Sensory Responses from Loading of Implants: A Pilot Study

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Purpose: *Osseointegrated implants lack a periodontal ligament. Nevertheless, masticatory function in subjects with implant-supported restorations appears similar to function in those with natural dentition. It is not clear how the neurophysiologic mechanisms that modulate jaw movement are associated with osseointegrated implants. This study examined the output from the inferior alveolar nerve during implant loading.* ***Materials and Methods:*** *In 3 dogs, 3 premolars were extracted in the mandible and 2 endosseous titanium implants were placed, allowed to osseointegrate for 3 months, and loaded with vibration force at the threshold response for tooth vibration, at 2× threshold, and at 3× threshold. Neurophysiologic recordings were made from the inferior alveolar nerve during loading of both implants and the adjacent molar and canine. The response magnitude in action potentials in the 50-ms poststimulus period and latency of inferior alveolar afferents in milliseconds were compared following implant loading.* ***Results:*** *Detectable inferior alveolar nerve responses were recorded following loading from both the implants and the teeth at 2× and 3× threshold. However, the response magnitude of teeth (canine, 2.38 ± 0.18 at 2×, 2.78 ± 0.2 at 3×; molar, 2.2 ± 0.16 at 2×, 2.5 ± 0.21 at 3×) was twice that of the implants (anterior, 1.3 ± 0.12 at 2×, 1.68 ± 0.13 at 3×; posterior, 0.8 ± 0.1 at 2×, 1.53 ± 0.15 at 3×). The differences in response magnitude between the teeth and implants were significant (P $< .05$). The latency of response was similar.* ***Discussion:*** *Management of the occlusion for implant-supported restorations has been empirically developed. An underlying assumption has been that implant-guided jaw function lacks significant proprioception to modulate mastication and related jaw movements. This animal study provides preliminary evidence that force application to implants does elicit a proprioceptive response.* ***Conclusion:*** *Loading of implants does elicit a sensory response that can be observed in the inferior alveolar nerve. The implications are that during occlusal function, information from regions associated with the implant can provide knowledge that could potentially modulate jaw activity in a manner similar to natural teeth.* INT J ORAL MAXILLOFAC IMPLANTS 2004;19:44–51

Key words: *dental implants, inferior alveolar nerve, proprioception*

Studies of implant loading have reported sensory perception thresholds that are 10 to 100 times higher than those reported for natural teeth.[1–3] This has important implications with regard to the design of the occlusal morphology for implant-supported restorations.[4] Some have attributed this difference to the lack of a periodontal ligament (PDL) and suggested that self-protective mechanisms present in the PDL surrounding natural teeth are not present for implants.[5] However, both the sensory response and the masticatory function of individuals with implant-supported dental restorations are much improved compared to individuals with complete dentures, even though a PDL is lacking in both situ-

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ations.[6,7] Furthermore, although endosseous implant-supported dental restorations can reliably improve mastication,[8] patients report that such restorations "feel different" than natural teeth.[9]

Studies[10] using passive force application to reduce the effects of vibration during loading have confirmed that the threshold for applied forces is significantly higher for implants. However, these perceptual differences are lessened at force levels above threshold.[10] Maximum masticatory forces for patients with implant-supported prostheses are similar to those with natural teeth[11] and are much higher than those of patients restored with removable prostheses.[7] A study of the jaw opening reflex reported a significantly higher threshold for this response in implants compared to natural teeth.[12]

It would therefore seem evident that some sensory mechanisms are present in the peri-implant environment. These, however, have not been adequately characterized. Some have hypothesized that periosteal and mucosal receptors substitute for those in the PDL.[13] However, while mucosal and periosteal receptors are present in all edentulous patients, the perceptual abilities of subjects with implant-supported restorations are significantly superior to those with removable prostheses.[14]

Alternatively, the functional capacities of implant-supported restorations may be partially explained if residual PDL axons or free nerve endings from the connective tissue or haversian systems are responsible for peri-implant proprioception. Loescher and Robinson[15] analyzed the properties of periodontal mechanoreceptors at varying times after sectioning of the inferior alveolar nerve (IAN). Although reinnervation occurred, the number of axons reinnervated was reduced by as much as 50% and the conduction velocities were reduced by 35% to 50%, depending on the applied load. This model may be applied to the healing implant-bone interface and appears to correlate with clinical observation. On the other hand, Linden and Scott[16] examined tooth extraction sites in the cat mandible after healing was complete and were unable to identify functional nerve fibers.

Nerve fibers have been identified in connective tissue, periosteum, and mandibular bone.[17–19] In bone, both myelinated and unmyelinated fibers have been reported in haversian systems and marrow spaces. With regard to implants, Weiner and associates[20] identified the presence of axons in the peri-implant region within 250 μm of the implant interface in both bone and connective tissue using immunohistochemical staining of neurofilament with a peroxidase. Wang and coworkers[21] examined the peri-implant area histologically using urea–silver nitrate staining and found abundant nerve fibers adjacent to the implants 3 months after placement. Three-dimensional reconstruction with computer-assisted image processing software demonstrated that the nerve fiber system encircled the implants. In a more recent study, Wada and associates[22] used immunohistochemical staining to identify neurofilament protein in the peri-implant region. Using histomorphometric analysis, they concluded that the density of the nerve fibers surrounding loaded implants was twice that observed around unloaded implants. However, while these findings are impressive, the functional significance of such fibers, in particular, their ability to mediate proprioceptive information about occlusal forces, is unknown. Nevertheless the presence of such fibers in the peri-implant region suggests that when the implant is loaded, the forces that are transmitted directly to the bone may be of sufficient magnitude to elicit responses from free nerve endings present in the connective tissue and bone in the peri-implant area.

To examine this hypothesis, namely that peri-implant nerve fibers may transmit proprioceptive information from occlusal loading, this experiment was designed to make recordings from the IAN while loading implants with a variable vibratory load and to examine the relationship between load and response for both implants and natural teeth in the same quadrant in the dog model.

MATERIALS AND METHODS

All aspects of this study were approved by the Institutional Animal Care and Use Committee at the University of Medicine and Dentistry of New Jersey. Three mongrel dogs (15 to 20 kg in weight) were each anesthetized with pentobarbital (50 mg/kg) and atropine (0.01 mg/kg) and then intubated to prevent aspiration. To prevent respiratory depression, the animals were placed on a ventilator and insufflated with a tidal volume of 0.6 L/min. Three mandibular premolars were surgically removed from one side of the mandible, the alveolar bone was trimmed, and primary flap closure was obtained.

After a 2-month healing period, each animal was again anesthetized using the same protocol, and two 4 × 8-mm endosseous implants (Nobel Biocare, Göteborg, Sweden) were placed in each of the edentulous areas. Osteotomies were made with copious water irrigation, implants with cover screws were placed, and the surgical sites were sutured with primary closure. The implant sites were allowed to heal for 3 months.

For the experimental protocol, each animal was again anesthetized as previously described. To stabilize the head, a clamp was screwed to the skull

Fig 1 *(Left)* Exposure of inferior alveolar nerve *(arrow)* lateral and posterior to regions of implants.

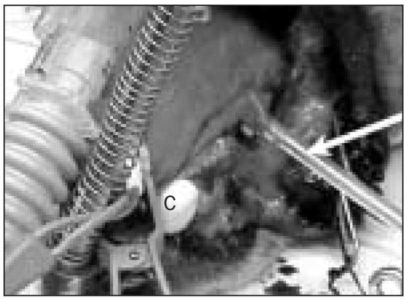

Fig 2 *(Right)* Experimental setup. The canine and anterior abutment are seen. The arrow identifies the bar connecting the anterior implant (with an impression coping) to the Ling vibrational system with autopolymerizing resin. The white resin coping covering the canine tooth (C) and is connected to the Ling vibrational system with autopolymerizing resin. The spring retractor in the left side of the photo kept the jaw open. Adjacent is the breathing tube from the respirator.

through a midline incision that reflected the scalp. A bar frame, supported by uprights screwed to the table, was then connected to the clamped skull. Clamps were placed over the incisors to secure the mandible to a custom platform screwed to the table.

A mucoperiosteal flap was raised to expose the lateral surface of the mandible distal to the terminal molar. The incision design consisted of a horizontal incision, which extended about 25 mm from the distobuccal line angle of the terminal molar. A vertical releasing incision was made from the mesial corner of the horizontal incision continuing through the mucobuccal fold to the inferior border of the mandible. A large round carbide bur and copious irrigation were used to make dimples in the cortical plate of the facial aspect of the mandible. The cortical bone was not perforated during the dimpling process. The dimples outlined a 10 × 15-mm rectangle, the base (the 15-mm side) of which coincided with the inferior border of the mandible. The dimples were then connected with the bur, again without perforating the cortical plate of the mandible. A sharp chisel placed into the outline of the rectangular window and light tapping with a mallet permitted the elevation of the cortical bone cover of the inferior alveolar canal, exposing the neurovascular bundle. Using a dissecting microscope (OPMI-1H; Zeiss, Thornwood, NY), the IAN was separated from the artery and vein and gently ligated with silk ligatures as far medial as possible.

To expose the implants, an incision was made in the mucosa along the crest of the edentulous ridge, a soft tissue flap was laid back, the cover screws were removed, and stainless steel impression copings (Nobel Biocare) were placed. An electromechanical force-generating system (Ling Dynamic Systems, Royston, Hertfordshire, United Kingdom) was used to apply damped loads to both the implants and the adjacent teeth while action potentials were recorded from the exposed IAN (Fig 1).

To connect the vibrator (V201; Ling Dynamic Systems) to the implants for loading, a 12-inch piece of 3⁄16-inch steel rod was screwed into the sprocket of the vibrator diaphragm and connected to the teeth and implants with autopolymerizing resin (Quikset; Holmes Dental, Hatboro, PA). To connect the vibrator to the natural teeth, resin copings were fabricated on stone casts obtained from impressions made at the time of implant placement for both the canine and the molar adjacent to the implants. During the experiment these copings were cemented on the teeth with polycarboxylate cement (Durelon; Premier Dental Manufacturing, Norristown, PA). The rod was attached to the coping with autopolymerizing resin. For the implants, the rod was connected to the impression coping with autopolymerizing resin. After the test was completed for each of the abutments, the rod was separated from either the steel impression coping or the resin coping with a steel 556 fissure bur HP (SS White Burs, Lakewood, NJ) mounted on a straight handpiece. The abutments were tested in the following order: canine, anterior implant, posterior implant, molar (Fig 2).

Vibrational loads were applied horizontally. Using a ring clamp and a magnetic stand, the vibrator was clamped to the surgical table in a horizontal orientation. The 3⁄16-inch rod was screwed into the sprocket on the vibrator diaphragm, and the vibrator assembly was rotated horizontally and adjusted until the steel rod contacted the coping of the intended abutment. The ring clamp was tightened to stabilize the vibrator, and the tip of the rod was connected to the abutment with autopolymerizing resin (Fig 3).

One tooth and 1 implant were connected to the vibrator at a time—either the canine and the anterior implant or the molar and the posterior implant. At the beginning of the experiment, the vibrator assembly was connected to the tooth of the tooth-implant pair, and the master gain on the amplifier (PA25E-CE, Ling Dynamic Systems) was increased until a threshold response (action potential) was

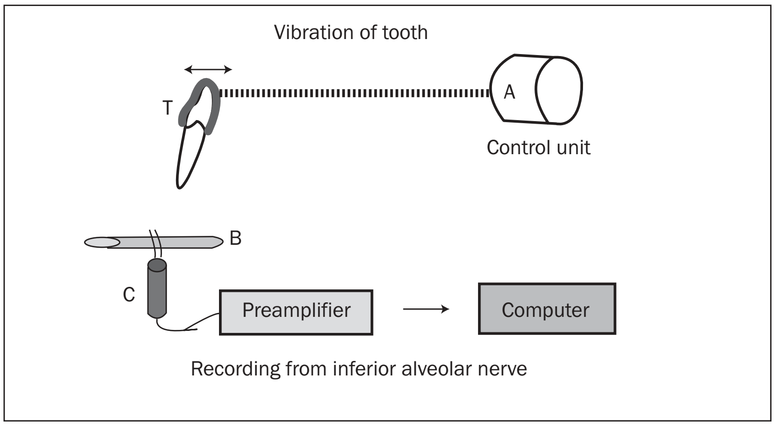

Fig 3 Schematic outline of the experimental setup. The tooth *(T)* is covered with a coping, which is attached by the bar to the vibrational unit *(A)*. The amplitude of the vibration is changed by adjusting the control unit. At the bottom of the figure, the inferior alveolar nerve *(B)* contacts the bipolar electrode *(C)*, which is connected in series to a preamplifier. The electromyographic (EMG) signal is passed through an A-D converter and saved in a microcomputer for analysis.

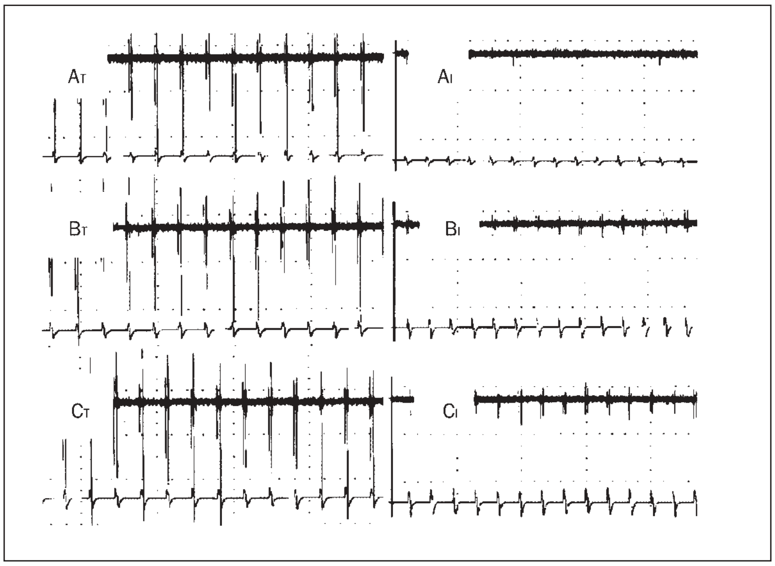

Fig 4 Traces of action potentials recorded from the IAN at threshold, 2× threshold, and 3× threshold. *(Top)* A_T represents the loading of the canine tooth at threshold; A_I represents the loading of the anterior implant at threshold. *(Center)* B_T represents the loading of the canine tooth at 2× threshold; B_I represents the loading of the anterior implant at 2× threshold. *(Bottom)* C_T represents the loading of canine tooth at 3× threshold; C_I represents the loading of the anterior implant at 3× threshold. Note that the response magnitudes from the teeth are larger than those from the implants at each level.

detected from the IAN. This initial response was called the baseline. Stimulation at 2× was achieved by doubling the amplitude of the baseline vibratory stimulation. Similarly, stimulation at 3× was achieved by tripling the baseline amplitude. The frequency of the vibration was held constant but the amplitude, and thus the load, was varied. Using 2 channels, an oscilloscope (R5103N; Tektronix, Beaverton, OR) was connected in series with both the vibrator and an analog-to-digital (A-D) converter (RC Electronics, Goleta, CA) to monitor both the amplitude of the vibration and the IAN output. Recordings were made at the tooth's threshold, 2× threshold, and 3× threshold for both the implant and the tooth for each pair. The rationale for using the threshold value for the tooth rather than a specific load value is that the PDL of the tooth and the implant-bone interface differ, such that it is likely that the loads experienced at these 2 interfaces are not the same.

Recordings were made from the exposed IAN using a custom-made, large-diameter bipolar platinum-iridium electrode. After exposure, the IAN was sectioned medially as it entered the ramus, and the distal section was placed on the electrode, which was immersed in a pool of warm paraffin oil. The electrode was connected to a probe head stage (super-Z; CWE Systems, Ardmore, PA) and the discharge was amplified (BMA-830; CWE Systems) with filters set at 5 to 10,000 Hz.

Amplified signals were visualized on the oscilloscope and passed through the A-D converter with a sampling rate of 10 kHz for storage on a microcomputer (Gateway, San Diego, CA) (Fig 4). A stimulus synchronization pulse was also recorded on a separate channel to mark the initiation of tooth or implant stimulation. Postacquisition, the data were filtered using a time-voltage window discriminator and template-matching algorithm to identify individual action potentials (Computerscope Enhanced

Table 1 Response Magnitudes

Site	Threshold	2× threshold	3× threshold
Canine	2.11 ± 0.21*	2.38 ± 0.18	2.78 ± 0.20
Anterior implant	No response	1.30 ± 0.12	1.68 ± 0.13
Molar	1.90 ± 0.17	2.20 ± 0.16	2.50 ± 0.21
Posterior implant	No response	0.80 ± 0.10	1.53 ± 0.15

*No. of action potentials generated in the 50-millisecond poststimulus period.

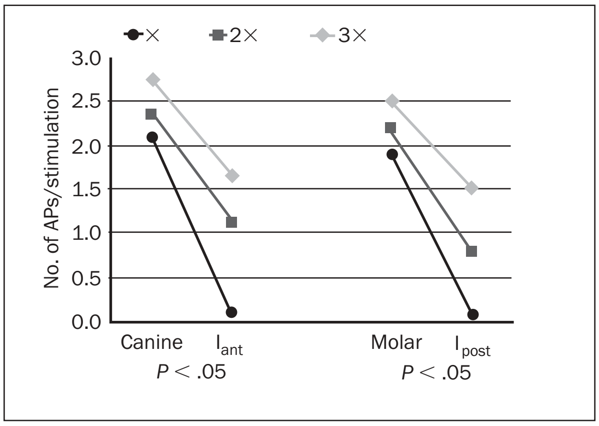

Fig 5 Results in response magnitude from loading canine versus anterior implant (I_{ant}) and first molar versus posterior implant (I_{post}). Note that at threshold for natural teeth (×) no responses were observed from implants. At highest load of 3× threshold differences in response magnitude between tooth and implant were reduced, $P < .05$. APs = action potentials.

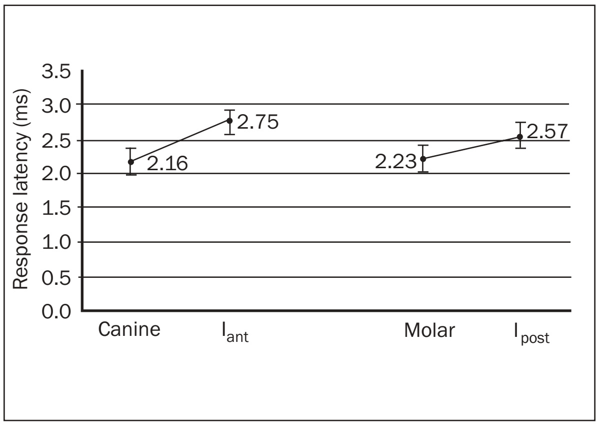

Fig 6 Results in response latency from loading canine versus anterior implant (I_{ant}) and first molar versus posterior implant (I_{post}). Although there appears to be an increase of approximately 20% in time required to obtain response after loading implant versus natural tooth, these differences were not significant.

Graphics Acquisition and Analysis System; RC Electronics). During a 50-millisecond poststimulus period, the average response magnitude (number of action potentials per stimulus) and response latency (time from onset of stimulus to first action potential) for implants and teeth were calculated from 3 stimulus trials, each consisting of 30 stimuli delivered at a rate of 2 Hz at threshold, 2× threshold, and 3× threshold. A schematic outline of the experimental setup is shown in Fig 3.

Since the data from the experiments were similar, the results presented here are a composite of the 3 experiments. After completion of the experiments, each animal was euthanized using Euthasol (Delmarva Pharmaceuticals, Midlothian, VA). For each animal, response magnitude and response latency were averaged for the trials and compared using paired t tests (canine versus implant and molar versus implant; significance level set at $P \leq .05$).

RESULTS

In these experiments, vibrational loading of implants located in the dog mandible resulted in activation of peripheral nerve fibers in the IAN. However, the teeth were significantly more sensitive to vibrational loading than the implants. Two characteristics of the response were examined, the response magnitude and the response latency. The response magnitude was measured by the number of action potentials generated during a 50-millisecond poststimulus period for each stimulus. No variation in the amplitude of the action potential could be expected, as nerve conduction along axons follows the all-or-none principle. The response latency was the time interval between initiation of the vibrational load and the first action potential observed and was measured in milliseconds.

No response was recorded from vibrational loading of the implant at the tooth's threshold in any of the trials. At 2× threshold and 3× threshold, the response from the anterior implant was approximately half that observed from the canine ($P \leq .05$) (Table 1, Figs 4 and 5). For the molar and the posterior implant, a similar magnitude difference was observed ($P \leq .05$). The magnitude differences reflect the number of action potentials recorded when a given vibrational load was applied (Fig 5).

Vibrational loading of natural teeth demonstrated a latency to the response in the IAN at a threshold that was approximately 20% shorter than that observed when vibrational loading of the implants was performed. A similar trend was observed at 2× and 3× threshold; however, these differences were not significant (Fig 6).

There was no difference in measured spontaneous activity in the IAN during tooth or implant stimulation. Furthermore, at the end of each experimental session, the IAN proximal to the implant or tooth was sectioned distal to the recording electrode to determine whether the observed response was originating in a site other than the peri-implant or periodontal/pulpal afferents. For both the implant and the adjacent teeth, all responses to stimulation were eliminated after the IAN was sectioned.

DISCUSSION

The results of this study provide additional support for the concept that implant-supported restorations have a functional capacity similar to that of natural dentition. The majority of previous research regarding implant-supported restorations has addressed biomechanical stability.[23] However, there is growing interest in the physiologic aspects of jaw function associated with implant-supported restorations. In the series of experiments reported here, action potentials were produced in the IAN at 2× and 3× the natural tooth threshold following both implant and natural tooth loading. The absence of altered spontaneous activity during tooth or implant loading and the elimination of stimulus-evoked activity following IAN section suggests that the neural response to implant loading is generated in the peri-implant zone and not other remote sites such as periosteum, mucosa, or temporomandibular joint afferents. Reliable implant-evoked responses were observed in spite of the fact that implants differ from natural teeth in that osseointegration of implants results in a close apposition between the implant and the surrounding bone, and that the PDL, which has Ruffini endings that interface between the tooth and alveolar bone, is not present in the peri-implant area.[13]

These structural differences suggest that a different signaling mechanism may be used for implants to modulate jaw movement. Several theories have been advanced. According to van Steenberghe,[5] the periosteum may be a source of proprioceptive response, since free nerve endings have been identified there. A second theory[24] postulates that occlusal loads result in strain of the bone surrounding the implant that is interpreted by the cytostructure of the osteocytes, resulting in an action potential generated in the axons of adjacent haversian systems. A third, more integrated hypothesis[25] associates these responses with muscle spindle and joint receptors that substitute for the PDL of natural teeth. Another theory, for which there is accumulating laboratory and clinical evidence, is that bone in the regions adjacent to the implant contains nerve fibers and that these may serve as a source of sensory response.[20–22] Bone strain, either compression or elongation, may serve to activate free nerve endings that project through the IAN to regions of the trigeminal system in the pons where jaw motor activity is mediated.[24]

Heraud and associates compared the effects of loading bone directly with those of implant loading and found them similar.[26] They concluded that bone does have an innervation and that loading implants stimulates the bone in the peri-implant region. Bonte and coworkers, on the other hand, while recording from the gasserian ganglion, observed responses from loading of the adjacent teeth, although no responses were observed from loading a series of maxillary implants.[27] Whatever the mechanism, it is becoming increasingly clear that 1 or more of the sensory systems present in the oral cavity provides significant proprioception that may serve to modulate jaw movement and function for implant-supported restorations.

For functional activities such as mastication, application of maximum occlusal force, and muscle coordination, Gartner and colleagues[11] demonstrated that the performances of subjects with implant-supported restorations and subjects with natural dentitions were very similar. The reaction time for jaw reflexes when loading implant-supported restorations is equivalent to that observed with natural teeth.[7] However, the ability to localize applied loads and to discriminate specific locations of force application appears to be poorer in people with implant-supported restorations.[28] While sensory input from regions in the oral cavity associated with implant-supported restorations does modulate oral motor activity, the overall sensitivity of implants appears to be less than that of natural teeth. Trulsson and Johansson,[29] who have studied periodontal responses to mechanical stimuli with differing force amplitudes, observed a markedly curved relationship between discharge rate and force amplitudes. At low forces the afferent nerves responded with the greatest sensitivity to force changes. In a study in which implants and natural teeth were compared, loads approximating the threshold of natural teeth elicited a reduced response from the implants. It was only with loads at 2× and 3× threshold that significant responses to implant loading were observed. However, even with these conditions, the responses were less than those observed around natural teeth. The functional significance of these differences is not clear.

Identification of sensory responses in the IAN to implant loading may lead to changes in the occlusal requirements for implant-supported crowns. Previously, it had been suggested that implant-supported restorations should be designed with "self-protecting" features, including restricted axial loading, "lighter" occlusal contacts (ie, that exert a lesser load with opposing teeth), and restricted contact with the opposing occlusion during lateral excursive movements.[30] The rationale for these features was that without proprioceptive information, there was a strong likelihood of excessive forces damaging the peri-implant bone. However, in light of the increasing evidence[20,22,24] that there may be sensory responses from the peri-implant area that may modulate jaw reflexes, it may be possible to utilize occlusal patterns similar to those of the natural dentition; namely, group function and mutual protection. As with the natural dentition, protective reflexes mediated by sensory responses from the peri-implant area may limit forces that could damage the peri-implant bone. However, further work is needed to understand the relationship between the biomechanical parameters that govern implant performance during occlusal loading and the physiologic mechanisms that govern jaw movement and the generation of occlusal loads. Until these understandings have been developed, clinical experience will continue to be an important basis for the use of implant-supported restorations.

The fundamental observation of this study, namely, that loading of implants evokes a response in the IAN, requires further analysis and investigation, particularly in view of its potential clinical significance. The number of animals utilized was small, but the results were consistent across the experiments. Clearly, these findings do not provide a definite conclusion regarding implant-mediated proprioception. Questions regarding the effects of occlusal forces varying in intensity or trajectory (eg, lateral versus vertical loading), occlusal forces with various types of foodstuffs, and occlusal forces during empty-mouth contacts such as clenching and bruxing will require further investigation. In addition to these physiologic questions, biologic questions such as the influence of the thickness of the bone surrounding the implant and the proximity of other structures such as the periosteum or teeth on the proproceptive responses have yet to be answered.

CONCLUSIONS

Within the limitations of this pilot animal study, the following conclusions may be made:

1. Vibration loading of implants in the dog mandible results in the generation of action potentials in the IAN.
2. The threshold for generation of action potentials from implant loading is higher than for the adjacent natural teeth.
3. The latency to the response is similar for both implants and natural teeth.

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