After the behavioral response paradigm was well performed by the animals, trigeminal tractotomy was carried out. General anesthesia was employed utilizing intramuscular ketamine (50 mg/kg) supplemented by intravenous pentobarbital. The anesthetized animal was placed in a pin-fixation head holder, and a smaller unilateral suboccipital craniectomy was carried out. The dura was opened and the obex identified under the operating microscope. Trigeminal tractotomy was carried out with a 3-mm fragment of a № 11 scalpel blade. The tuberculum gracilis and cuneatus were identified, as well as the tuberculum cinereum formed by the subjacent spinal tract and nucleus of the trigeminal nerve. The plane of the rootlets of the spinal accessory nerve formed the ventral limit of the lesion; the dorsal limit was usually extended into the tuberculum cuneatus to assure section of the ventral aspect of the spinal tract and nucleus. The intent of the lesion was to destroy the trigeminal spinal tract and underlying nucleus as close to the level of the obex as possible. In two animals, examination of facial sensation within a few days of tractotomy revealed only minimal facial sensory change. Therefore, a repeat procedure with enlargement of the lesion was accomplished.

Two pharmacological agents, intramuscular strychnine (0.25 mg/kg) or oral L-dopa (50 mg/kg) were administered following surgical lesions in five animals, and observations were made of the effect of these drugs on dental pulp and cutaneous electrical thresholds and facial pin-scratch responses. Repeated drug administration was carried out on several different days to obtain an accurate assessment of the effect.

Following completion of behavioral testing, animals were reanesthetized and the brain was fixed by intracardiac perfusion with saline solution followed by buffered formalin. Serial sections were made and stained with Luxol fast blue for myelin and counterstained with carbol-fuchsin for cellular detail. Sections were examined with the light microscope to determine the completeness and extent of each lesion.

**Results**

**Dental Pulp Stimulation**

Slight elevations in escape thresholds for dental pulp stimulation ipsilateral to the side of tractotomy were observed in eight of the 10 animals. The degree of elevation, however, was slight (mean 0.10 mA or 13% of control) and the mean escape threshold after tractotomy (Table 1 and Fig. 1) of 0.85 ± 0.12 mA (SD) was not significantly different from the pretractotomy value of 0.75 ± 0.08 mA, using the t test for correlated means. Likewise, for dental pulp stimulation contralateral to the side of tractotomy, there was no significant difference in the pre- and postlesion escape thresholds (Table 1 and Fig. 1).

In two recently studied animals, a comparison was made, with analysis of variance, of the number of escape responses exhibited at each level of stimulus intensity applied on the side ipsilateral to the tractotomy, before and after the lesion. No significant differences were noted (F = 0.375, p > 0.02 in one animal; F = 16.1, p > 0.2 in the second animal). In addition, the number of responses at each stimulus intensity were compared on the sides ipsilateral and contralateral to the lesion in a single animal. Again using analysis of variance across all stimulus intensity levels, no statistically significant differences were noted (F = 1.57, p > 0.2). These findings confirm that the escape thresholds to dental stimulation in these two animals were unchanged as a result of tractotomy.

**Cutaneous Electrical Stimulation**

Intradermal electrical stimulation of facial skin was carried out in the center of the most analgesic zone as determined by pin-prick examination. In all animals, this area was within the distribution of the maxillary division, on the cheek, about 3 cm from the midline. On the side ipsilateral to tractotomy, mean escape thresholds were markedly elevated in all animals (0.88

---

**TABLE 1**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Dental Stimulation</th>
<th>Cutaneous Stimulation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ipsilateral</td>
<td>Contra-lateral</td>
</tr>
<tr>
<td></td>
<td>Ipsilateral</td>
<td>Contra-lateral</td>
</tr>
<tr>
<td>control</td>
<td>0.75</td>
<td>0.83</td>
</tr>
<tr>
<td></td>
<td>± 0.08</td>
<td>± 0.15</td>
</tr>
<tr>
<td>after tractotomy</td>
<td>0.85</td>
<td>0.80</td>
</tr>
<tr>
<td>(rt side)</td>
<td>± 0.12</td>
<td>± 0.14</td>
</tr>
<tr>
<td></td>
<td>± 0.21†</td>
<td>± 0.12</td>
</tr>
</tbody>
</table>

* Mean escape threshold (mA) ± standard deviation.
† Statistically significant, p < 0.01.
Trigeminal tractotomy in macaques

MA or 110% of control) when compared to preoperative values (Table 1 and Fig. 1). The mean escape threshold for cutaneous electrical stimulation seen after tractotomy (1.68 ± 0.21 mA) was significantly elevated (p < 0.01) when compared with the pretractotomy levels (0.80 ± 0.15 mA). No significant changes were noted contralateral to the side of tractotomy (Table 1 and Fig. 1).

The increase in escape threshold to cutaneous stimulation was confirmed in two recent animals by comparison of the number of escape responses made at each stimulus intensity, with analysis of variance. Following tractotomy, there was a significant decrease in escape responses ipsilateral as compared to contralateral to tractotomy (f = 5.40, p < 0.001 in one animal; f = 11.58, p < 0.001 in the second animal).

**Cutaneous Pin-Scratch**

Only two of the 10 animals manifested apparent analgesia to pin-scratch over the entire side of the face ipsilateral to the tractotomy. A typical pattern of response to facial pin-scratch is shown in Fig. 3A. In general, animals manifested reduced but easily identified aversive responses when stimulated near the midline of the face. This effect tended to involve all three major trigeminal divisions, although the maxillary and ophthalmic divisions were most affected. Most often this area of apparent hypalgesia involved the nose, the adjacent cheek and upper lip, and the periorbital area. In some animals, the medial aspect of the forehead and the lower lip near the midline also manifested reduced but noticeable responses to pin-scratch.

Complete absence of response to pin-scratch was always seen in the peripheral portions of the face (see Figs. 3A and 4A). These included the frontal scalp and the lateral aspect of the forehead, cheek, upper lip, and chin. In two animals, the entire ipsilateral portion of the face appeared analgesic. Examination of intraoral pin-scratch responses was difficult, but responses in this area correlated with responses near the midline of the face, which were usually reduced compared to the contralateral side. The two animals with complete cutaneous facial hemianalgesia also exhibited intraoral analgesia to pin-scratch.

**Effect of Strychnine**

Subconvulsive doses of strychnine induced a state of general motor hyperactivity in all animals such that an abrupt noise or movement on the part of the examiners resulted in a brief generalized myoclonic spasm. Strychnine produced no significant change in escape thresholds to dental pulp stimulation on the side contralateral to tractotomy (Table 2 and Fig. 2). Ipsilateral to the tractotomy there was a slight (0.1 mA; 10% of control), but statistically insignificant, reduction in mean escape threshold (Table 2).

The effect of strychnine on escape thresholds to cutaneous electrical stimulation was more marked and reliable. Escape thresholds ipsilateral to tractotomy
TABLE 2

Effect of strychnine after tractotomy*

<table>
<thead>
<tr>
<th>Sample</th>
<th>Dental Stimulation</th>
<th>Cutaneous Facial Stimulation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ipsi-lateral</td>
<td>Contralateral</td>
</tr>
<tr>
<td>after tractotomy</td>
<td>0.95 ± 0.11</td>
<td>1.50 ± 0.30</td>
</tr>
<tr>
<td>after strychnine</td>
<td>0.85 ± 0.14</td>
<td>1.00 ± 0.18†</td>
</tr>
</tbody>
</table>

* Mean escape threshold (mA) ± standard deviation.
† Statistically significant, p < 0.05.

were decreased in every animal tested (mean 0.5 mA or 33% of control) after strychnine administration (Table 2 and Fig. 2). The reduction in threshold from 1.50 ± 0.30 mA to 1.00 ± 0.18 mA was statistically significant (p < 0.05). The escape levels observed after strychnine remained slightly elevated compared to pretractotomy levels, however. Thus, although strychnine reduced the elevated escape thresholds to cutaneous electrical stimulation produced by tractotomy, it did not reduce those thresholds to the control or pretractotomy level. Contralateral to the tractotomy, there was no effect of strychnine on escape thresholds for cutaneous stimulation (Table 2 and Fig. 2).

The effect of strychnine on response to facial pin-scratch was also reproducible and significant (Fig. 3). Thirty to 60 minutes after strychnine administration, a marked reduction in size of the zone of analgesia to pin-scratch was seen, and in a few animals no area of facial skin remained analgesic. Concomitantly, zones of hypalgesia or normal response usually enlarged to encompass most or all of the previously analgesic zone. No animal, however, had normal responses to pin-scratch over the entire face after strychnine. Some zones of reduced responsiveness to pin-scratch always remained.

Effect of L-Dopa

Oral administration of L-dopa had no reliable effect on escape thresholds to dental pulp stimulation observed after trigeminal tractotomy. The mean escape threshold to dental stimulation ipsilateral to tractotomy, seen after L-dopa administration (1.10 ± 0.38

![Fig. 2](image-url)

FIG. 2. Block graph showing the effect of strychnine on mean escape thresholds to electrical stimulation of dental pulp and facial skin expressed in milliamperes (mA). The drug was given after unilateral trigeminal tractotomy. Results are shown for stimulation on the sides ipsilateral and contralateral to the tractotomy. * = statistically significant difference, p < 0.05.
Trigeminal tractotomy in macaques

mA, was not significantly different from that seen prior to administration of the drug (0.88 ± 0.14 mA, Table 3). Likewise, no changes were seen contralateral to the tractotomy when L-dopa was given. Although one of five animals tested showed a slight decrease in escape threshold to cutaneous electrical stimulation ipsilateral to tractotomy after L-dopa administration (0.25 mA, or 25% of control), overall there were no significant changes in cutaneous escape thresholds (Table 3). The effect of L-dopa on response to facial pin-scratch was unpredictable. In some animals (Fig. 4), the effect was similar to that seen with strychnine; that is, there was a marked reduction in size of the analgesic zones with a concomitant expansion of hypalgesic zones. In other animals, a much smaller effect or no change in behavior was noted.

Fig. 3. Results of pin-scratch examination 2 months after right-sided trigeminal tractotomy showing the effect of strychnine (25 mg/kg intramuscularly). Cross hatched area = no response; stippled area = decreased response. Responses are shown before strychnine administration (control) and 20, 30, 60, and 90 minutes after the drug was given.

Fig. 4. Results of pin-scratch examination following right-sided trigeminal tractotomy showing the effect of L-dopa (50 mg/kg orally). A and B: control; C and D: 60 minutes after administration; E and F: 4 hours after administration.
Histological Findings

Examination of serial brain-stem sections revealed complete tractotomy in every animal. The spinal trigeminal tract was completely destroyed, along with the subjacent spinal nucleus (Fig. 5). Thus, complete interruption of the descending primary afferent fibers was accomplished, along with interruption of the ascending intranuclear connections between the nucleus caudalis and the rostral spinal trigeminal subnuclei oralis and interpolaris and the nucleus principalis. Significant destruction of adjacent structures, such as the nucleus cuneatus and medullary reticular formation, was also seen, with an overall decrease in size of the brain stem ipsilateral to the lesion. The total rostrocaudal extent of the lesions varied from 1.8 to 5.4 mm. The maximum rostral extent of a single lesion was 3.1 mm above the obex and the maximum caudal extent was 3.2 mm below the obex. Specific patterns of alteration in dental or cutaneous sensory perception could not be correlated with specific lesion locations. This findings most likely relates to the small overall variation in lesion location compared with the maximum rostrocaudal extent of the spinal trigeminal nucleus.

Discussion

It has generally been accepted and recently restated that the nucleus caudalis is an essential element of the trigeminal brain-stem complex in relation to facial nociception. This function was originally attributed to the location of specific nociceptive relay neurons in the nucleus caudalis. Although initial attempts to identify such neurons were unsuccessful, nociceptive units were subsequently identified in both the superficial and deep portions of this subnucleus.

Specific and polymodal nociceptive neurons have also been identified in rostral portions of the spinal trigeminal nucleus and in the principal or main sensory nucleus. Furthermore, a column of neurons responsive to electrical stimulation of the dental pulp has been identified extending caudally from the main sensory nucleus to several millimeters below the obex, into the rostral end of the nucleus caudalis. Interestingly, the representation of dental nociceptors appears quantitatively greater in the rostral subnuclei compared to the relatively sparse representation or lack of representation of high-threshold or wide dynamic-range mechanical nociceptors rostrally. The demonstration of elevated escape threshold to noxious cutaneous heat stimuli after lesions in rostral trigeminal nuclei strongly suggests that thermal nociceptors are also located rostrally, although they have not yet been demonstrated physiologically.

An alternative hypothesis to explain the presumed essential role of the nucleus caudalis in facial nociception was based upon observations of differential excitability changes in trigeminal primary afferent fibers in response to noxious and innocuous stimuli. It was proposed that the nucleus caudalis acted to modulate differentially the firing of neurons in more rostral portions of the spinal nucleus and main sensory nucleus in order to code a stimulus as noxious or innocuous, perhaps by a gating mechanism. Additionally, physiological studies after acute tractotomy suggested that the modulating effect of the nucleus caudalis on more rostral trigeminal nuclei was significant, but observations after chronic tractotomy did not support this idea. Thus, the specific modulating effect of the nucleus caudalis on more rostral nuclei appeared slight.

Several recent observations have prompted reconsideration of classical concepts concerning facial nociception. Denny-Brown and Yanagisawa demonstrated that the cutaneous facial analgesia resulting from trigeminal tractotomy in monkeys could be reversed pharmacologically. If tractotomy interrupts all nociceptive primary afferent fibers prior to their synapse in the nucleus caudalis, one would expect this procedure to produce complete unilateral facial analgesia, which could not be manipulated pharmacologically. Denny-Brown's findings appeared to contradict an exclusive role of the nucleus caudalis in cutaneous facial nociception. Subsequently, Vylický, et al., reported that trigeminal tractotomy in cats did not produce apparent analgesia to electrical stimulation of the dental pulp. Additionally, Rosenfeld, et al., showed that radiofrequency lesions in the rostral trigeminal nuclei of rats produced significant elevations in escape thresholds to noxious thermal stimuli applied to the face. These observations appear to contradict an exclusive role for the nucleus caudalis in orofacial nociception.

The present experiments are clearly consistent with the observations of both Vylický, et al., and Denny-Brown and Yanagisawa. First, they indicate that trigeminal tractotomy produces no significant elevation in the escape threshold of monkeys to electrical stimulation of the dental pulp. If one assumes that electrical stimulation of dental pulp produces the sensation of pain, then the present experiments demonstrate that trigeminal tractotomy does not produce dental analgesia.

The use of electrical stimulation of dental pulp as a painful stimulus has been evaluated in humans. At
threshold levels, human volunteers report nonpainful tapping or "pre-pain" sensations in response to electrical tooth stimulation. At suprathreshold levels, however, they report exclusively painful sensations. Nord and Ross have indicated certain facial movements in primates in response to electrical tooth pulp stimulation at stimulus intensities below escape levels and have attributed the former to perception of the stimulus by the animal at a pre-pain level. We have also seen such responses, primarily in incompletely trained animals. In our experience, well trained animals have onset of facial motor activity and escape responses at identical stimulus intensities. Furthermore, the force and speed of escape responses manifested by the animals we studied strongly suggested that these lever presses were in response to a painful stimulus.

The alterations in pin-scratch responses noted in our experiments after tractotomy are similar to those obtained, also in monkeys, by Denny-Brown and Yanagisawa and in patients following similar lesions. The lack of analgesia in paramedian regions after tractotomy had been attributed to a less caudal penetration of primary afferent fibers from these midline zones as they descend in the spinal trigeminal tract. No physiological basis was thought to exist to support this idea, since the facial homunculus was believed to be represented at all rostrocaudal levels of the spinal trigeminal nucleus. The present and previous experiments, however, suggest that nociceptive information related to midline portions of the face, including the oral cavity and teeth, may pass centrally from the trigeminal brain-stem complex to higher centers, primarily from its rostral portions. A recent electrophysiological reexamination of somatotopic representation within the nucleus caudalis suggests that the relative representation of the peripheral portion of the face is greater caudally, and the paramedian regions are represented to a quantitatively greater degree rostrally. It is uncertain if this somatotopic pattern extends further rostrally into the subnuclei interpolaris or oralis.

The heavy relative representation of the dental pulp rostrally in the subnuclei oralis and interpolaris, as well as in the nucleus principalis, is clearly different from the representation of cutaneous trigeminal nociceptors. The latter are represented most heavily in the subnucleus caudalis, and sparsely or not at all.
rostrally. It remains unclear whether the rostrally located dental nociceptive neurons normally function to transmit information centrally concerning dental pain or whether they represent a redundant system to more caudally located dental nociceptors in the nucleus caudalis. In any event, it appears that after tractotomy, neurons in the spinal trigeminal nucleus located rostral to the obex, acting free of the physiological influence of the nucleus caudalis, may subserve nociception for teeth, intraoral structures, and para-median cutaneous regions.

Results of this study are less definitive in relation to the majority of cutaneous facial nociceptive supply. Clearly, cutaneous facial analgesia resulting from trigeminal tractotomy is incomplete in distribution and in magnitude. All animals manifested escape responses to cutaneous electrical stimulation, even in zones apparently totally analgesic to pin-prick stimulation. On the other hand, our results demonstrate that thresholds for escape from cutaneous electrical stimulation are significantly elevated following trigeminal tractotomy, whereas thresholds for escape from dental stimulation are unaffected. The implication of these findings is that the effect of tractotomy is a relative, rather than an absolute phenomenon, and appears to affect cutaneous nociception to a greater degree than dental nociception. This view is consistent with the previously described greater rostral representation of dental nociceptive neurons compared to mechanical nociceptors. It should be pointed out that the analgesia seen after spinthalamic tractotomy (cordotomy) is also relative and can be overcome by an elevation in electrical stimulus intensity. Comparisons of spinthalamic tractotomy and trigeminal tractotomy may not be justified, however, since the former interrupts secondary and higher-order neuron projections, whereas trigeminal tractotomy interrupts primary afferent as well as higher-order neurons.

Denny-Brown and Yanagisawa have suggested that cutaneous facial nociception depends on spatial and temporal summation within the entire spinal trigeminal nucleus rather than upon activation of a specific nociceptive afferent system relayed via the nucleus caudalis. They suggested that nearly all areas of facial skin receive afferent supply not only from the trigeminal nerve but also from another cranial nerve (seventh, ninth, or tenth) or the upper cervical nerve roots (C1-4). Evidence of multiple afferent inputs to the nucleus caudalis-dorsal horn region of the lower medulla and upper cervical cord from the fifth, seventh, ninth, and tenth cranial nerves and the upper cervical nerve roots provided an anatomical framework for this idea. It appears that nociceptive orofacial afferent fibers. The lack of effect of tractotomy on dental pain sensation may indicate that nociceptive processing from the dental pulp occurs rostral to the nucleus caudalis. Although the potential contribution of other cranial nerves and the upper cervical nerve roots to dental pain sensation remains unresolved at present, preliminary experiments in our laboratory indicate that such alternate pathways are insignificant.

The results of this study are consistent with other findings that suggest that the concept of pain as a qualitatively different, all-or-none phenomenon requires reevaluation. The ability to qualitatively alter apparent pain thresholds in animals and in man suggests that pain may be a summated result of general somatosensory input rather than a qualitatively different sensation. This idea, postulated by Denny-Brown and Yanagisawa, appears to be consistent with our results.

In the past, it has been difficult to understand persistent pain and incomplete sensory loss after procedures such as cordotomy, rhizotomy, and tractotomy. It appears that the accepted approaches to these and similar phenomena may require reconsideration in the light of newer concepts concerning the processing of somatosensory information.

Acknowledgments

The authors thank Dr. Ronald Katz of the UCLA De-
Trigeminal tractotomy in macaques

The Department of Anesthesiology for assistance in completion of this project. Members of the Department of Oral Surgery, particularly Dr. Jeffrey Simon, kindly assisted with development and use of the dental electrode technique. Dr. Samuel G. Nord and Mr. David Rollince of Syracuse, New York, provided much valuable advice and encouragement. We thank Lucia M. Miller for assistance with manuscript preparation and Jan Wilson for technical assistance.

References
35. Olivecrona H: Tractotomy for relief of trigeminal neu-
nalgia. Arch Neurol Psychiatry 47:544–564, 1942