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Physiological properties of intradental mechanoreceptors

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A major role of tooth receptors in signaling overt or impending tissue damage (nociception) has been previously established by substantial evidence from mechanical, thermal and chemical stimulation of exposed dentin. We report evidence showing that some intradental receptors in canine teeth of the cat detect mechanical transients applied to intact enamel. This new finding suggests that dental innervation may play an important non-nociceptive role in oral function such as detecting tooth contact during mastication and swallowing.

Previous studies have utilized nocuous chemical, mechanical and thermal stimuli to activate intradental receptors[1,12]. In these reports, all stimuli were delivered to an exposed dentinal surface. The adequate, natural stimulus for intradental receptors in intact teeth has not been fully elucidated. Some of these receptors may respond to heating of the intact enamel[23]. Whether the tooth contains only nociceptors is still controversial[26]. Recent anatomical and physiological evidence has shown that signals generated by intradental receptors can be transmitted over fast-conducting pathways. Some tooth pulp afferents have extradental conduction velocities that are identical to those of Aβ nerve fibers[6,19]. Large myelinated Aβ nerve fibers have also been found within the tooth pulp[4,13,16]. Additionally, short latency tooth pulp-evoked potentials and unit responses have been recorded throughout the trigeminal system[11,21,27,28].

Our results show that nerve endings in teeth can provide sensory information that is not nociceptive. Primary afferent neurons originating from receptors within the canine tooth responded adequately to innocuous mechanical stimulation. These intradental mechanoreceptors have Pacinian corpuscle-like response properties such as high frequency tuning or transient detection, lack of linear or spatial directionality, short recovery cycles and absence of fatigue[3]. This previously unknown population of tooth receptors may have been overlooked in earlier studies[1,12] because evidence for Aβ tooth pulp afferents[6,19] was not available to suggest the possible existence of low threshold intradental receptors. Moreover, it had been assumed that all innocuous mechanoreceptive responses originated from receptors in the periodontal ligament and no tests were made to determine their possible intradental origin.

We employed methods that permitted: (1) application of mechanical forces to an intact tooth while recording spike discharge activity of primary afferent neurons in the trigeminal semilunar ganglion (SLG); (2) electrical stimulation of the tooth pulp to determine afferent fiber conduction velocity; and (3) application of an impulse collision test and a cold block test to identify intradental fibers. Fifteen adult cats (2.4–4.7 kg) were anesthetized with sodium thiopental and halothane and paralyzed with gallamine triethiodide. The mandibular division of the SLG was exposed by an extensive craniotomy, hemispherectomy and dissection of dura overlying the SLG. Each half of the mandible was secured with cable ties wrapped around a steel rod that was mounted onto a heavy aluminium plate. Ganglion cell activity was recorded

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extracellularly through a glass micropipette electrode filled with 0.5 M sodium acetate and Pontamine sky blue dye (15–20 MΩ impedance). The gingiva overlying the lateral side of the canine root was cut and reflected. Two pairs of bipolar stimulating electrodes were implanted into the lateral, labial side of the ipsilateral, mandibular canine tooth (Figs. 1 and 2). The cathode of the distal pair of electrodes was located on or 2–3 mm above the enamel–cementum junction (tooth neck). The uninsulated end of a teflon-coated, multistrand stainless steel wire was embedded with silver amalgam into each excavated tooth cavity (1 mm diameter) that ended in the pulp canal. Exposed silver amalgam and insulated wires at the tooth surface were covered by dental resin. The mean impedances measured across the distal pair and proximal pair of electrodes, respectively, were 23.5 ± 12.7 KΩ and 8.6 ± 2.5 KΩ. Monophasic pulses of 0.1 ms duration were delivered at 2/s and 10 mA to the proximal pair of tooth stimulating electrodes while searching for ganglion cell activity.

Nineteen SLG cells that responded only to a moving mechanical stimulus applied to the canine tooth in any direction were selected for study. All cells were found along the midline of the mandibular division of the SLG and none had spontaneous or resting activity. These cells were activated by threshold current intensities that were delivered to the distal and proximal pairs of electrodes at 3.4 ± 2.4 mA and 2.9 ± 2.5 mA, respectively. The range of threshold current intensities used to stimulate the tooth through implanted bipolar electrodes and at short pulse duration was consistent with those current intensity ranges that have been reported to elicit innocuous sensations in humans[2,10], aversive titration thresholds in monkeys[24,25], and short latency responses from tooth pulp afferents[6,19]. Electrical stimulus spread was unlikely because SLG cells activated by both distal and proximal electrode pairs were unaffected by mechanical stimulation to the oral mucosa, skin of the face, gingiva, alveolar bone surface or tongue. Confinement of excitation to intradental neural elements following bipolar electrical stimulation of the dentine or pulp at high intensity has been demonstrated[6,14,22].

Onset latencies of the spike discharge evoked by stimulation through the distal (S1) and proximal (S2) pairs of electrodes, respectively, were from 0.8 to 4.8 ms (mean 1.5 ± 1.0 ms, S.D.) and from 0.7 to 4.4 ms (1.1 ± 0.8 ms). An example of the difference in discharge latencies due to S1 and S2 stimulation is shown in Fig. 1A. Conduction velocities within the tooth between S1 and S2 stimulating electrodes were from 0.5 to 55.0 m/s (mean 20.0 ± 17.0 m/s, S.D.), whereas, conduction velocities between S2 and the SLG cells were from 13.6 to 86.0 m/s (62.5 ± 17.5 m/s). Intradental and extradental conduction velocities, respectively, were predominantly in the range of conduction velocities associated with myelinated Aδ and Aβ fibers. Evidence that these SLG cells had intradental innervation was obtained by testing for collision of an S1-initiated, orthodromic impulse with an S3-initiated, antidromic impulse. Intradental collision of impulses was established in 9 of 15 cells tested. An example is illustrated in Fig. 1B–G. For this test, the polarities of the S2 electrodes were reversed to form the S3 electrodes that were used to elicit antidromic but not orthodromic impulses (Fig. 1B). The S3 stimulus current intensity was reduced to a level at which no orthodromic response was observed. If the time interval between S1 and S3 stimulation was less than the nerve conduction time from S1 to S3, an antidromic impulse from S3 left a portion of intradental nerve in a refractory state and thus blocked conduction of an orthodromic impulse from S1 (Fig. 1C–G). The inability to establish impulse collision in 6 of the 15 cells tested may have been due to an absence of S3-evoked antidromic impulses. Measurement of S3-evoked antidromic impulses at the S1 electrodes was not possible due to their short response latency and temporal overlap with the S3-evoked stimulus artifact. Further evidence of intradental innervation was obtained by selectively blocking S1-evoked orthodromic impulses with cold Ringer's solution (5 °C) applied to a section of pulp located between the distal (S1) and proximal (S2) pairs of electrodes (Fig. 2). This procedure did not affect discharges evoked by stimulation at the proximal tooth electrodes (S2) or at the electrodes on the inferior alveolar nerve (S3).

Neither steady pressure nor displacement of the tooth was an effective stimulus (Fig. 3A). The adequate stimulus for these SLG cells was a single mechanical transient such as a tooth tap (Fig. 3B) or repeated transients such as tooth vibration (Fig. 3C–F). A rapidly adapting response was elicited by applying a moving stimulus to any point on the tooth crown and in any direction relative to that

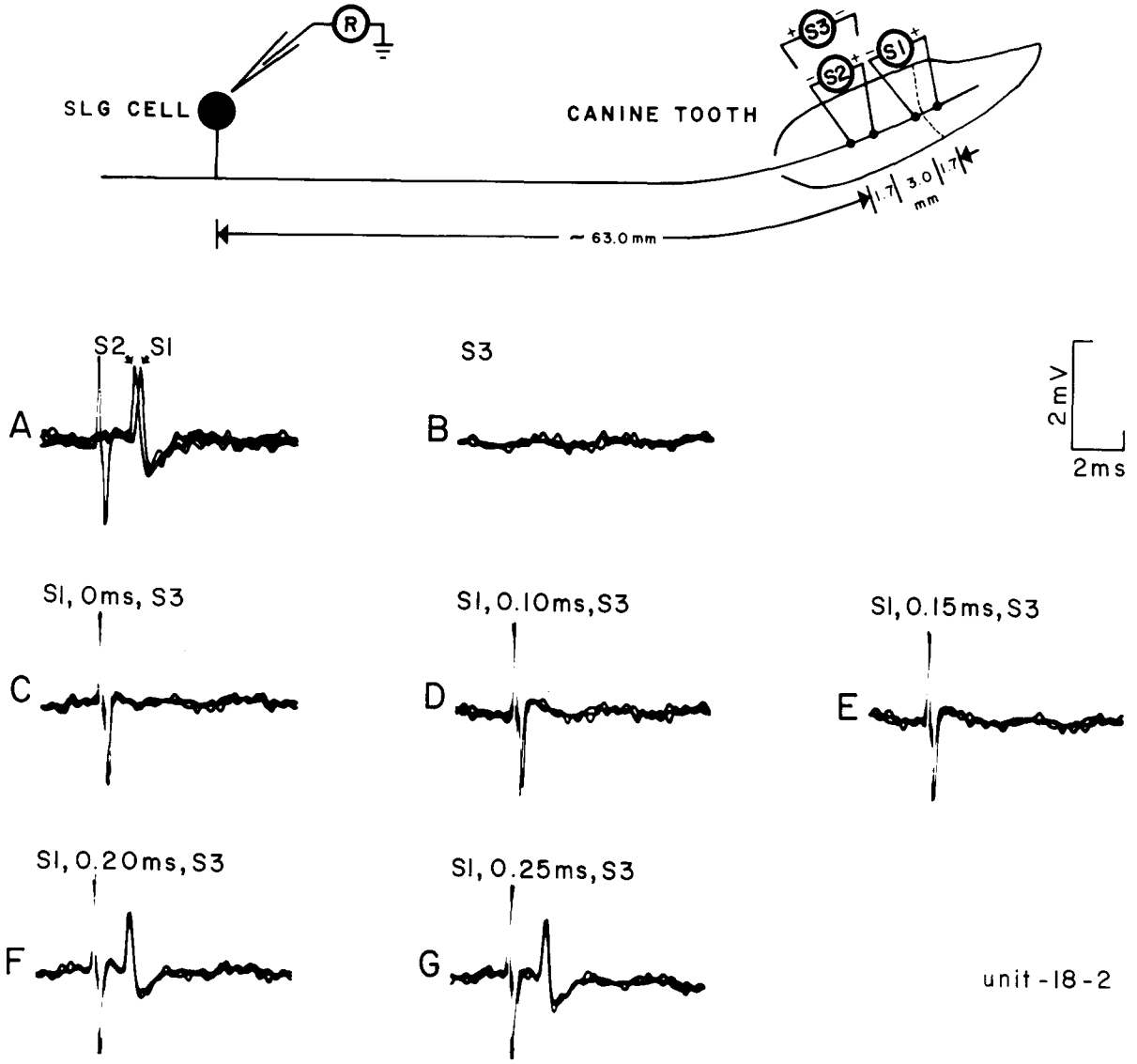

Fig. 1. Evidence for activation of intradental receptors: impulse collision test. Two pairs of bipolar (wire) stimulating electrodes were implanted into the lateral, labial side of the mandibular canine tooth. Dotted line on tooth indicates the enamel–cementum junction. Activity from a single neuron in the mandibular division of the semilunar or gasserian ganglion (SLG) was recorded extracellularly. Overlapping traces are displayed in 10 ms oscilloscope sweep lengths. 2 ms of baseline activity precedes stimulus onset. A: stimuli applied to the distal (S1) and proximal (S2) pairs of tooth electrodes at threshold current intensities evoked action potentials with onset latencies of 1.2 ms and 1.4 ms, respectively. Conduction velocities from S1 to S2 and from S2 to ganglion, respectively, were 24 and 53 m/s. Shock artifacts were elicited by S1 stimulation. B: polarity of the proximal pair of stimulating electrodes (S2) was reversed (S3) to produce antidromically conducted action potentials for the impulse collision test. No orthodromically conducted action potentials from S3 were observed at the ganglion recording site. C: stimuli were simultaneously applied to the distal (S1) and proximal (S3) electrodes. D–G: stimulus was applied to S1 and then to S3 after interstimulus intervals of 0.10 ms (D), 0.15 ms (E), 0.20 ms (F) or 0.25 ms (G). Orthodromic conduction of an action potential evoked by stimulation at S1 was blocked by subsequent stimulation at S3 if the interstimulus interval was less than 0.20 ms.

point. One or two spikes were evoked by contact or retraction of the stimulus probe. Application of the same static (pressure) and dynamic (tap, vibration) forces to adjacent gingiva, to perioral tissues and to all other teeth did not evoke responses from these single canine-related SLG cells. No responses were evoked by applying a heat stimulus from a flame-treated probe or a cold stimulus from fragments of

solidified carbon dioxide to the tooth crown for at least 1 min. The ability of these intradental mechanoreceptors to provide frequency coding or discharge signatures for different stimulus textures such as rough and smooth surfaces is illustrated in Fig. 3G. Contamination of these evoked responses by collateral afferent input from receptors in the gingiva or periodontal ligament is unlikely. Lisney and

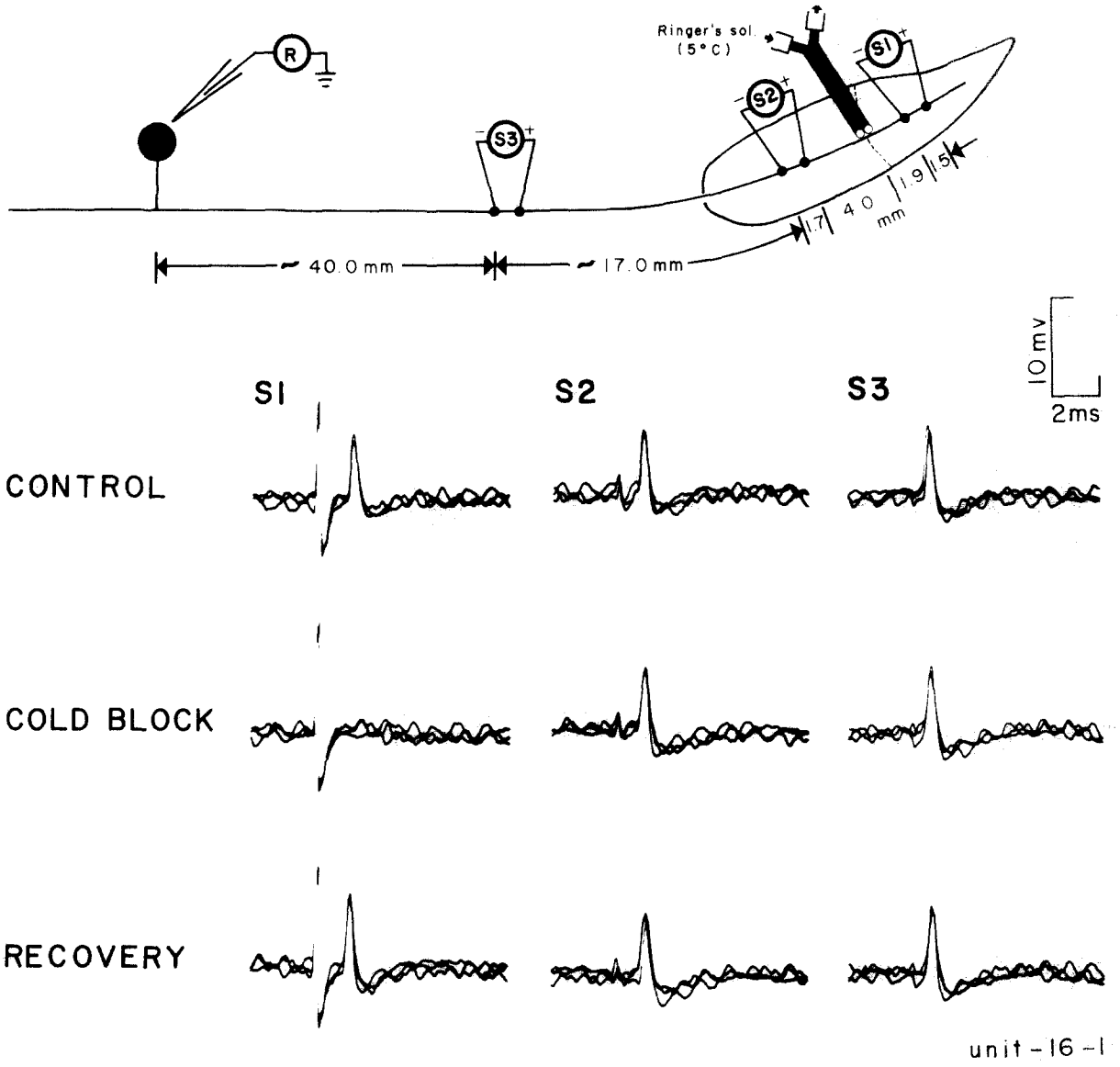

Fig. 2. Evidence for activation of intradental receptors: cold block test. Two pairs of bipolar (wire) stimulating electrodes were implanted into the lateral, labial side of the mandibular canine tooth. Dotted line on tooth indicates the enamel–cementum junction. One pair of bipolar (platinum–iridium ball) stimulating electrodes were placed on the surface of the inferior alveolar nerve (IAN). Activity from a single neuron in the mandibular division of the semilunar ganglion (SLG) was recorded extracellularly. Overlapping traces in each panel are displayed in 10 ms oscilloscope sweep lengths. 2 ms of baseline activity precedes stimulus onset. Stimuli applied to the distal (S1) and proximal (S2) pairs of tooth electrodes and to the IAN (S3) at threshold current intensities elicited action potentials with onset latencies of 1.2 ms, 1.0 ms and 0.6 ms, respectively. Conduction velocities from S1 to S2, from S2 to S3, from S2 to SLG and from S3 to SLG, respectively, were 38, 43, 57 and 67 m/s. Two cannulae (23-gauge) were implanted into the labial side of the tooth between the S1 and S2 electrodes to permit inflow and outflow of Ringer's solution through the pulp cavity. Continuous infusion of 5 °C Ringer's solution blocked S1-evoked discharges but not S2- or S3-evoked discharges. Subsequent infusion of warm Ringer's solution reversed the blockade of nerve impulse conduction.

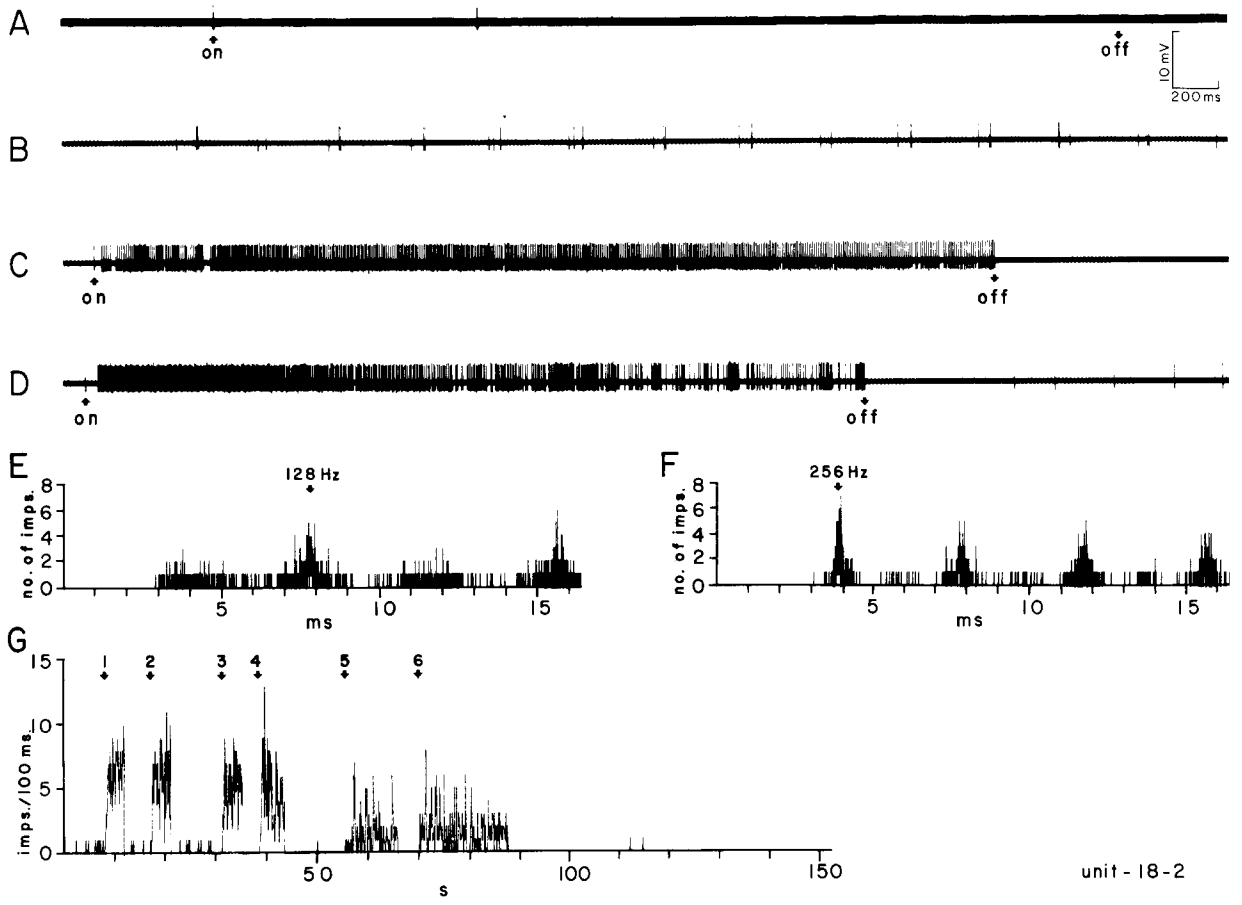

Fig. 3. Responses evoked by mechanical stimulation of the tooth. Various forces were applied to the labial side of the mandibular canine tooth in the lateral to medial direction. A: steady pressure. B: taps. Both pressure and tap stimuli were applied with a blunt probe to the tooth crown. C: 128 Hz tuning fork. D: 256 Hz tuning fork. Afterdischarges lasting several minutes were observed after high frequency stimulation in this cell. E and F: time interval histograms represent spike discharges evoked by 128 Hz and 256 Hz tuning forks. Damping of tuning fork vibrations desynchronized some discharges and reduced the frequency of other discharges to lower octaves. G: peristimulus histogram represents spike discharges evoked by rubbing sandpaper of different grit sizes (fine to coarse, arrows 1 to 4) across the anterior, labial side of the tooth. Responses following arrows 5 and 6, respectively, were evoked by rubbing relatively smooth wooden and metal rods across the same tooth surface.

Matthews[20] found tooth pulp units that responded to strong mechanical stimulation of adjacent labial gingiva but did not respond to hot or cold stimuli applied to the tooth or to displacement of the tooth which would excite receptors in the periodontal ligament. None of our tooth pulp units responded to stimulation of gingiva or to static tooth displacement. A recent anatomical study[7] showed that collateralization of an axon to innervate both the tooth pulp and periodontal tissues (gingiva and periodontal ligament) of the mandibular canine tooth in the cat is 'rare and generally unconvincing'.

Further studies are needed to determine which sites in the central nervous system receive and process intradental input related to innocuous, mechanical transients. These sites might include brainstem, thalamic and cortical loci where short latency, tooth pulp-evoked activity has been found[11,26]. Moreover, the precise location and morphology of intradental receptors that detect stimulus transients need to be elucidated. In mature teeth, free sensory nerve endings are found in the coronal plexus of Raschkow, odontobastic layer, predentin and dentin[4]. An important feature of a Pacinian corpuscle is a lamellar structure separated by fluid spaces and a specialized axonal organization; this lamellation filters out low frequency mechanical stimuli[17]. It is possible that fluid-filled dentinal tubules with their axially oriented,

unmyelinated axons also dampen low frequency, mechanical transients and thus permit receptors to respond only to high frequency stimuli. Several sensory transduction mechanisms for dentinal nerve endings have been proposed[1,4,12]. Of particular importance is the recent observation that the periodontal ligament does not contain Pacinian corpuscle-like structures[5] and the possibility that previous reports[15] may have mistaken preterminal axon bundles for encapsulated receptors in the periodontal ligament. Cash and Linden[8] suggested that only one type of periodontal mechanoreceptor exists in the periodontal ligament; these receptors do not have Pacinian corpuscle-like response properties.

Our study presents the first evidence of physiologically identified intradental receptors that detect mechanical transients applied to intact teeth. These tooth receptors may underlie the ill-defined, 'prepain' sensations and non-painful, jaw reflex activity evoked by electrical tooth stimulation[9]. Whether or not afferent input from these intradental receptors when activated by low threshold mechanical stimuli is perceived remains uncertain in view of equivocal results from studies on tactile detection thresholds in vital and non-vital teeth[18]. In contrast, numerous studies have described intradental nociceptors that detect nocuous mechanical, thermal or chemical stimuli applied invasively to exposed dentin[1,12]. It will be an important task to determine if the two receptor populations are different or identical. We speculate that intradental transient detectors provide signals about the contact of opposing teeth along their occlusal surfaces and the texture of foods during mastication and in fewer instances, provide signals about severe abrasion or percussion of tooth enamel.

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