THE EFFECT OF PRESSURE ON A MAXIMUM INCISAL BITE FORCE IN MAN

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Summary—The maximum bite force an individual can exert on an upper central incisor when the force is transmitted through a point on the incisal edge (no cover) was compared with maximum bite force when distributed over a full acrylic cap (full cover). Eighteen participants rapidly produced a maximum bite force three times each under no-cover and full-cover conditions. The magnitude and direction of the maximum bite force were monitored by a transducer placed between upper and lower incisors. There was no significant change in the direction of the bite force under the two conditions. The average maximum bite force was significantly larger (mean = 4.9%, SD = 4.6%, p < 0.001) in the full-cover condition. The increase in maximum bite force was attributed to the reduced pressure on the crown under the full-cover condition when compared with the no-cover condition. This implies the existence of mechanoreceptors within the pulp of a tooth because periodontal mechanoreceptors can affect feedback only by monitoring differences in the force on a tooth, not differences in pressure on the crown.

Key words: pressure, human, pulp, bite force, mechanoreceptors.

INTRODUCTION

It has been widely accepted that intradental receptors are exclusively involved in the sensation of pain whereas their role in the control of mastication is questioned. However, some pulpal receptors in cats apparently responded to small, transient forces (10–60 mN) rapidly applied to the tooth crown (Dong et al., 1985). These mechanoreceptors were not directionally sensitive and, unlike periodontal mechanoreceptors, discharged only a few spikes during the ramp phase of a transient force. Transiently tapping (10–150 N) a canine of an immobilized cat induced EMG activity in the digastric muscle (Olgart et al., 1988); removing the coronal pulp or cooling the crown with ethyl chloride abolished the response Olgart et al. concluded that the withdrawal reflex might have been mediated via pulpal A-fibres stimulated by the deformed tooth. However, it is not known from animal studies whether pain was involved.

The human tactile threshold to mechanical force was found to be in pulpless teeth (10–45 mN) than in vital teeth and in teeth covered by a metal cap (Loewenstein and Rathkamp, 1955), although it was argued that this difference was due to the effect of some degenerative periodontal receptors (Linden, 1975). Non-painful electrical stimulation of human incisor teeth elicited inhibitory effects in the masseter muscle (Matthews et al., 1976) and a successful stimulus to the dental pulp was not always associated with pain (Hannam et al., 1974; Matthews et al., 1976; Brown et al., 1985; Mason et al., 1985). A recent study in cats (Matthews and Vongsavan, 1994) has revealed the possible role of pulpal nerves in regulating pulpal pressure by means of vasodilatation. All of the above evidence suggests that pulpal nerves could be involved in sensory mechanisms other than pain.

A-δ and C sensory nerve fibres have been identified in the dental pulps of cats (Beasley and Holland, 1978; Lisney, 1978; Cadden et al., 1983; Virtanen et al., 1983), dogs (Wagers and Smith, 1960; Matthews, 1977; Narhi and Hirvonen, 1987) and humans (Graf and Bjorlin, 1951; Matthews et al., 1959; Reader and Foreman, 1981). The A-δ fibres are myelinated and have larger diameters and faster conduction velocities (>2 m/s and usually <30 m/s) than unmyelinated C fibres (<2 m/s) (Lisney, 1978; Narhi and Haegerstam, 1983). It is thought that both exclusively mediate noxious sensations and contribute to pain sensation, as elsewhere in the body (Mumford and Bowsher, 1976; Sessle, 1987). However, some fibres with faster conduction velocities (>30 m/s), classified as A-β fibres, have been found, and it is suggested that they mediate non-painful sensation (McGrath et al., 1983; Virtanen et al., 1987; Narhi et al., 1992). Moreover, some pulpal afferents, like periodontal mechanoreceptors, were found to have their cell...
bodies in the trigeminal mesencephalic nucleus (Chiego et al., 1980), suggesting their possible role in proprioception (Byers, 1984).

We have now investigated whether some pulpal receptors could subconsciously control the production of bite force without involving pain. Instead of using the small loads associated with tactile thresholds, we studied the response to heavy loads associated with maximum bite forces. For reasons that will be apparent later we tested whether covering the crown of a tooth changes the maximum bite force that an individual can produce.

MATERIAL AND METHODS

A U-shaped transducer was used to measure bite forces in three dimensions (Fig. 1A). Two stacked rosettes, each comprising three strain gauges (Intertechnology Inc. Calgary, Alberta, Canada), are bonded to the two vertical sides of the transducer. The six strain values are used to calculate the magnitude and direction in three dimensions of a bite force applied to the horizontal bars of the transducer (Fig. 1B).

The transducer was stabilized by moulding an acrylic resin overlay (Dura Lay) between its lower horizontal plate and the lower incisal edges. A 2-mm high acrylic wedge was built on the upper horizontal plate so that the upper incisor could be loaded at a point, the apex of the wedge (Fig. 2). The wedge was covered by a strip of fine sandpaper to prevent the tooth from slipping. A line pencilled on the sandpaper was used to ensure that the upper incisal edge was centred on the transducer. The distance between the upper and lower incisal edges was about 6 mm.

The study was approved by an Ethics Committee. Having given informed consent, 18 individuals (13 males and five females), with no evidence of tooth pathology or history of mandibular joint pain, participated. Upper and lower dental impressions were used to make plaster models on which two identical acrylic caps were made for an upper central incisor (Caulk Ortho-Resin, clear) and acrylic overlays for lower incisors (Dura Lay). The choice of left or right upper incisor was random. The incisal edge of each cap was made less than 0.5-mm thick so as to minimize the increase in jaw opening with the cap in place. A vertical line was drawn in the same position down the centre of each cap (Fig. 2B). A hole was made in the centre of the incisal edge of one cap so that when the participant bit together the force would be transmitted directly to the incisal edge of the tooth rather than spread over its whole surface through the acrylic crown (Fig. 3). In this way the participant was made unaware of the true condition of the experiment (i.e. whether biting with no cover or full cover).

The transducer with its lower overlay attached was fitted over the lower incisor teeth. The participant was guided to open and then lightly close with the lower jaw centred in the frontal plane (checked by the vertical line drawn on the acrylic and the

Fig. 1. (A) The (inverted) U-shaped transducer. Note the orientation of the rosette strain gauges on both sides. The jaw separation caused by the transducer was 5–6 mm. (B) The lower incisors were covered by acrylic and the upper incisor tip bit on a wedge.
Incisal coverage and maximum bite force

The relation between the upper and lower incisor teeth with (A) no cover, (B) full cover. Note the mandibular protrusion required to centre both upper and lower incisor teeth on the transducer. The transducer was sometimes tilted anteriorly to protect the soft tissues. The thickness of the acrylic cap at the contact point with the wedge was about 0.5 mm.

Fig. 3. The relation between the upper and lower incisor teeth with (A) no cover, (B) full cover. Note the mandibular protrusion required to centre both upper and lower incisor teeth on the transducer. The transducer was sometimes tilted anteriorly to protect the soft tissues. The thickness of the acrylic cap at the contact point with the wedge was about 0.5 mm.

upper incisor biting at the point on the wedge marked by the pencilled line. Individuals were asked to clench rapidly as hard as possible on the occluding upper incisor under two different conditions: (1) on the full crown (full cover) and (2) on the crown with a hole at its tip (no cover). They practised biting before starting the measurements and were asked to try to use the same strategy for each trial.

Measurements of the maximum bite force and its direction under each of the two conditions were repeated three times randomly and recorded at 5 Hz. A 3-min break was provided between each trial. Recording began just before the trial started and ended as soon as the subject relaxed. The duration of the maximum bite force was always less than 1 s.

It was not always possible to orient the transducer on the plaster models so that its horizontal plates were parallel to the occlusal plane, because of interference between a vertical wall of the transducer and the lingual side of the alveolar process. Its spatial orientation with respect to the lower occlusal plane was measured on the models. The angles measured on participants were later transformed into angles with respect to the lower occlusal plane.

Several individuals produced one maximum bite force which was very small compared with the others, due to some unknown discomfort. In order to eliminate these clearly abnormal results we rejected the smallest maximum bite force for every participant and averaged only the larger two results. Each averaged maximum was normalized by expressing it as the percentage of the largest single maximum recorded for that individual. Bite-force directions under different conditions were compared both in the frontal (left–right) and sagittal (front–back) planes by a paired t-test. The possibility of intraparticipant differences in the % maximum bite force for the two different conditions was also tested by a paired t-test.

**RESULTS**

Most participants reported a mild sensation of strain on the upper incisor after each trial but this disappeared during the 3-min break; none reported pain. They took between 330 and 900 ms to reach their maximum bite forces, the rate of change ranging from 158 to 400 N/s.

All the participants bit nearly vertically (symmetrically) in the frontal plane but the angle varied from about 20° forward to 20° backward in the sagittal plane (Fig. 4A). For a given individual, however, there was no significant difference in the bite direction under the two different conditions.

![Fig. 4. (A) Polar coordinate diagrams plotting the grand averages for all 18 participants. (B) The typical bite-force directions for the six bite trials in an individual participant. Each circle represents 10° away from the vertical. (F, front; B, back; R, right; L, left of the participant.)](image)
Table 1. The average normalized maximum incisal bite force (expressed as percentage of the single largest maximum bite force (MBF) recorded in each participant) in all participants for no cover and full cover (see text)

<table>
<thead>
<tr>
<th>Participant</th>
<th>Sex</th>
<th>Maximum MBF (N)</th>
<th>No cover (% MBF)</th>
<th>Full cover (% MBF)</th>
<th>Increase</th>
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<tr>
<td>R4</td>
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<td>89.2</td>
<td>+4.3</td>
</tr>
<tr>
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<td>M</td>
<td>220</td>
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</tr>
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<td>F1</td>
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<td>+7.2</td>
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<tr>
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<tr>
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</table>

M, male; F, female.

The variation of maximum bite force was large (90–370 N). The maximum and average percentages for the two different conditions are shown in Table 1.

The percentage maximum bite force recorded for the full cover was significantly larger than that for no cover (p < 0.001). The maximum bite force increased (range 2.3–12.3%) in 12 participants, was unchanged in five and decreased by 2.7% in one.

**DISCUSSION**

Hylander (1978) and Osborn and Mao (1993) have measured the directions of bite forces on incisor teeth. In both those studies the bite force was tilted anteriorly, although in the endurance tests of Osborn and Mao it moved toward vertical as the participants tired. Unlike those two experiments in which the bite forces were measured when the lower jaw was retruded, we measured the bite force with the lower jaw protruded toward the edge-to-edge position. Different amounts of protrusion may account for the variability in the bite direction in the sagittal plane and the backward direction in some participants (Fig. 4). A more forward position of the lower incisors results in a more backward bite direction, whereas a more backward position results in a more forward bite direction. In the frontal plane, all participants bit almost vertically as might be expected from the symmetrical jaw position when biting incisally.

There was little difference (< 5° in the cone of a three-dimensional angle) between the bite-force directions used by any given participant under different conditions (Fig. 4B). The result accords with those of Mao and Osborn (1994), who showed that the bite-force direction on a given tooth used by a given individual is constant regardless of its magnitude.

Most participants, when asked, reported feeling mild strain on the upper incisor tooth but not on the lower teeth, probably because the bite force was supported by only one upper tooth as opposed to two to three lower teeth. An alternative explanation is that the upper incisor is more proclined and may receive a larger torque, depending on the direction of the bite force.

Participants were asked to increase their bite force very rapidly for two reasons. First, with a rapid bite force it seemed unlikely that a voluntary correction would be made during the experiment. A change in maximum bite force would be an involuntary response. Second, it has been suggested that intradental mechanoreceptors are activated only by transient forces (Olgart et al., 1988; Dong et al., 1993).

The maximum incisal bite force ranged from 90 to 370 N. Different investigators have reported values from 50 to 240 N (Helkimo and Ingervall, 1978; Hellsing, 1980; Waltimo et al., 1993; Osborn and Mao, 1993). The variation may be due to muscle size, the shape of bones and the articulating joint tissues, the amount of jaw separation and/or instrumentation. The participant’s motivation and sensitivity to discomfort (not necessarily pain) may also affect a maximum voluntary effort.

The maximum bite force was significantly larger when the upper incisor crown was covered. We dismissed the following explanations for the results. (1) The maximum bite force might be limited by a pain threshold in the periodontal ligament. No participant complained of pain and there is no reason...
for such a threshold to change if the crown of the tooth is covered. (2) The maximum bite force might be limited by pain related to pulpal receptors (Robinson, 1964). But, again, no participant complained of pain and it was unlikely that the type of deformation studied by Robinson would have occurred here. (3) Up to a certain limit, increasing jaw separation increases the maximum bite force (Manns et al., 1979). In our own recent study of the effect of jaw opening on incisal maximum bite forces (Paphangkorakit and Osborn, 1997), the predicted increase in the maximum bite forces for an increased jaw separation of 0.5 mm was < 1%, as opposed to increases up to 12% observed here (Table 1). (4) There could be a training effect where participants perform better with practice. Our participants practised before the experiments but the sequence of tests was randomized. (5) The possibility of a change in bite direction, which would affect the maximum bite force, was discounted by the observations (Fig. 4B). (6) A change in the point at which the bite force is applied to a transducer changes the measured force, but we took care to ensure that each individual always bit in the same place on the wedge (Fig. 2).

The acrylic cap spread the load over the covered surface instead of allowing it to be concentrated at a point. Thus, for a load of 100 N, the pressure on the tooth enamel was roughly 100 N/mm² without a cap (contact area approx. 1 mm²) and about 1 N/mm² with the full cover (contact area approx. 100 mm² when the labial or palatal surface is considered as the load-bearing area for a backward or forward bite direction, respectively).

The periodontal ligament detects the torque of a force applied to a tooth, not the pressure or the point of application. Thus a force of 75 N applied to a point on the crown (Fig. 5B) has exactly the same mechanical effect on the periodontal ligament as a 75-N force spread over a large area (Fig. 5A), provided the resultant is in the same direction and acts at the same point (as in our experiment). In the two cases the only difference is the pressure on the enamel and, through the enamel, on the dentine that supports it. We postulate the existence of high-threshold intradental coronal mechanoreceptors that are responsible for limiting the maximum bite force when a tooth is subjected to a large transient bite force. They are unlikely to be the same as the low-threshold receptors whose existence others have postulated (Loewenstein and Rathkamp, 1955; Dong et al., 1985, 1993). The threshold would also presumably be lower than that of the pulpal nociceptors because none of our participants complained of pain.

The generally accepted 'hydrodynamic mechanism' of dentine sensitivity (Brannstrom, 1963) suggests that fluid moving through dentine tubules is the source of a successful stimulus. The movement of fluid through dentine has been demonstrated by placing solutions of high osmotic pressure on exposed dentine (Anderson et al., 1967). Using finite element analyses Spears et al. (1993) have shown that, if tooth enamel is anisotropic, stress from a force applied to the crown of a tooth is dissipated across the enamel–dentine junction into the dentine. Presumably the stress strains the dentine, especially that close to the loading point, and fluid is displaced through the strained tubules (Fig. 6). Transient fluid movement may stimulate nerve endings in either dentinal tubules, predentine, or the subodontoblastic plexus. The speed and volume of moving fluid may both contribute to the pulpal response. First, rapidly applied forces (as in our experiment) move fluid more rapidly and might be expected to enhance a response. Second, the more a given force is localized on a tooth the larger and more localized is the pressure increase, and the larger the local strain and the volume of local fluid movement. If the same force is spread over a larger area the stress is

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**Fig. 5.** The periodontal ligament can receive the same torque (and therefore provide the same sensory input) under different conditions. In both diagrams the moment arm is X²F: (A) 75-N force spread around the tip of the tooth, (B) 75-N force concentrated at the tip of the tooth.

**Fig. 6.** (A) Diagram showing how a bite force might deform dentinal tubules especially those around the load point. (B) An enlarged dentinal tubule close to the cusp tip is distorted and fluid is displaced into the pulpal end of the tubule (dashed lines represent the distorted condition).
reduced, but more widespread, and local flow is reduced, thereby reducing the response.

If the pulp contains mechanoreceptors that respond to fluid moving through distorted dentine and the adjacent pulp, then the deposition of peri-
tubular and secondary dentine would, perhaps, result in a reduced flow of the fluid and a concomi-
tant reduced sensitivity. This might account for
some of the different responses of our participants.

The function of pulpal mechanoreceptors, if they
exist, might be to protect a tooth by monitoring
whether potentially harmful pressure might be used
to break food. Excessive force as opposed to pressure
would be monitored by periodontal mechanore-
ceptors. But pulpal mechanoreceptors could also be
used to improve bite performance. For a given bite pressure the pressure on a nut, for example, can be
increased by reducing the area of contact between it
and the incisors. By encouraging an individual to
reposition the nut, the mechanoreceptors could be
used to increase the pressure on the nut without
increasing the force on the tooth. Finally, most food substances are anisotropic and yield more readily to force in a particular direction. A combi-
nation of pulpal and periodontal mechanoreceptors
might more readily find the most efficient position and orientation to place food between the incisors.

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